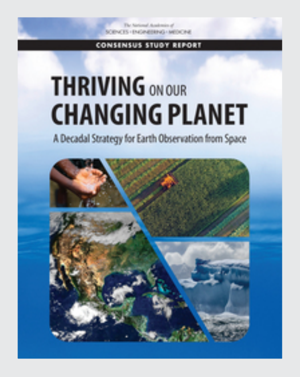

Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space (2018)

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THRIVING ON OUR CHANGING PLANET

A Decadal Strategy for Earth Observation from Space

Committee on the Decadal Survey for Earth Science and Applications from Space

Space Studies Board

Division on Engineering and Physical Sciences

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The National Academies of
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Preface

This report is the final product of the 2017-2027 decadal survey[1] for Earth science and applications from space ("ESAS 2017"), the second decadal survey in Earth science and applications from space carried out by the National Academies of Sciences, Engineering, and Medicine. The survey effort began in earnest in late 2015 with the appointment of the steering committee to conduct the study and the appointment of its supporting study panels. As shown in the statement of task (reprinted in Appendix E), the study's overarching task is to generate "recommendations for the environmental monitoring and Earth science and applications communities for an integrated and sustainable approach to the conduct of the U.S. government's civilian space-based Earth-system science programs." As discussed in Chapter 1 of this report, the interpretation of this charge resulted in recommendations that would, within known constraints such as anticipated budgets, advance Earth system science and deliver critical information to support a broad range of national economic and societal needs.

NOTE: This report is the edited and corrected version of the prepublication report released to the public on January 5, 2018. Along with customary editorial changes, the decadal survey committee has taken this opportunity to provide clarifications to the report, including the following of particular note:

- To better explain opportunities to address the underlying science of the seven Targeted Observables (TOs) that could not be allocated to a flight opportunity of the recommended program, the committee has added a table (Table 3.8) that summarizes options to address unallocated TOs within the recommended program.
- Footnote "b" to Table 3.2, footnote 7 from the Climate Panel (Chapter 9), and footnote 2 from the Earth Surface and Interior Panel (Chapter 10) now address the differing scientific objectives of the panels with respect to monitoring decadal changes in sea level, which result in different measurement requirements for the same observable.
- The caption to Figure 3.1 has been expanded to provide greater insight into the considerations that informed the prioritizations of the objectives and observables.
- TO-3, formerly "Aquatic Biogeochemistry," has been relabeled more accurately as "Aquatic-Coastal Biogeochemistry."

[1] Decadal surveys are notable in their ability to sample thoroughly the research interests, aspirations, and needs of a scientific community. Through a rigorous process, a primary survey committee and thematic panels of community members construct a prioritized program of science goals and objectives and define an executable strategy for achieving them. These reports play a critical role in defining the nation's agenda in that science area for the following 10 years—and often beyond. See National Academies of Sciences, Engineering, and Medicine, 2015, *The Space Science Decadal Surveys: Lessons Learned and Best Practices*, Washington, DC: The National Academies Press, https://doi.org/10.17226/21788.

The inaugural decadal survey[2] in this scientific domain, published in 2007, organized its work around the overarching theme of Earth system science for societal benefit. Perhaps its most notable achievement was that the various communities that constitute Earth science, which span a set of diverse disciplinary boundaries and had no tradition of coming together, were able to reach consensus on decadal research priorities. The resulting integrated program proved highly beneficial both to the sponsoring agencies and to a nation whose needs for the information and data products derived from agency programs were accelerating rapidly.[3]

ESAS 2017 was sponsored by the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS)—federal agencies with responsibilities for the planning and execution of civilian programs of Earth observations from space. Internally, the survey effort at the National Academies was led by the Space Studies Board with the close collaboration and cooperation of the staff and volunteers at the Board on Atmospheric Sciences and Climate, the Board on Earth Sciences and Resources, the Ocean Studies Board, the Polar Research Board, and the Water Sciences and Technology Board.

The survey was carried out by an appointed steering committee, which was solely responsible for this final report, including all findings and recommendations, and five appointed interdisciplinary study panels. In addition, the steering committee was informed by several informal working groups, some focusing on specific elements of the task statement and others focusing on cross-disciplinary topics (e.g., technology and innovation) and "integrating themes" (e.g., the carbon, water, and energy cycles). This structure—one of several considered—allowed for a rich and comprehensive study process by approaching the topics in the statement of task from multiple vantage points.

Designated "liaisons"—from the steering committee to each of the panels and from each panel to each of the other four panels—helped to avoid the stovepiping of information. In addition, steering committee liaisons attended panel meetings, and panel liaisons had the opportunity to attend other panel meetings. Panels met three times during the course of the study; at two of these meetings, joint sessions with a concurrently held steering committee meeting took place. The steering committee held seven in-person meetings during the course of the study. Between meetings, both the steering committee and the panels held numerous virtual meetings via WebEx. Further information on the decadal survey's organization is available at http://www.nas.edu/esas2017.

Much of the initial work of the decadal survey took place within the study panels. Their focus areas/themes were chosen so that together they spanned the major components of the Earth system. The panel organization, which was devised and confirmed by the steering committee early in the survey process, was also informed by community input received in the first request for information (RFI;[4] see Appendix D).

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[2] See National Research Council, 2007, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, Washington, DC: The National Academies Press, https://doi.org/10.17226/11820. For a review of the successes and shortcomings of the survey, see National Research Council, 2012, *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey*, Washington, DC: The National Academies Press, https://doi.org/10.17226/13405.

[3] As inferred by the size of data archives and the number of data users and data retrievals. For example, see slide 18 in the presentation by Program Executive for Earth Science Data Systems, Earth Science Division (DK), Science Mission Directorate, NASA Headquarters, "NASA's Earth Science Data Systems Program," February 16, 2016, https://smd-prod.s3.amazonaws.com/science-blue/s3fs-public/atoms/files/5-Big_Data-Earth_Science-tagged.pdf. The growth in Landsat use is discussed in M.A. Wulder, J.C. White, T.R. Loveland, C.E. Woodcock, A.S. Belward, W.B. Cohen, E.A. Fosnight, J. Shaw, J.G. Masek, and D.P. Roy, 2016, The global Landsat archive: Status, consolidation, and direction, *Remote Sensing of Environment* 185:271-283. To manage its growing data archives, National Oceanic and Atmospheric Administration has initiated a "Big Data Project" (see http://www.noaa.gov/big-data-project).

[4] The first request for information (RFI) was issued in advance of the initiation of the survey and requested community input to help understand the role of space-based observations in addressing the key challenges and questions for Earth system science in the coming decade. By design, it did not ask the community for ideas on how to address an identified challenge or question. Building on the first RFI, the second RFI requested ideas for specific science and applications targets (i.e., objectives) that promised to substantially advance understanding in one or more of the Earth system science themes associated with the survey's study panels.

Other considerations included the desire for a structure that was responsive to the agency missions and goals of the sponsors and consistent with the decadal survey statement of task.

The panels were responsible for receiving and analyzing community input; in particular, community responses to the survey-issued second RFI. Each panel included members whose collective expertise spanned the panel's topical focus areas from science to applications. With input from the panels, the steering committee then developed proposed observing system priorities that integrated goals for understanding and monitoring the Earth system with those that emphasize the use of observations in a range of applied settings. The panels and their focus areas were as follows:[5]

I. *Global Hydrological Cycles and Water Resources*
The movement, distribution, and availability of water and how these are changing over time.
II. *Weather and Air Quality: Minutes to Subseasonal*
Atmospheric dynamics, thermodynamics, chemistry, and their interactions at land and ocean interfaces.
III. *Marine and Terrestrial Ecosystems and Natural Resource Management*
Biogeochemical cycles, ecosystem functioning, biodiversity, and factors that influence health and ecosystem services.
IV. *Climate Variability and Change: Seasonal to Centennial*
Forcings and feedbacks of the ocean, atmosphere, land, and cryosphere within the coupled climate system.
V. *Earth Surface and Interior: Dynamics and Hazards*
Core, mantle, lithosphere, and surface processes; system interactions; and the hazards they generate.

ESAS 2017 STATEMENT OF TASK

To address the elements of the ESAS 2017 statement of task, the steering committee (the "committee") focused its work in the following four broad areas:

1. Assessment of the past decade's progress,
2. Establishment of a vision and strategy for the future decade,
3. Prioritization of science and applications targets and mapping these to an observing plan,
4. Development of guidance on implementation of the plan specific to the requests made by
    a. NASA
    b. NOAA and USGS.

Within areas 2 and 3 of this list, the statement of task requests that priorities focus on science, applications, and observations, rather than the instruments and missions required to carry out those observations. In particular, the statement of task requests that the committee "recommend NASA research activities to advance Earth system science and applications by means of a set of prioritized strategic '*science targets*' [expanded by the steering committee to be science and applications targets] for the space-based observation opportunities in the decade 2018-2027." As described in more detail in Chapter 3, a "science target" is "a

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[5] Throughout this report, references to panels are also abbreviated as follows: Global Hydrological Cycles and Water Resources = "Hydrology" or "H"; Weather and Air Quality: Minutes to Subseasonal = "Weather" or "W"; Marine and Terrestrial Ecosystems and Natural Resource Management = "Ecosystems" or "E"; Climate Variability and Change: Seasonal to Centennial = "Climate" or "C"; and Earth Surface and Interior: Dynamics and Hazards = "Solid Earth" or "S."

set of science objectives related by a common space-based observable." The steering committee defined the observable associated with each science target as a "targeted observable."

ESAS 2017: STRUCTURE AND KEY FEATURES OF THE REPORT

The structure and key features of this report reflect its rather detailed statement of task. In particular,

- As requested, the committee's recommended strategy is one that will advance fundamental understanding of the Earth system and provide knowledge that can be applied in service to society.
- The report, per the statement of task, provides recommended approaches to facilitate the development of a robust, resilient, and appropriately balanced U.S. program of Earth observations from space.
  - — Responding to task elements specific to NASA, the report provides a prioritized list of top-level science and application "objectives," with attention to gaps and opportunities in the program of record and the feasibility of measurement approaches. Task elements pertaining to NASA also include specific requests for an analysis of the balance between major program elements in the Earth Science Division (ESD) and, within its flight element, the balance among investments into the various program elements.
  - — Task elements pertaining specifically to NOAA and USGS focus on how to make existing and planned programs more effective with respect to their utility to users and their cost-effectiveness, including through technology innovation.
- Per the 2008 NASA Authorization Act,[6] ESAS 2017 arranged for an independent Cost Assessment and Technical Evaluation (CATE)[7] of the major candidate investments being considered for prioritization. This analysis was performed by the Aerospace Corporation, which also performed CATEs as part of recent National Academies decadal surveys in solar and space physics, planetary science, and astronomy and astrophysics (see Chapter 3 for details).
  - — To facilitate the development and implementation of its recommended program for NASA's ESD, the ESAS 2017 committee assumed the availability of resources at the levels anticipated at the time the survey was initiated.[8] It also provides "decision rules" to guide responses in the event of unexpected technical or budgetary problems.
- The ESAS 2017 steering committee and its study panels carefully considered opportunities to lower the cost of making research-quality Earth observations by leveraging advances in technology, international partnerships, and the capabilities emerging in the commercial sector. Attention was also given to the exploitation of "big data" for Earth science.
- NASA, like all federal agencies, is faced with difficult choices among competing priorities for investment. Within the ESD, these choices include whether to invest in the continuation of one existing data stream over another or to develop a new measurement capability sought by the research

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[6] Section 1104 of the 2008 Act, "Directs the Administrator to enter into agreements periodically with the National Academies for decadal surveys to take stock of the status and opportunities for Earth and space science discipline fields and aeronautics research and to recommend priorities for research and programmatic areas over the next decade." Further, the Act, "Requires that such agreements include independent estimates of life cycle costs and technical readiness of missions assessed in the surveys whenever possible." See National Aeronautics and Space Administration Authorization Act of 2008, P.L. 110-422, Section 1104 (October 15, 2008).

[7] See Appendix B, "Implementing the CATE Process," in National Academies of Sciences, Engineering, and Medicine, 2015, *The Space Science Decadal Surveys: Lessons Learned and Best Practices*, Washington, DC: The National Academies Press, https://doi.org/10.17226/21788.

[8] As explained in Chapter 3, NASA officials provided the survey with a budget history and indicated that large-scale changes to recent funding levels were not anticipated. Recommendations in the present report are based on the assumption that the then current budget would only grow with inflation.

community. In developing a recommended program that could be executed within the highly constrained budgets anticipated by NASA, the steering committee and panels also faced the difficult challenge of striking an appropriate balance between these competing demands. The transfer of responsibility from NOAA to NASA for several "continuity" measurements without budget increases commensurate with the new responsibility added to the challenge.[9]

- Survey deliberations benefited from a close read of several high-level guidance documents from the executive branch.[10]

Finally, this report would not have been possible without the assistance of the sponsoring agencies and colleagues in the research and applications community. The steering committee is grateful to leaders across NASA, NOAA, and USGS for their support of the survey effort; in particular, they provided the detailed programmatic information that the committee and panels required to understand the context for their prioritization. In addition, the decadal survey could not have been completed without the substantial and substantive work that colleagues put into the composition of white papers and participation in town hall meetings. These inputs were especially important to the work of the interdisciplinary panels whose outputs form the basis of the exciting science and applications that are the foundation of the survey's recommended program. We would also like to acknowledge the assistance of the Aerospace Corporation, which provided an independent analysis of the cost and technical feasibility of options to realize survey science priorities.

OUTLINE OF THE REPORT

This report is organized in two parts, as follows; shown in bold is the major theme of each chapter:

PART I—Report of the Steering Committee. The full steering committee report.

Chapter 1. A **Vision** for the Decade.

Chapter 2. A Decadal **Strategy**. This chapter reviews progress over the past decade, assesses emerging scientific and societal needs, and builds from that foundation to identify a strategic framework for the next decade.

Chapter 3. A Prioritized **Program** for Science, Applications, and Observations. This chapter describes the process used by the committee to identify and prioritize observational needs, and presents the recommended strategy to provide a robust and balanced U.S. program of Earth observations from space that is consistent with agency-provided budget expectations.

Chapter 4. Agency Programmatic **Context**. This chapter addresses some of the key agency-specific issues identified as being important programmatically in the implementation of the recommended program.

Chapter 5. Conclusion.

PART II—Panel Inputs. Chapters contributed by the five study panels.

Chapter 6. Global Hydrological Cycles and Water Resources

Chapter 7. Weather and Air Quality: Minutes to Subseasonal

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[9] The present survey benefited from the analysis framework presented in National Academies of Sciences, Engineering, and Medicine, 2015, *Continuity of NASA Earth Observations from Space: A Value Framework*, Washington, DC: The National Academies Press, https://doi.org/10.17226/21789.

[10] These are discussed in Tim Stryker, Director, U.S. Group on Earth Observations Program, "National Civil Earth Observations Planning and Assessment," presented at the ASPRS 2015 Annual Conference, May 7, 2015, https://calval.cr.usgs.gov/wordpress/wp-content/uploads/ASPRS-slides_Stryker_final.pdf.

Chapter 8. Marine and Terrestrial Ecosystems and Natural Resource Management
Chapter 9. Climate Variability and Change: Seasonal to Centennial
Chapter 10. Earth Surface and Interior: Dynamics and Hazards

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Mark Abbott, Woods Hole Oceanographic Institution,
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Carl Wunsch, NAS, Harvard University.

Although the reviewers listed earlier provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Charles F. Kennel, NAS, University of California, San Diego, and Thomas H. Vonder Haar, NAE, Colorado State University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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[2] Member, National Academy of Engineering.

IN MEMORY OF MOLLY MACAULEY

Molly Macauley, a member of the steering committee, passed away during the committee's tenure in July 2016. Molly was a very special person, a true friend to many of us, and a tremendous colleague to all. Her contributions, from the perspective of an economist, impacted the entire field of Earth observation. Her clarity of thought strongly influenced the early directions of this committee; that clarity was deeply missed during the remainder of our work. Molly had an unparalleled talent for voicing unanticipated perspectives that redirected discussions and brought difficult issues into instant focus. She ensured that we stayed grounded in the reality of how our work directly and deeply impacts people's lives. She drove us to quantify that value and communicate it clearly. Her loss will continue to be felt by our entire community for a long time.

Waleed Abdalati and Bill Gail
On Behalf of the Steering Committee, Panels, and Staff

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PART I: REPORT OF THE STEERING COMMITTEE

PART II: PANEL INPUTS

APPENDIXES[1]

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[1] Note that Appendixes A through G are not included in the print version of this report. They appear in the electronic version of the report, which is posted as a free PDF on the National Academies Press website at https://www.nap.edu/catalog/24938.

PART I

Report of the Steering Committee

Summary

This report, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, of the National Academies of Sciences, Engineering, and Medicine's 2017-2027 decadal survey for Earth science and applications from space (ESAS 2017) is the second such decadal survey of the National Academies. This summary provides a comprehensive overview of the present decadal survey and its key findings and recommendations; however, readers should note that space limitations do not permit a detailed discussion of each of the report's 17 findings and 20 recommendations.

EARTH OBSERVATION FROM SPACE: A TRANSFORMATIVE CAPABILITY

From the time of the earliest humans, knowledge about Earth has been fundamental to our fate and prospects. Over the past 60 years, particularly rapid progress has been achieved in acquiring such scientific and practical knowledge, due in large part to the special perspective provided by "satellite-based Earth observations."

The vantage point of space enables us to see the extent to which Earth's ever-changing processes influence our lives. These processes operate at local spatial scales, such as the flows of rivers that provide freshwater and the weather and climate conditions that determine crop yields, as well as at global spatial scales, such as changes in the ocean currents that impact commercial fishing and contribute to global change and climate variability. The space-based vantage point also ensures that we can observe processes occurring over a wide range of time scales, from the abrupt (such as earthquakes) to the decadal (such as growth and shrinkage of the world's great ice sheets), and at all time scales in between.

Empowered by this perspective, we are coming to recognize the complex and continually changing ways by which Earth's processes occur, along with the critical roles their observation and understanding play throughout our lives.

Finding 1.1: Space-based Earth observations provide a global perspective of Earth that has

- Over the last 60 years, transformed our "scientific understanding" of the planet, revealing it to be an integrated system of dynamic interactions between the atmosphere, ocean, land, ice, and human society across a range of spatial and temporal scales, irrespective of geographic, political, or disciplinary boundaries.

- In the past decade in particular, enabled "societal applications" that provide tremendous value to individuals, businesses, the nation, and the world. Such applications are growing in breadth and depth, becoming an essential information infrastructure element for society as they are integrated into people's daily lives.

THRIVING ON OUR CHANGING PLANET

This ability to observe our planet comprehensively matters to each of us. Earth information—for use in Internet maps, daily weather forecasts, land-use planning, transportation efficiency, and agricultural productivity, to name a few—is central to our lives, providing substantial contributions to our economies, our national security, and our personal safety. It helps ensure we are a ***thriving*** society.

The Earth information we have come to rely on throughout our daily lives is the result of a sustained commitment to both exploratory and applied Earth science, and to what has become a sophisticated national and international infrastructure of observing systems, scientific research, and applications. A particular strength of the Earth science and applications field is the extent to which curiosity-based science is inextricably integrated with applications-oriented science and societal benefits. Ongoing commitment to this inspirational and practical science has returned benefits to society many times over, and will continue to do so with further support.

Among the most intellectually and practically important revelations from the past 60 years of space-based observation is the extent to which *Earth is* ***changing****, in multiple ways and for many reasons.* Daily changes, such as weather, were obvious to even the earliest humans, even if not explainable. Longer-term changes, particularly those occurring on global scales, are only now becoming understood and gaining public recognition. Some of these changes are climate related, such as alteration of the El Niño Southern Oscillation (ENSO), but many are not. In addition to climate, changes in air quality, water availability, agricultural soil nutrients, and other Earth resources are being driven largely by human actions. Successfully managing risks and identifying opportunities associated with these changes requires a clear understanding of both the human-driven and the natural processes that underlie them.

A CHALLENGING VISION FOR THE DECADE AND BEYOND

A changing Earth is one we can never understand just from past experience. Its evolving and emerging characteristics must be continually explored through observation. Our scientific curiosity must seek and reveal the new and altered processes that will result from change, if we are to continue applying our knowledge effectively for society's benefit. Decisions we make this decade will be pivotal for predicting the potential for future changes and for influencing whether and how those changes occur. Embracing this new paradigm of understanding a changing Earth, and building a program to address it, is our major challenge for the coming decade and beyond.

Recommendation 2.1: Earth science and applications are a key part of the nation's information infrastructure, warranting a U.S. program of Earth observations from space that is robust, resilient, and appropriately balanced. NASA, NOAA, and USGS, in collaboration with other interested U.S. agencies, should ensure efficient and effective use of U.S. resources by strategically coordinating and advancing this program at the national level, as also recommended in the 2007 Earth Science and Applications from Space (ESAS) decadal survey.

This context of both societal need and intellectual opportunity provided the basis for developing the Earth observation program proposed in this report. Society's fundamental desire to thrive, the expanding scientific knowledge needed to support that desire, and the growing capacity to apply that knowledge are all central motivations for this committee's recommendations. Embracing the goal of understanding Earth in pursuit of this vision—*to thrive on our changing planet*—motivates a new paradigm for the coming decade and beyond.

Earth Science and Applications Paradigm for the Coming Decade

Earth science and derived Earth information have become an integral component of our daily lives, our business successes, and society's capacity to thrive. Extending this societal progress requires that we focus on understanding and reliably predicting the many ways our planet is changing.

A STRUCTURED APPROACH TO ACHIEVING PROGRESS

The next decade is one in which progress will not come easily. Financial and human resource constraints are likely to present challenges to progress (Chapter 1). Succeeding compels NASA, NOAA, and USGS to develop, adopt, and implement strategies to advance both technology and programmatic processes. The committee recommends eight elements (numbered only for identification) of a suggested *strategic framework* (Chapter 2):

1. Commit to sustained science and applications;
2. Embrace innovative methodologies for integrated science/applications;
3. Amplify the cross-benefit of science and applications;
4. Leverage external resources and partnerships;
5. Institutionalize programmatic agility and balance;
6. Exploit external trends in technology and user needs;
7. Expand use of competition; and
8. Pursue ambitious science, despite constraint.

The challenges ahead, and the need for innovative and strategic thinking to overcome them, are reflected in the following community challenge.

Decadal Community Challenge

Pursue increasingly ambitious objectives and innovative solutions that enhance and accelerate the science/applications value of space-based Earth observation and analysis to the nation and to the world in a way that delivers great value, even when resources are constrained, and ensures that further investment will pay substantial dividends.

The committee believes that meeting the challenge described earlier will motivate the scientific community to pioneer *novel approaches* in how it conducts its scientific research, with an emphasis on programmatic and technological innovation to accomplish more with less, with greater attention to the potential benefits of domestic and international partnerships along with the growing capability of commercial sources (Chapters 3 and 4).

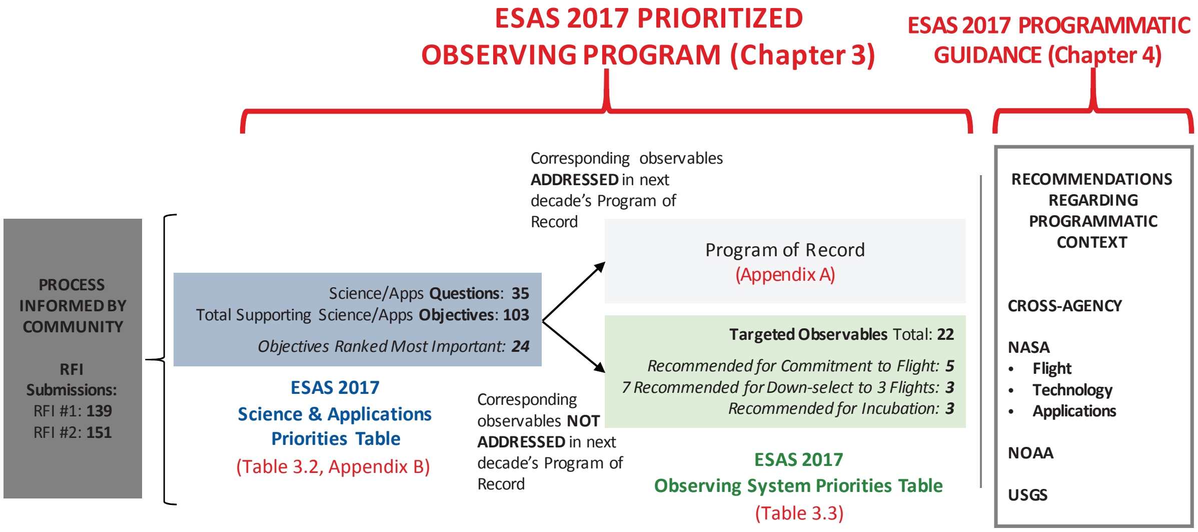

FIGURE S.1 Roadmap for the 2017 Earth Science and Applications from Space (ESAS 2017) decadal survey report based on the survey committee's approach to identifying priorities for the coming decade, starting from community requests for information (RFIs), refining this input to determine priority science and applications questions and objectives, and then identifying new observing system priorities (assuming completion of the program of record). These priorities are complemented by programmatic recommendations.

The committee conducted its work in close collaboration with the decadal survey's five study panels, each interdisciplinary and together spanning all of the disciplines associated with Earth system science. The survey process is summarized in Figure S.1. It was designed to converge—from a large number of community-provided possibilities—to a final, small set of Science and Applications Priorities (shown in blue) and Observing System Priorities (shown in green) that are required to address the nation's Earth science and applications needs. *This process assumed that the existing and planned instruments in the Program of Record (POR) are implemented as expected.*

ESTABLISHING SCIENCE AND APPLICATIONS PRIORITIES

Starting from an initial set of 290 community-submitted ideas, the five interdisciplinary panels, and then the committee narrowed this large set of ideas to a set of *35 key Earth science and applications questions* to be addressed over the next decade. Together, these questions comprehensively address those areas for which advances are most needed in both curiosity-driven and practically focused Earth science and the corresponding practical uses of Earth information. To identify the observational capabilities required to answer these questions, the committee then defined a set of underlying science and applications objectives, evaluating and assigning each to one of three prioritization categories: Most Important (MI), Very Important (VI), and Important (I).

This process informed the committee's Recommendation 3.1 that NASA, NOAA, and USGS pursue the key science and applications questions summarized in Table S.1 (and described in more detail in the body

TABLE S.1 Science and Applications Priorities for the Decade 2017-2027 (see note following table for description)

Science and Applications Area	Science and Applications Questions Addressed by Most Important Objectives
Coupling of the Water and Energy Cycles	**(H-1)** How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods? **(H-2)** How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally, and globally, and what are the short- and long-term consequences?
Ecosystem Change	**(E-1)** What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space? **(E-2)** What are the fluxes (of carbon, water, nutrients, and energy) *between* ecosystems and the atmosphere, the ocean, and the solid Earth, and how and why are they changing? **(E-3)** What are the fluxes (of carbon, water, nutrients, and energy) *within* ecosystems, and how and why are they changing?
Extending and Improving Weather and Air Quality Forecasts	**(W-1)** What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean, and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations? **(W-2)** How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months? **(W-4)** Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do? **(W-5)** What processes determine the spatiotemporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?
Reducing Climate Uncertainty and Informing Societal Response	**(C-2)** How can we reduce the uncertainty in the amount of future warming of the Earth as a function of fossil fuel emissions, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?
Sea-Level Rise	**(C-1)** How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage? **(S-3)** How will local sea level change along coastlines around the world in the next decade to century?
Surface Dynamics, Geological Hazards, and Disasters	**(S-1)** How can large-scale geological hazards be accurately forecasted in a socially relevant time frame? **(S-2)** How do geological disasters directly impact the Earth system and society following an event? **(S-4)** What processes and interactions determine the rates of landscape change?

Very Important (Summarized)	Important (Summarized)
(H-4) Influence of water cycle on natural hazards and preparedness **(W-3)** Influence of Earth surface variations on weather and air quality **(C-3)** Impacts of carbon cycle variations on climate and ecosystems **(C-4)** Earth system response to air-sea interactions **(C-5)** Impact of aerosols on global warming **(C-6)** Improving seasonal to decadal climate forecasts **(C-7)** Changes in decadal scale atmospheric/ocean circulation and impacts **(C-8)** Consequence of amplified polar climate change on Earth system	**(H-3)** Freshwater availability and impacts on ecosystems/society **(W-6)** Long-term air pollution trends and impacts **(W-7)** Processes influencing tropospheric ozone and its atmospheric impacts **(W-8)** Methane variations and impacts on tropospheric composition and chemistry **(W-9)** Cloud microphysical property dependence on aerosols and precipitation **(W-10)** Cloud impacts on radiative forcing and weather predictability **(E-4)** Quantifying carbon sinks and their changes **(E-5)** Stability of carbon sinks

TABLE S.1 Continued

Very Important (Summarized)	Important (Summarized)
(S-5) How energy flows from the core to Earth's surface **(S-6)** Impact of deep underground water on geologic processes and water supplies	**(C-9)** Impacts of ozone layer change **(S-7)** Improving discovery of energy, mineral, and soil resources

NOTE: The highest-priority questions (defined as those associated with Most Important objectives) are listed in full; other questions associated with Very Important or Important objectives are briefly summarized. No further priority is assumed within categories, and the topics are listed alphabetically. Letter and number combinations in parentheses refer to the panel (H = Hydrology, W = Weather, E = Ecosystems, C = Climate, S = Solid Earth) and the numbering of each panel's questions. Complete versions of this table are provided in Table 3.2 and in Appendix B.

of the report; complete versions of this table are provided in Table 3.2 and Appendix B). These questions address the central science and applications priorities for the coming decade.

Recommendation 3.1: NASA, NOAA, and USGS, working in coordination, according to their appropriate roles and recognizing their agency mission and priorities, should implement an integrated programmatic approach to advancing Earth science and applications that is based on the *questions and objectives* listed in Table 3.2, "Science and Applications Priorities for the Decade 2017-2027."

By pursuing these priorities, important advances will be made in areas that are both scientifically challenging and of direct impact to how we live. A major component of the committee's observing program recommendations is a commitment to a set of observation capabilities, outlined in the next section that will enable substantial progress in all of the following science and applications areas:

- Providing critical information on the *make-up and distribution of aerosols and clouds*, which in turn improve predictions of future climate conditions and help us assess the impacts of aerosols on human health;
- Addressing key questions about how *changing cloud cover and precipitation* will affect climate, weather, and Earth's energy balance in the future, advancing understanding of the movement of air and energy in the atmosphere and its impact on weather, precipitation, and severe storms;
- Determining the extent to which the *shrinking of glaciers and ice sheets*, and their contributions to sea-level rise, is accelerating, decelerating, or remaining unchanged;
- Quantifying *trends in water stored on land* (e.g., in aquifers) and the implications for issues such as water availability for human consumption and irrigation;
- Understanding *alterations to surface characteristics and landscapes* (e.g., snow cover, snowmelt, landslides, earthquakes, eruptions, urbanization, land-cover, and land use) and the implications for applications such as risk management and resource management;
- Assessing the *evolving characteristics and health of terrestrial vegetation and aquatic ecosystems*, which is important for understanding key consequences such as crop yields, carbon uptake, and biodiversity; and
- Examining *movement of land and ice surfaces* to determine, in the case of ice, the likelihood of rapid ice loss and significantly accelerated rates of sea-level rise, and in the case of land, changes in strain rates that impact and provide critical insights into earthquakes, volcanic eruptions, landslides, and tectonic plate deformation.

In addition, the committee is proposing competitive observational opportunities, also outlined in the next section, to address at least three of the following science and applications areas:

- Understanding the *sources and sinks of carbon dioxide and methane* and the processes that will affect their concentrations in the future;
- Understanding *glacier and ice sheet contributions to rates of sea-level rise* and how they are likely to impact sea-level rise in the future;
- Improving understanding of *ocean circulation*, the exchanges between the ocean and atmosphere, and their impacts on weather and climate;
- Assessing *changes in ozone and other gases* and the associated implications for human health, air quality, and climate;
- Determining the *amount and melt rates of snow* and the associated implications for water resources, weather, climate, flooding, drought, and so on;
- Quantifying biomass and characterizing ecosystem structure to assess *carbon uptake from the atmosphere and changes in land cover* and to support resource management; and
- Providing critical insights into the *transport of pollutants, wind energy, cloud processes, and how energy moves* between the land or ocean surfaces and the atmosphere.

The recommended program will advance scientific knowledge in areas that are ripe for discovery and that have direct impact on the way we live today. The knowledge developed in the coming decade, through this science, holds great promise for informing actions and investments for a successful future.

IMPLEMENTING AN INNOVATIVE OBSERVING PROGRAM

Addressing the committee's priority science and applications questions requires an ongoing commitment to existing and planned instruments and satellites in the POR. The committee's recommended observing program builds from this, filling gaps in the POR where observations are needed to address the key science and applications objectives for the coming decade. This observing program is summarized in Table S.2 (Table 3.3 in Chapter 3) and in the accompanying Recommendation 3.2. Most observables are allocated to two new NASA flight program elements: a committed group of observations termed "Designated," along with a competed group termed "Earth System Explorer." Within these two new flight program elements, eight of the priority observation needs from Table S.2 are expected to be implemented as instruments, instrument suites, or missions. In addition, several observables are assigned to a new program element called "Incubation," intended to accelerate readiness of high-priority observables not yet feasible for cost-effective flight implementation. Finally, an expansion of the Venture program is proposed for competed small missions to add a focus on continuity-driven observations. Together, these new program elements complement existing NASA flight program elements such as the Venture program.

The foundational observations in Table S.2—the five shown in the "Designated" column that are recommended specifically by the committee for implementation, and the three to be competitively selected from among the identified set of seven "Earth System Explorer" candidates—augment the existing POR and ensure that the survey's 35 priority science and applications questions can be effectively addressed, to the extent that resources allow. In keeping with the study's statement of task, specific missions and instruments were not identified, ensuring that the sponsoring agencies will have discretion for identifying the most cost-effective and appropriate space-based approaches to implementing the recommended set of observations. Each of the new NASA flight program elements promises innovative means for using

TABLE S.2 Observing System Priorities (see note following table for description)

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Aerosols	*Aerosol properties, aerosol vertical profiles, and cloud properties* to understand their effects on climate and air quality	Backscatter lidar and multichannel/multiangle/polarization imaging radiometer flown together on the same platform	X		
Clouds, Convection, and Precipitation	*Coupled cloud-precipitation state and dynamics* for monitoring global hydrological cycle and understanding contributing processes including cloud feedback	Dual-frequency radar, with multifrequency passive microwave and sub-mm radiometer	X		
Mass Change	*Large-scale Earth dynamics* measured by the changing mass distribution within and between the Earth's atmosphere, oceans, groundwater, and ice sheets	Spacecraft ranging measurement of gravity anomaly	X		
Surface Biology and Geology	*Earth surface geology and biology*, ground/water temperature, snow reflectivity, active geologic processes, vegetation traits, and algal biomass	Hyperspectral imagery in the visible and shortwave infrared (IR), multi- or hyperspectral imagery in the thermal IR	X		
Surface Deformation and Change	*Earth surface dynamics* from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	X		
Greenhouse Gases	*CO_2 and methane fluxes and trends*, global and regional with quantification of point sources and identification of sources and sinks	Multispectral shortwave IR and thermal IR sounders; or lidar*		X	
Ice Elevation	*Global ice characterization* including elevation change of land ice to assess sea-level contributions and freeboard height of sea ice to assess sea ice/ocean/atmosphere interaction	Lidar*		X	
Ocean Surface Winds and Currents	*Coincident high-accuracy currents and vector winds* to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift	Doppler scatterometer		X	
Ozone and Trace Gases	*Vertical profiles of ozone and trace gases* (including water vapor, CO, NO_2, methane, and N_2O) globally and with high spatial resolution	UV/VIS/IR microwave limb/nadir sounding and UV/VIS/IR solar/stellar occultation		X	
Snow Depth and Snow Water Equivalent	*Snow depth and snow water equivalent*, including high spatial resolution in mountain areas	Radar (Ka/Ku band) altimeter; or lidar*		X	
Terrestrial Ecosystem Structure	*3D structure of terrestrial ecosystem* including forest canopy and aboveground biomass and changes in aboveground carbon stock from processes such as deforestation and forest degradation	Lidar*		X	
Atmospheric Winds	*3D winds in troposphere/planetary boundary layer (PBL)* for transport of pollutants/carbon/aerosol and water vapor, wind energy, cloud dynamics and convection, and large-scale circulation	Active sensing (lidar, radar, scatterometer); or passive imagery or radiometry-based atmospheric motion vectors (AMVs) tracking; or lidar*		X	X

TABLE S.2 Continued

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Planetary Boundary Layer	*Diurnal 3D PBL thermodynamic properties and 2D PBL structure* to understand the impact of PBL processes on weather and air quality through high vertical and temporal profiling of PBL temperature, moisture, and heights	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL lidar; and lidar* for PBL height			X
Surface Topography and Vegetation	*High-resolution global topography*, including bare surface land topography, ice topography, vegetation structure, and shallow water bathymetry	Radar; or lidar*			X

* Could potentially be addressed by a multifunction lidar designed to address two or more of the Targeted Observables

Other ESAS 2017 Targeted Observables, Not Allocated to a Flight Program Element

Aquatic-Coastal Biogeochemistry	Radiance Inter-calibration	Surface Water Height
Magnetic Field Changes	Salinity	
Ocean Ecosystem Structure	Soil Moisture	

NOTE: Observations (Targeted Observables) identified by the steering committee as needed in the coming decade, beyond what is in the Program of Record, allocated as noted in the last three columns (and color-coded) to three new NASA flight program elements (*Designated*, *Earth System Explorer*, *Incubation*; as defined in the accompanying text). Within categories, the targeted observables are listed alphabetically. Targeted Observables included in the original priority consideration but not allocated to a program element are listed at the bottom of the table (see Appendix C for a complete summary).

competition and other programmatic tools to increase the cadence and quality of flight programs, while optimizing cost and risk.

Recommendation 3.2: NASA should implement a set of space-based observation capabilities based on this report's proposed program (which was designed to be affordable, comprehensive, robust, and balanced) by implementing its portion of the Program of Record and adding observations described in Table 3.3, "Observing System Priorities." The implemented program should be guided by the budgetary considerations and decision rules contained in this report and accomplished through five distinct program elements:

1. ***Program of Record.* The series of existing or previously planned observations, which must be completed as planned. Execution of the ESAS 2017 recommendation requires that the total cost to NASA of the Program of Record flight missions from fiscal year (FY) 2018 through FY 2027—October 1, 2017 through September 30, 2027—be capped at $3.6 billion.**
2. ***Designated.* A program element for ESAS-designated cost-capped medium- and large-size missions to address observables essential to the overall program, directed or competed at the discretion of NASA.**
3. ***Earth System Explorer.* A *new* program element involving competitive opportunities for cost-capped medium-size instruments and missions serving specified ESAS-priority observations.**

4. ***Incubation*. A *new* program element, focused on investment for priority observation capabilities needing advancement prior to cost-effective implementation, including an innovation fund to respond to emerging needs.**
5. ***Earth Venture*. Earth Venture program element, as recommended in ESAS 2007, with the addition of a *new* Venture-continuity component to provide opportunity for low-cost sustained observations.**

The committee is confident, based on analyses of technical readiness and cost performed during the study, that the recommended observations have feasible implementations that can be accomplished on schedule and within the stated cost caps. The proposed program was designed both to fit within anticipated budgets (assumed for the purposes of this report to grow only with inflation) and to ensure balance in the mission portfolio among program elements (Figure S.2). As appropriate, candidate instruments and missions were formally subjected to a Cost Assessment and Technical Evaluation (CATE) to assess budget needs. The committee considered management of development cost to be of critical importance to effective implementation of this program, in order to avoid impacting other programs and altering the desired programmatic balance. Should budgets be more or less than anticipated, the report includes decision rules for altering plans in a manner that seeks to ensure the overall program integrity.

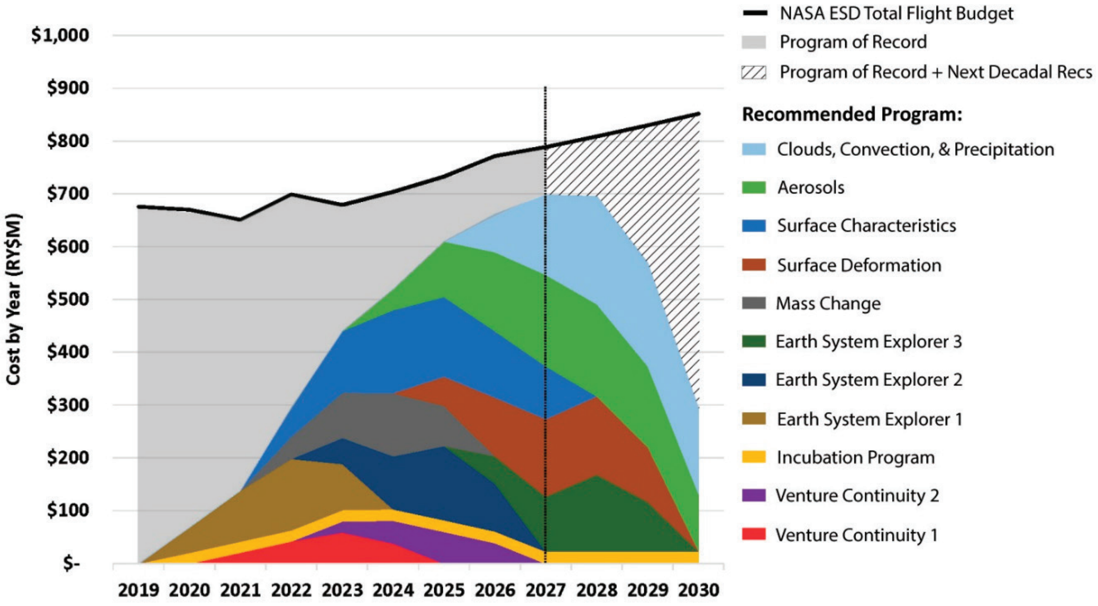

FIGURE S.2 The 2017 Earth Science and Applications from Space (ESAS 2017) real-year dollar estimated costs (colored wedges), broken down by NASA flight program element proposed in this report, as compared to the anticipated flight budget (black line), showing how the ESAS 2017 costs fit within the available $3.4 billion budget through 2027. The total NASA budget for flight elements assumes growth at the rate of inflation for years beyond the current budget projection. Only the investments related to ESAS 2017 recommendations are shown. The gap between the estimated costs and the available budget represents funds that have been committed to other non-ESAS mission-related activities.

ENABLING THE PROGRAM

Finally, none of this happens without "robust supporting programs" at NASA, NOAA, and USGS that provide the enabling resources for developing the recommended space-based observing systems and evaluating the data they produce. In particular, these supporting programs are central to transforming scientific advances into applications and societal benefits. The committee has proposed a variety of programmatic actions intended to improve the ability of each agency to deliver on its space-based observation programs.

Key among these are findings and recommendations associated with the following: ensuring balanced and robust programmatic structures (Findings 4.4 and 4.5); recognizing the importance of sustained land imaging through the USGS Landsat program (Finding 4.10); and leveraging partnering opportunities (such as the European Union's Copernicus/Sentinel program noted in Recommendation 4.5) that enhance operational efficiencies and ensure that the agencies can accomplish the most possible within their available resources (Finding 4.10; Recommendations 4.5, 4.11, and 4.12).

Finding 4.4: A robust and resilient Earth Science Division (ESD) program has the following attributes**:**

- A healthy cadence of small/medium missions to provide the community with regular flight opportunities, to leverage advances in technologies and capabilities, and to rapidly respond to emerging science needs;
- A small number of large cost-constrained missions, whose implementation does not draw excessive resources from smaller and more frequent opportunities;
- Strong partnerships with U.S. government and non-U.S. space agencies;
- Complementary programs for airborne, in situ, and other supporting observations;
- Periodic assessment of the return on investment provided by each program element; and
- A robust mechanism for trading the need for continuity of existing measurement against new measurements.

Finding 4.5: Maximizing the success of NASA's Earth science program requires balanced investments across its program elements, each critically important to the overall program. The *flight* program provides observations that the *research and analysis* program draws on to perform scientific exploration, the *applied sciences* program transforms the science into real-world benefits, and the *technology* program accelerates the inclusion of technology advances in flight programs. The current balance across these four program elements is largely appropriate, enabling a robust and resilient Earth science program, and can be effectively maintained using decision rules such as recommended in this report. Some adjustment of balance within each program element is warranted, as recommended in this report.

Finding 4.10: Extension of Landsat capability through synergy with other space-based observations opens new opportunities for Landsat data usage, as has been demonstrated with the European Space Agency (ESA) through cross-calibration and data sharing for Sentinel-2. These successes serve as a model for future partnerships and further synergies with other space-based observations.

Recommendation 4.5: Because expanded and extended international partnerships can benefit the nation:

- **NASA should consider enhancing existing partnerships and seeking new partnerships when implementing the observation priorities of this decadal survey.**
- **NOAA should strengthen and expand its already strong international partnerships, by (1) coordinating with partners to further ensure complementary capabilities and operational backup while**

minimizing unneeded redundancy; and (2) extending partnerships to the more complete observing system life cycle that includes scientific and technological development of future capabilities.
- **USGS should extend the impact of the Sustainable Land Imaging (SLI) program through further partnerships such as that with the European Sentinel program.**

Recommendation 4.11: NOAA should establish itself among the leading government agencies that exploit potential value of commercial data sources, assessing both their benefits and risks in its observational data portfolio. It should innovate new government/commercial partnerships as needed to accomplish that goal, pioneer new business models when required, and seek acceptable solutions to present barriers such as international partner use rights. NOAA's commercial data partnerships should ensure access to needed information on data characteristics and quality as necessary and appropriate, and be robust against loss of any single source/provider if the data are essential to NOAA core functions.

Recommendation 4.12: NOAA should establish, with NASA, a flexible framework for joint activities that advance the capability and cost-effectiveness of NOAA's observation capabilities. This framework should enable implementation of specific project collaborations, each of which may have its own unique requirements, and should ensure (1) clear roles, (2) mutual interests, (3) life-cycle interaction, (4) multidisciplinary methodologies, (5) multielement expertise, and (6) appropriate budget mechanisms.

ANTICIPATED PROGRESS WITHIN THE DECADE

In this report, the committee identifies the science and applications, observations, and programmatic support needed to bring to fruition its vision of understanding deeply the nature of our changing planet. With implementation of its recommended plan, the committee expects the following to have been accomplished by the end of the survey decade:

Programmatic implementation within the agencies will be made more efficient by
- *Increasing Program Cost-Effectiveness.* Promote expanded competition with medium-size missions to take better advantage of innovation and leveraged partnerships.
- *Institutionalizing Sustained Science Continuity*. Establish methods to prioritize and facilitate the continuation of observations deemed critical to monitoring societally important aspects of the planet, after initial scientific exploration has been accomplished.
- *Enabling Untapped NASA-NOAA Synergies.* Establish more effective means for NASA-NOAA partnership to jointly develop the next generation of weather instruments, accelerating NOAA's integration of advanced operational capabilities.

Improved observations will enable exciting new science and applications by
- *Initiating or Deploying More Than Eight New Priority Observations of Our Planet.* Develop or launch missions and instruments to address new or extended priority observation areas that serve science and applications. Five are prescribed in the committee's recommended program for NASA, and three are to be chosen from among seven candidate areas prioritized by the committee to form the basis of a new class of NASA competed medium-size missions. These new observation priorities will be complemented by an additional two new small missions and six new instruments to be selected through NASA's existing Earth Venture program element, and two opportunities for sustained observations to be selected through the new Venture-Continuity strand of this program. The existing and planned POR will also be implemented as expected.

- *Achieving Breakthroughs on Key Scientific Questions.* Advance knowledge throughout portions of the survey's 35 key science questions (Table S.1, above) that address critical unknowns about the Earth system and promise new societal applications and benefits.

Businesses and individuals will receive enhanced value from scientific advances and improved Earth information, such as

- *Increased Benefits to Operational System End-Users.* Enhanced processes and tools to leverage lost-cost commercial and international space-based observations will allow NOAA and USGS to have greater impact on the communities they serve.
- *Accelerated Public Benefits of Science.* Improved capacity for transitioning science to applications will make it possible to more quickly and effectively achieve the societal benefits of scientific exploration, generating applications more responsive to evolving societal needs.
- *Development of Innovative Commercial Applications.* New observations and data products enable innovative commercial applications that have the potential for substantial economic benefit to both developers and end users.

Building on the success and discoveries of the past several decades, this report's balanced program provides a pathway to realizing remarkable scientific and societal benefits from space-based Earth observations. It ensures that the United States will *continue to be a visionary leader and partner* in Earth observation over the coming decade, inspiring the next generation of Earth science and applications innovation and the people who make that possible.

1

A Vision for the Decade

Ongoing understanding and prediction of Earth's changing environment, using space-based observations, provides essential knowledge that helps make society safe, secure, and prosperous. These benefits are in turn made possible by the investments we choose to make in observing and exploring our planet and in transforming new discoveries into useful knowledge.

From the time of the earliest humans, knowledge about Earth has been fundamental to our fate and prospects. Our ever-growing understanding of Earth's dynamic processes and long-term changes, along with their causes, has helped enable society's advance. Yet today Earth is changing in ways that are very different from the past, largely as a consequence of our own influences. From growing demand for limited resources, to air quality degradation, to climate change, human impacts that were once local or regional are now increasingly global. Similarly, where human impacts were once largely transient, today they may last millennia. As a result, accumulated knowledge about Earth's past is no longer a sufficient guide to the future. Increasingly, we must observe and understand the ways that nature's patterns and processes are being altered—alterations that will likely pose significant challenges and present new prospects for both society and ecosystems, requiring environmental awareness to successfully manage.

Examples are increasingly abundant. Evolving rainfall patterns may open new agricultural opportunities, but will likely bring drought to other currently fertile regions. Without an understanding of where, when, and how these changes will occur, our agriculture faces economic risk. An ice-free summer Arctic will introduce major perturbations to climate, weather, and ecosystem patterns, but will also provide access to new resources and reduced shipping times. Managing the risks and understanding the opportunities inherent to a changing world requires observations and knowledge—not only of the changes that are occurring, but also of the reasons for them and the associated implications.

This tension—between society's deep dependence on knowledge about our planet in order to thrive, and the challenges of acquiring and updating this knowledge as our planet changes—reflects an emerging aspect of civilization's progress. It is the theme embodied in this report's title *Thriving on Our Changing Planet*. The word "thriving" was chosen carefully for its breadth: it encompasses economic success, intellectual progress, societal prosperity, personal well-being, scientific exploration, and much more. The committee's proposed program of science and applications priorities, and the observations needed to pursue them, addresses the scientific and societal challenges inherent in this tension.

ALL IN A DECADE

The successes of modern civilization have been achieved in no small part through advanced understanding of our planet's behavior and its fundamental resources. Characterizing and explaining the ways in which Earth changes over time, and identifying the complex natural and human mechanisms by which that change occurs, have been critical elements of our nation's scientific progress. Earth continually amazes us, as we make new discoveries that reveal its beauty, complexity, and wonder.

As we move forward, society's growing dependence on Earth information[1] (illustrated in Figure 1.1)—for our daily lives, our businesses, and our government policies—requires ongoing investments in the observation, understanding, and prediction of Earth's environment. Earth observations from space are critical in this effort. Over the past few decades, the United States has been a clear leader of the global effort to acquire sophisticated observational data from satellites. Such investments in knowledge and its applications support our efforts to continue thriving on our complex, ever-changing planet.

Even a mere decade reveals the pace of advance and the many successes we have experienced. Over *the past decade*, new types of Earth information have empowered us all:

- *Individuals.* Greater access to this information has *helped us as individuals* by placing at our fingertips a wide variety of vital information about the world around us, helping each of us make important decisions. Examples range from minute-by-minute weather information to satellite images that allow us all to explore and navigate in our home towns and "visit" even the most remote places on Earth.
- *Businesses.* Scientific discoveries and the resulting applications have helped us *advance business interests*, such as making our agriculture more productive, our energy use more efficient, and our transportation more reliable. Many companies have leveraged technology originally developed for Earth observations to provide valuable services, ranging from consumer Internet mapping to weather-based shipping optimization and much more.
- *Society.* Being able to observe the Earth in new ways has helped us *prosper as a society*. Our revolutionary ability to view the world as a whole from space allows us to watch the natural course of rivers and forests change, to observe changes in our climate, to discern our role within those and other changes, to understand the risks and benefits of our actions and inactions with regard to our planet, and to apply the resulting knowledge. This expanded perspective has positioned us to benefit from the economic opportunities it creates, increased our resilience to the environment's risks, and inspired citizens and nations everywhere with the wonder of Earth's scientific challenges.

Progress during the past decade, building on advances from prior decades, confirms the special ability of Earth satellites to comprehensively observe the entire Earth in detail and to reveal new aspects of our planet's complex behavior.[2] Over time, we have augmented what was once a sparse surface-based observ-

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[1] A growing body of literature characterizing how society uses Earth information and quantifying its benefits to individuals, businesses, and governments (e.g., Boulding, 1966; Daly and Townsend, 1996; Williamson et al., 2002; Macauley, 2006; Sagoff, 2007, 2008; Lazo et al., 2011; Trenberth et al., 2016; Hsiang et al., 2017; NWS, 2017). Nevertheless, there is no definitive study of the value of U.S. Earth observation to the nation. In Europe the economic benefit-cost ratio of the European Space Agency (ESA) Global Monitoring for Environmental Security (GMES) program, now known as Copernicus, has been estimated to be 10:1 (Booz and Co., 2011). Similarly, Australia assessed the direct and indirect contributions of space-based Earth observation to be 0.3 percent of its gross domestic product (ACIL Tasman, 2010). (See also Figure 1.1 and Box 4.1, later.)

[2] See *Earth Observations from Space: The First 50 Years of Scientific Achievements* (NRC, 2008), which explores the history and

ing network with a powerful space-based infrastructure for observation and prediction on global scales, making it possible to monitor aspects of the Earth system not previously accessible using surface-based observations alone.[3] The global view from satellite observations remains unmatched in its ability to resolve the dynamics and variability of Earth processes. Using both space and in situ observations, we increasingly understand the extent to which Earth is an *intricately connected global system,* within which interactions between the atmosphere, land, ice, and oceans affect us on time scales of minutes to decades. Characterizing these Earth system interactions is key to understanding how the Earth system functions today, how it supports life, how conditions might change in the future, and how humans influence such change. The challenge is to further advance this knowledge, and to progressively apply it in ways that improve our lives and help us plan for the future.

By building from this knowledge base, what can we expect in *the next decade*? While significant progress has been made this decade and previously, it is surprising how much we still do not know about the Earth system and the human interaction with it, especially in the least accessible regions (Box 1.1). Today, Earth's ongoing change makes the job of understanding and predicting our planet even more difficult than in the past. Through both natural variability and human influences, Earth and its environment are evolving around us—sometimes in ways we can readily predict and other times in ways we have yet to explain. To sustain prospects for adapting in the future, society needs a more comprehensive understanding of how and why our environment is changing and what the associated implications will be.

This report identifies the science and applications, observations, and programmatic support needed over the next 10 years to bring to fruition this vision of more deeply understanding our changing planet. With implementation of its recommended plan, the committee expects the following to have been accomplished by the end of the survey interval:

Programmatic implementation within the agencies will be made more efficient by

- *Increasing Program Cost-Effectiveness.* Promote expanded competition with medium-size missions to take better advantage of innovation and leveraged partnerships.
- *Institutionalizing Sustained Science Continuity*. Establish methods to prioritize and facilitate the continuation of observations deemed critical to monitoring societally important aspects of the planet, after initial scientific exploration has been accomplished.
- *Enabling Untapped NASA-NOAA Synergies.* Establish more effective means for NASA-NOAA partnership to jointly development the next generation of weather instruments, accelerating NOAA's integration of advanced operational capabilities.

Improved observations will enable exciting new science and applications by

- *Initiating or Deploying More Than Eight New Priority Observations of Our Planet.* Develop or launch missions and instruments to address new or extended priority observation areas that serve science and applications. Five are prescribed in the committee's recommended program for NASA, and three are to be chosen from among seven candidate areas prioritized by the committee to form the basis of a new class of NASA competed medium-size missions. These new observation priorities will be complemented by an additional two new small missions and six new instruments to be selected through NASA's existing Earth Venture program element, and two opportunities for

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value of Earth observation satellites in depth.

[3] The committee fully recognizes that accomplishing science today and achieving societal benefits from science requires treating information as an end-to-end process, involving observations, analysis, modeling, archive, automated analytics, applications, data communication, and far more. Our strategic guidance in Chapter 2 recognizes this, and the topic is addressed at a simple level in Chapter 4. Nevertheless, this report's focus is the space-based observing system, so the important topic of an end-to-end information infrastructure is not comprehensively addressed.

THE IMPORTANCE OF EARTH INFORMATION

Earth-observing satellites provide critical information about our planet. This information supports a broad range of societal needs and enables the scientific discovery required to meet those needs, making us all healthier, safer, and more efficient.

HELPING PLAN OUR DAY

300 billion *weather forecasts used by Americans every year*

100+ million *American adults use internet-based mapping services*

Americans rely on sophisticated Earth information throughout their everyday lives, from weather forecasts to navigation applications in their cars. Satellites are the original sources of much of the data.

PROTECTING OUR HEALTH

6.5 million *premature deaths from air pollution around the world every year*

Earth-observing satellites track the concentration of harmful pollutants across the country, providing air quality data for rural areas without ground-based monitoring systems and measuring the effects of air quality regulations.

50% *of the world's population is at risk from malaria.*

Satellite observations of temperature, vegetation, and rainfall help predict the spread of mosquito-borne illnesses like malaria, Zika, and West Nile Virus.

FIGURE 1.1 We all depend extensively on Earth information. Sometimes to the minute, our daily lives are guided and enhanced (often in ways we do not readily recognize) by the many personal, business, and government decisions that rely on knowledge about our planet. Science provides the foundation that makes it all possible. SOURCE: Data available as

KEEPING US SECURE

*The estimated value of NASA and NOAA information services to the U.S. Navy's operational effectiveness is **$2 billion** per year.*

The U.S. Navy and other U.S. defense agencies partner with NASA and NOAA to use satellite data, to access operational services, and to leverage their scientific progress.

MITIGATING NATURAL DISASTERS

*Extreme weather and fires have cost the federal government more than **$350 billion** over the past decade.*

Satellite measurements play a critical role in tracking the paths of hurricanes and wildfires so that we can warn populations at risk, assess the damages, and avoid future costs.

ENSURING RESOURCE AVAILABILITY

*Advanced technology, including many types of Earth information, will unlock up to **$1.6 trillion** in economic savings for energy generation and use by 2035.*

Satellite observations can also help ensure water availability, which is particularly important to the 20% of the world now living in areas of water scarcity.

follows: Helping Plan Our Day—Lazo et al., 2009; comScore, 2014. Protecting Our Health—WHO, 2016, 2017. Keeping Us Secure—Titley, 2016. Mitigating Natural Disasters—*GAO Highlights*, 2017. Ensuring Resource Availability—UN-Water, 2007; McKinsey Global Institute, 2017.

BOX 1.1 A CHANGING EARTH CREATES OPPORTUNITY AND RISK FOR US ALL

In our changing world, Earth observations from space are important for supporting humanity's ability to thrive. Such observations enable scientific breakthroughs and have direct impacts on our economy, national security, public safety, and quality of life.

The widely reported multidecadal decline in Arctic sea ice provides a clear example. It presents us with a challenging confluence of risk and societal opportunity, complete with underlying international, commercial, and military implications over the next decade. The rates of changes are extraordinarily high. Space-based observations have recorded a decline in the summer's ice extent at a rate of 13 percent per decade, along with a reduction in multiyear ice to one-quarter of its historic amount. The Northwest Passage and trans-Arctic shipping routes may open soon to regular transit.

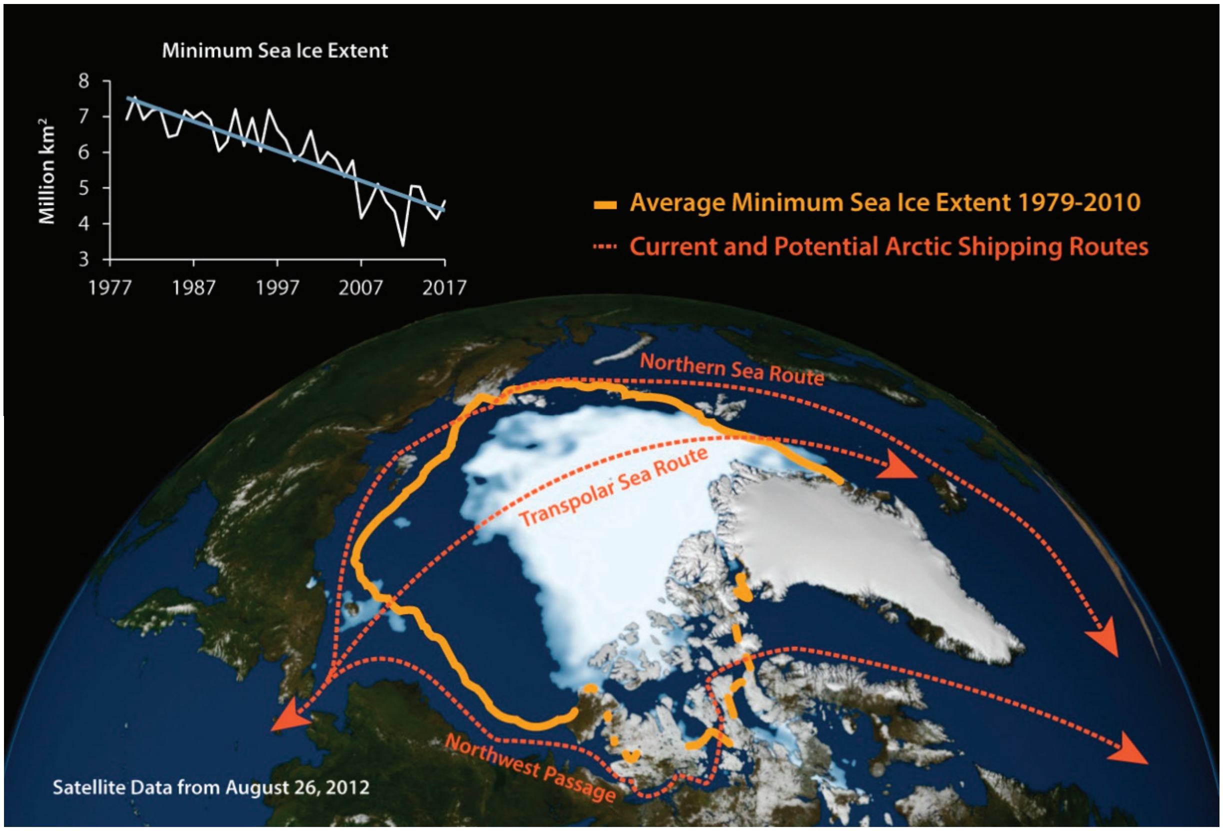

FIGURE 1.1.1. Late summer 2012 Arctic sea-ice area (in white), overlaid with current and potential Arctic shipping routes (dotted red lines) resulting from sea-ice loss. These routes substantially decrease shipping times between Europe and Asia and other parts of the world. The orange line shows the average extent of the annual Arctic sea-ice minimum for 1979-2010, and the inset shows the monthly average values of sea-ice extent for each September (the month at which the ice reaches its minimum extent) during the full satellite record, 1979-2017. In 2012, the Arctic sea-ice cover shrunk to its lowest level ever observed in the satellite record.

BOX 1.1 Continued

These dramatic changes are causing energy companies to examine how access to an estimated 15 percent of the world's remaining petroleum deposits could reduce oil and gasoline prices. The transportation industry is working to understand how a 25 percent reduction in ocean shipping time between Europe and Asia may improve global trade. Governments are developing policies aimed at pursuing these opportunities and addressing the risks. The Arctic, seemingly so far away, is changing in ways that have direct and growing impacts on our daily lives.

We have seen the beginnings of all this already. On the Northern Sea Route (Figure 1.1.1) from Western Europe to Eastern Asia, traffic increased by nearly a factor of 20 from 2010 to 2013. Russia planted a flag on the North Pole seabed in 2015 as a territorial claim. Oil exploration is expanding.

One consequence is that many nations are rapidly building their Arctic military capacity. The *US Navy Arctic Roadmap 2014-2030* was developed with the changing Arctic in mind, to guide future strategic operations. The roadmap calls for additional research on rising seas and improved ability to predict sea ice thickness, as well as assessments of the surveillance and facility needs in this critical region of our world. Future observations and the associated analyses will inform the federal investment decisions necessary to secure U.S. interests in the Arctic.

The practical unknowns are extensive, motivating the need for additional monitoring and predictive capability. How will major cities or agricultural regions be impacted as the open Arctic Ocean alters weather patterns reaching lower latitudes? Will nations successfully develop agreements and treaties on new uses of the Arctic, and can we be confident they are complying? What are the consequences for native cultures in this region? Will delicate ecosystems adapt and thrive or struggle and decline, and what should we do to protect them? What information will be needed to address these kinds of questions and determine whether we successfully cope with the changes, manage them, or simply exploit them?

These same unknowns also create new and compelling scientific questions. How soon might the Arctic Ocean become completely ice free in summers? How will changes in the critical Arctic environment alter global climate? What are the mechanisms driving these changes and responses?

The Arctic has never been static, but recent changes have been exceptionally dramatic. The needed scientific exploration has only begun, and the practical capabilities necessary to successfully manage and adapt to these changes require additional development. With the scientific, economic, political, and strategic landscape evolving so rapidly, the need for frequently updated, large-scale information about the ice, ocean, land, and atmosphere in this remote region has never been greater. Space-based Earth observations, which provide that critical information, are essential to making well-informed decisions about our nation's actions and investments in the future.

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sustained observations to be selected through the new Venture-Continuity strand of this program. The existing and planned Program of Record (POR) will also be implemented as expected.

- *Achieving Breakthroughs on Key Scientific Questions.* Advance knowledge throughout portions of the survey's 35 key science questions (see Table S.1) that address critical unknowns about the Earth system and promise new societal applications and benefits.

Businesses and individuals will receive enhanced value from scientific advances and improved Earth information

- *Increased Benefits to Operational System End Users.* Enhanced processes and tools to leverage low-cost commercial and international space-based observations will allow NOAA and USGS to have greater impact on the communities they serve.
- *Accelerated Public Benefits of Science.* Improved capacity for transitioning science to applications will make it possible to more quickly and effectively achieve the societal benefits of scientific exploration, generating applications more responsive to evolving societal needs.
- *Development of Innovative Commercial Applications.* New observations and data products enable innovative commercial applications that have the potential for substantial economic benefit to both developers and end users.

THE TRANSFORMATIVE IMPACT OF SPACE-BASED OBSERVATIONS

Earth is a dynamic planet on which the interconnected atmosphere, ocean, land, and ice interact across a range of spatial and temporal scales, irrespective of geographic, political, or disciplinary boundaries. Today's leading science often occurs at the system level, with the aim of understanding the linkages between these elements, the processes that connect them, and how variability occurs among them. Even a conceptually simple phenomenon such as sea-level rise (Figure 1.2) illustrates the complexity of Earth system science that must be considered to explain it, to predict its behavior, and to address the diverse societal impacts.

Multidecadal space-based observations are particularly important to this understanding. They allow us to better investigate Earth's variability across many scales of time and space, and to develop insights needed to understand the fundamental Earth system processes that are relevant to our lives. Since Earth is our home, our survival and quality of life depend on how well we understand its behavior. A commitment to monitoring, understanding, and predicting complex and dynamical Earth systems is a scientific and societal imperative.

The science alone is inspiring and compelling, but understanding and reliably predicting the Earth system is a *vital economic, societal, and national security need* as well. This need for accurate predictions applies across many U.S. industries (ranging from energy resources to aircraft operations), for which significant functions and products depend on effective use of Earth information. In agriculture, for example, revenue and profits depend on efficient crop management and associated water usage that follows from an understanding of daily and seasonal weather and climate conditions. Weather variability alone—only one driver of the need for Earth information—has been estimated to influence as much as 13 percent of the year-to-year variability of U.S. state economies (Figure 1.3), with the interannual aggregate dollar variation in U.S. economic activity that is attributable to weather variability estimated to be 3.4 percent of U.S. gross domestic product (GDP; see Lazo et al., 2011). Space-based observations are a critical source of the needed Earth information used by companies and other providers of applications, with significant return on investment to the economy.

Space-based Earth observations are also vital for national security.[4] As an example, understanding atmospheric and oceanic processes (such as sea-level rise and the impacts of ocean warming on ocean circulation associated with climate change) and their implications is critical for naval operations. Operations of all armed services depend on environmental information, such as accurate weather forecasts, characteristics and changes of terrestrial landscapes, atmospheric conditions and processes, coastal information, and more. Satellite observations play a crucial role in addressing these needs. On a broader level,

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[4] There is increasing academic, business, and government recognition of the national security impact of Earth information, and of climate change in particular (e.g., Barnett, 2003; Nordås and Gleditsch, 2007; Smith, 2007). That recognition is less established at the public level.

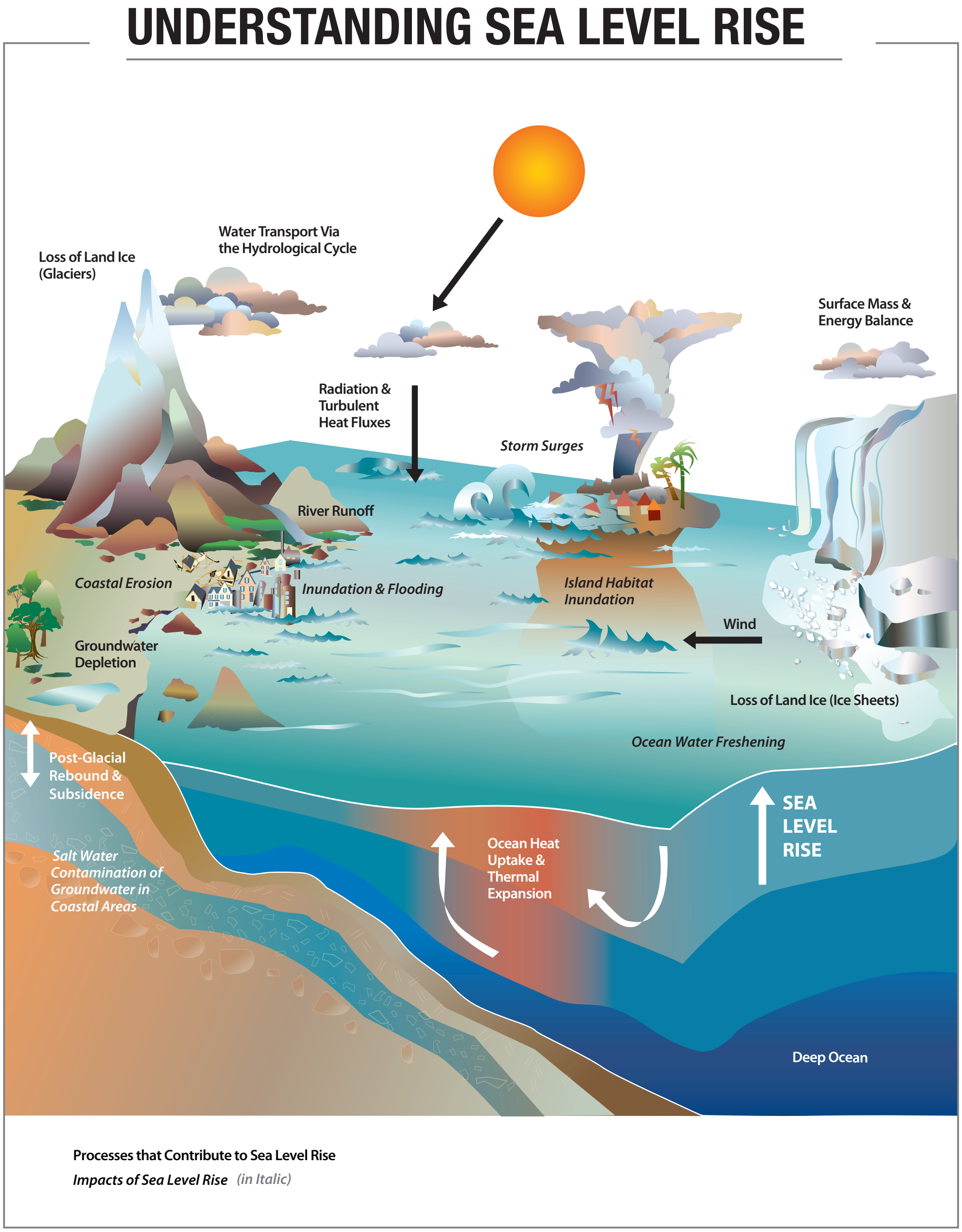

FIGURE 1.2 The complex interacting components of the Earth system that contribute to sea-level rise and its consequences.

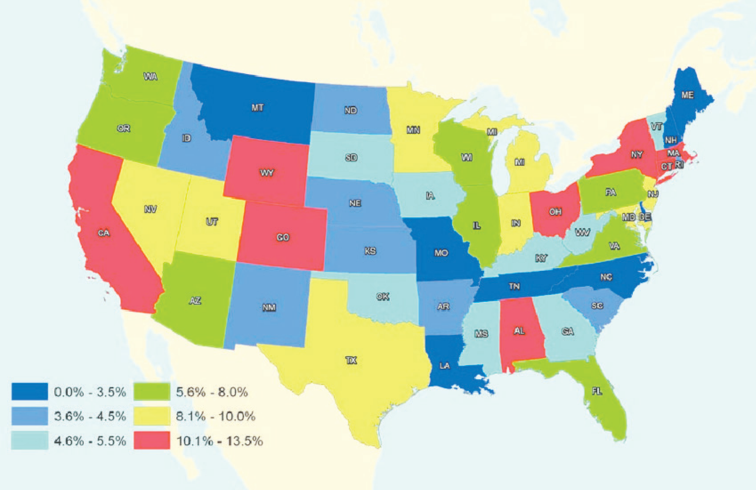

FIGURE 1.3 The sensitivity (annual variation) of each state's gross state product due to routine weather variability, such as drought and flood (Lazo et al., 2011). The impact can be as large as 13 percent in some states, with half of all states greater than 5 percent.

understanding the role of climate and other environmental changes is important for anticipating future sources of geopolitical instability.

Finding 1.1: Space-based Earth observations provide a global perspective of Earth that has

- Over the past 60 years, transformed our "scientific understanding" of the planet, revealing it to be an integrated system of dynamic interactions between the atmosphere, ocean, land, ice, and human society across a range of spatial and temporal scales irrespective of geographic, political, or disciplinary boundaries.
- In the past decade in particular, enabled "societal applications" that provide tremendous value to individuals, businesses, the nation, and the world. Such applications are growing in breadth and depth, becoming an essential information infrastructure element for society as they are integrated into people's daily lives.

BUILDING ON PROGRESS

U.S. investments in Earth observations over the last decade have led to important scientific advancement, and generated considerable economic value (see Chapter 2). This progress has occurred across a wide range of Earth science disciplines, addressing broad societal needs: assessing risks from sea-level rise, understanding the genesis and evolution of severe storms and tornadoes, measuring the health and productivity of our lands and oceans all over the world, managing air pollution risks, and improving weather forecasts. The decadal survey committee's vision for the next decade builds on these successes, recognizing that society's need for improved science and Earth information is growing rapidly.[5]

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[5] The proliferating use of Internet mapping over the last decade is perhaps the best-known example, though merely indicative of a broad-based trend. Internet mapping integrates space-based, aerial, and ground-based Earth observation data (obtained and used with rapidly advancing fidelity), provides the foundation for value-added services ranging from shipping logistics to commodities speculation, and is an essential information source for a growing set of applications built for financial services, energy, transportation, agriculture, consumers, and many other sectors.

This vision leads to the committee's recognition of a new Earth science paradigm for the coming decade, building from two important prior themes. In the 1980s and 1990s, Earth scientists and applications specialists began formally viewing Earth as a system, moving beyond study of its individual land, ocean, and atmosphere components. This helped us recognize critical system-scale processes, such as for the El Niño/La Niña oscillation that has such enormous economic and security impacts throughout the world, and begin forecasting them. In the 2000s, we recognized that explicitly integrating pursuit of the societal benefits of Earth research needed to be central to all of our thinking. The natural extension of this thematic progress leads to the following paradigm.

Earth Science and Applications Paradigm for the Coming Decade

Earth science and derived Earth information have become an integral component of our daily lives, our business successes, and society's capacity to thrive. Extending this societal progress requires that we focus on understanding and reliably predicting the many ways our planet is changing.

The coming decade is important for many reasons. Decisions we make this decade regarding investments in needed capabilities will determine our capacity during the next decade and beyond to predict Earth's future changes, including the role of human actions, and to influence the extent to which those changes will impact society. As we recognize the interdependence of and interconnections between human activities and our land, oceans, and atmosphere, there is an increasing need for reliable, science-based guidance to support policy and investment decisions related to fisheries management, river and water basin management, coastal construction, air quality, floods, hurricanes, droughts, changes in ecosystems, wildfires, sea-level rise, navigability of the Arctic, and adaption to climate change—to name just a few.

AN AMBITIOUS COMMUNITY CHALLENGE

It is essential that advances in our understanding of the Earth system support the nation's growing industrial, agricultural, and environmental needs. Satellite observations will play a crucial role in ensuring that they do. Yet, over the last decade and more, investments in Earth observation capabilities have failed to keep pace with these needs. This is particularly evident in NASA's Earth science program, which (as shown by the budget in Figure 1.4) has actually seen a decline in its budget from the levels that led in the 1990s to the development of NASA's Earth Observing System (EOS) and the Mission to Planet Earth (MTPE).

The committee recognizes that resource constraints are likely to remain a practical concern during the next decade, and that new resources must be applied wisely when available.[6] The importance of an effective Earth system science and applications enterprise requires that our entire community of scientists and practitioners rise to the following community challenge within the next decade:

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[6] Various proposals for reducing agency budgets and eliminating particular Program of Record (POR) missions have been proposed over the year prior to publication of this report. While the committee was aware of the proposals and their undesirable impacts, it was not the committee's role to speculate on potential outcomes of in-process budget proposals. Instead, the committee focused on ensuring appropriate justification of both the POR and new observing system capabilities, and on clear rules for adjusting the program when available resources either exceed or do not meet the committee's nominal budget growth expectation. To the extent that future budget issues could lead to a situation similar to that faced in the first decadal survey (NRC, 2007), which described the observing system as "at risk of collapse," it is critical to regularly reinforce the strategic importance of Earth observation to the nation's governmental organizations, businesses, and individuals.

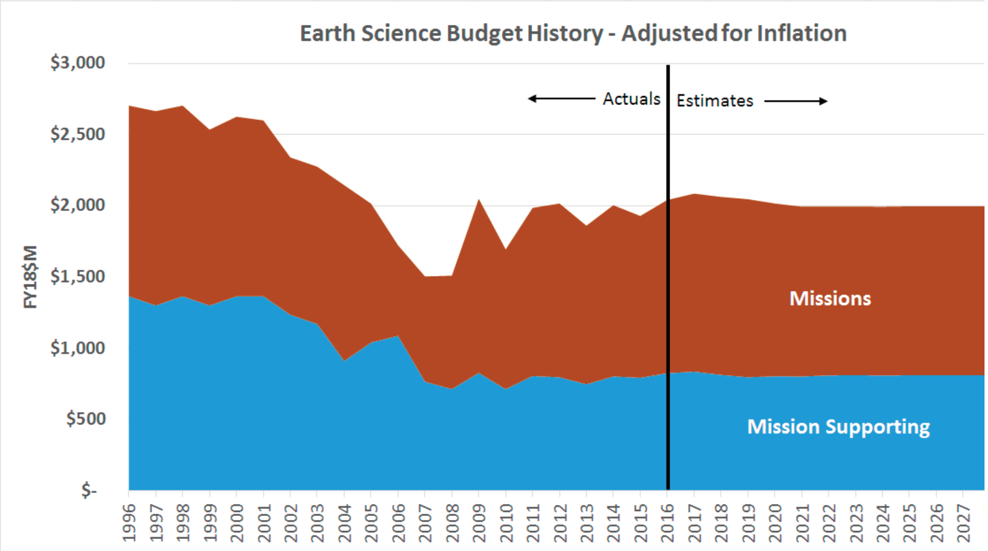

FIGURE 1.4 The NASA Earth Science budget 1996-2016+ ($FY2018), showing both mission and non-mission contributions. For the period following known budget requests, a simple inflation-adjusted increase is assured.

Decadal Community Challenge

Pursue increasingly ambitious objectives and innovative solutions that enhance and accelerate the science/applications value of space-based Earth observation and analysis to the nation and to the world in a way that delivers great value, even when resources are constrained, and ensures that further investment will pay substantial dividends.

Succeeding requires a deep commitment on the part of scientists, our government, and citizens. It will require innovation and discipline, inspiration and dedication. But substantive progress can and must be made in the coming decade. It is a worthy and ambitious goal that will pay off many times over in civilization's more comprehensive understanding of our changing environment, more efficient stewardship of Earth's resources, and more effective management of risks against environmental stresses.

Ultimately, a long-term goal of Earth system science research and its applications is *a comprehensive capacity to understand, monitor, predict, and steward important aspects of our Earth and its future, across all important scales of space (local to global) and time (minutes to decades), and in all relevant domains.* The complexity and growing number of societal needs is increasingly evident; the extent of the potential societal benefits presents a strong motivation for this goal. It is a goal that should push us all to reach high, as the opportunities enabled by success—and the consequences of failure, to ourselves and to this planet—are both tremendous.

THE 2017 DECADAL SURVEY

In keeping with the Decadal Community Challenge, this report proposes an achievable plan of space-based observations to monitor and understand our planet over the next decade, without sacrificing pursuit of ambitious goals. Implementing this program will contribute to safeguarding and improving the quality of life for all citizens.

All three of the report's sponsoring agencies play essential roles. Sustained NASA, NOAA, and USGS systems are needed to ensure that we have long-term, uninterrupted observations of the Earth system that supports many aspects of our lives. NASA missions already scheduled to be launched, and new science/applications proposed here, have been selected to provide a portfolio of data that will strategically build on existing capabilities, allowing us to substantially advance our ability to understand, explain, and manage observed changes and thus to improve Earth prediction. The recommended program will complement existing U.S. and international programs to provide critical new and follow-on observations of the most fundamental Earth system parameters. Implementation of this program will enable not just more accurate predictions at short time scales (e.g., <14-day weather forecasting), but also extend environmental forecasts into the subseasonal range (e.g., 2 weeks to 2 months) and yield more robust projections at decadal and longer time scales as well (e.g., sea-level rise, drought trends, and climate shifts) as the changing climate and other influences shape the world in which we will live.

Building on the success and discoveries of the last several decades, the report's balanced program provides a pathway to realizing tremendous scientific and societal benefits from space-based Earth observations. It ensures the United States will *continue to be a visionary leader and partner* in Earth observation over the coming decade, inspiring the next generation of Earth science and applications innovation and the people who make it possible.

REFERENCES

ACIL Tasman. 2010. "The Economic Value of Earth Observation from Space: A Review of the Value to Australia of Earth Observation from Space." ACIL Tasman Pty Ltd., Prepared for the Cooperative Research Centre for Spatial Information (CRC-SI) and Geoscience Australia.

Barnett, J. 2003. Security and climate change. *Global Environmental Change* 13(1):7-17.

Booz and Co. 2011. *Cost-Benefit Analysis for GMES.* Final Version II. European Commission: Directorate-General for Enterprise and Industry, London, U.K. September 19. https://www.copernicus.eu/sites/default/files/library/ec_gmes_cba_final_en.pdf.

Boulding, K.E. 1966. The Economics of the Coming Spaceship Earth. Pp. 3-14 in *Environmental Quality in a Growing Economy* (H. Jarrett, ed.). Baltimore, MD: Resources for the Future/Johns Hopkins University Press.

comScore, Inc. 2014. "The U.S. Mobile App Report." August 14. https://www.comscore.com/Insights/Presentations-and-Whitepapers/2014/The-US-Mobile-App-Report.

Daly, H.E., and K.N. Townsend. 1996. *Valuing the Earth: Economics, Ecology, Ethics*. Cambridge, MA: MIT Press.

GAO Highlights. 2017. "Climate Change: Information on Potential Economic Effects Could Help Guide Federal Efforts to Reduce Fiscal Exposure." September. https://www.gao.gov/assets/690/687465.pdf.

Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D.J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, and T. Houser. 2017. Estimating economic damage from climate change in the United States. *Science* 356(6345):1362-1369.

Lazo, J.K., R.E. Morss, and J.L. Demuth. 2009. 300 billion served—Sources, perceptions, uses, and values of weather forecasts. *Bulletin of the American Meteorological Society* 90(6):785-798.

Lazo, J.K., M. Lawson, P.H. Larsen, and D.M. Waldman. 2011. U.S. economic sensitivity to weather variability. *Bulletin of the American Meteorological Society* 92(6):709-720.

Macauley, M.K. 2006. The value of information: Measuring the contribution of space-derived Earth science data to resource management. *Space Policy* 22(4):274-282.

McKinsey Global Institute. 2017. *How Technology Is Reshaping Supply and Demand for Natural Resources.* February. https://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/how-technology-is-reshaping-supply-and-demand-for-natural-resources.

Nordås, R., and N.P. Gleditsch, 2007. Climate change and conflict. *Political Geography* XXVI(6):627-638.

NRC (National Research Council). 2007. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. Washington, DC: The National Academies Press.

NRC. 2008. *Earth Observations from Space: The First 50 Years of Scientific Achievements.* Washington, DC: The National Academies Press.

NWS (National Weather Service). 2017. *National Weather Service Enterprise Analysis Report: Finding on Changes in the Private Weather Industry*. June 8. https://www.weather.gov/media/about/Final_NWS%20Enterprise%20Analysis%20Report_June%202017.pdf.

Sagoff, M. 2007. *The Economy of the Earth: Philosophy, Law, and the Environment*. New York, NY: Cambridge University Press.

Sagoff, M. 2008. *The Economy of the Earth. Philosophy, Law, and the Environment.* New York, NY: Cambridge University Press.

Smith, P.J. 2007. Climate change, mass migration and the military response. *Orbis* 51(4):617-633.

Titley, D. 2016. “Cutting NASA Earth Observations Would Be a Costly Mistake,” *Defense One.* December 2. http://www.defenseone.com/technology/2016/12/cutting-nasa-earth-observations-would-be-costly-mistake/133586/.

Trenberth, K.E., M. Marquis, and S. Zebiak. 2016. The vital need for a climate information system. *Nature Climate Change* 6:1057-1059, doi:10.1038/NCLIM-16101680.

UN-Water. 2007. *Coping with Water Scarcity: Challenge of the Twenty-First Century.* http://www.fao.org/3/a-aq444e.pdf.

Williamson, R.A., H.R. Hertzfeld, J. Cordes, and J.M. Logsdon. 2002. The socioeconomic benefits of Earth science and applications research: Reducing the risks and costs of natural disasters in the USA. *Space Policy* 18:57-65.

WHO (World Health Organization). 2016. *Burden of Disease from the Joint Effects of Household and Ambient Air Pollution for 2012*. http://www.who.int/airpollution/data/AP_jointeffect_ BoD_results_Nov2016.pdf.

WHO. 2017. “Malaria Fact Sheet,” http://www.who.int/mediacentre/factsheets/fs094/en/.

2

A Decadal Strategy

Achieving the vision set forth in Chapter 1 requires us to first more fully understand where we are and where we are going and then define and pursue a strategy to accomplish the vision. This chapter reviews the strengths and weaknesses associated with our progress over the last decade, assesses the emerging scientific and societal needs we must serve, and builds from that foundation to identify a strategic framework for the next decade.

PROGRESS SINCE ESAS 2007

Programmatic Overview

In carrying out the 2007 Earth Science and Applications from Space decadal survey (ESAS 2007), participants endeavored to "set a new agenda for Earth observations from space in which ensuring practical benefits for humankind plays a role equal to that of acquiring new knowledge about Earth" (NRC, 2007). The reports *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation* (NRC, 2005) and *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (NRC, 2007) were the interim and final reports, respectively, that resulted from that effort.

ESAS 2007 called for a set of missions[1] (Tables 2.1 and 2.2) and supporting activities that would advance scientific understanding of key processes in the Earth system and provide information to enhance management of natural resources. Recommendations were directed to the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and U.S. Geological Survey (USGS). Progress since the report for each agency is discussed separately in the following text.

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[1] ESAS 2007 provided recommendations in the form of named missions. In contrast, the statement of task for ESAS 2017 requests recommended science, applications, and observations.

TABLE 2.1 Missions Recommended for NASA (or Joint with NOAA) in ESAS 2007

Decadal Survey Mission	Mission Description	Orbit	Instruments	Rough Cost (FY 2006 $ Million)
2010-2013				
CLARREO (NASA portion)	Solar and Earth radiation, spectrally resolved forcing, and response of the climate system	LEO, Precessing	Absolute, spectrally resolved interferometer	200
SMAP	Soil moisture and freeze/thaw for weather and water cycle processes	LEO, SSO	L-band radar L-band radiometer	300
ICESat-2	Ice-sheet height changes for climate change diagnosis	LEO, non-SSO	Laser altimeter	300
DESDynI	Surface and ice-sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	LEO, SSO	L-band InSAR Laser altimeter	700
2013-2016				
HyspIRI	Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health	LEO, SSO	Hyperspectral spectrometer	300
ASCENDS	Day/night, all-latitude, all-season CO_2 column integrals for climate emissions	LEO, SSO	Multifrequency laser	400
SWOT	Ocean, lake, and river water levels for ocean and inland water dynamics	LEO, SSO	Ku- or Ka-band radar Ku-band altimeter Microwave radiometer	450
GEO-CAPE	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	GEO	High-spatial-resolution hyperspectral spectrometer Low-spatial-resolution imaging spectrometer IR correlation radiometer	550
ACE	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry	LEO, SSO	Backscatter lidar Multiangle polarimeter Doppler radar	800
2016-2020				
LIST	Land surface topography for landslide hazards and water runoff	LEO, SSO	Laser altimeter	300
PATH	High-frequency, all-weather temperature and humidity soundings for weather forecasting and sea-surface temperature[a]	GEO	Microwave array spectrometer	450
GRACE-II	High-temporal-resolution gravity fields for tracking large-scale water movement	LEO, SSO	Microwave or laser ranging system	450
SCLP	Snow accumulation for freshwater availability	LEO, SSO	Ku- and X-band radars K- and Ka-band radiometers	500
GACM	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	LEO, SSO	UV spectrometer IR spectrometer Microwave limb sounder	600
3D-Winds (Demo)	Tropospheric winds for weather forecasting and pollution transport	LEO, SSO	Doppler lidar	650

[a] Cloud-independent, high-temporal-resolution, lower-accuracy sea-surface temperature measurement to complement, not replace, global operational high-accuracy sea-surface temperature measurement.

NOTE: Colors denote mission cost categories as estimated by the committee. Pink, green, and blue shading indicates large-cost ($600 million to $900 million), medium-cost ($300 million to $600 million), and small-cost (<$300 million) missions, respectively. The missions are described in detail in Part II of NRC (2007), and Part III provides the foundation for their selection. LEO, low Earth orbit; SSO, Sun-synchronous orbit; GEO, geostationary Earth orbit.

SOURCE: NRC (2007).

TABLE 2.2 Missions Recommended for NOAA (or Joint with NASA) in ESAS 2007

Decadal Survey Mission	Mission Description	Orbit	Instruments	Rough Cost (FY 2006 $ Million)
2010-2013				
CLARREO (instrument reflight components)	Solar and Earth radiation characteristics for understanding climate forcing	LEO, SSO	Broadband radiometers	65
GPSRO	High-accuracy, all-weather temperature, water vapor, and electron density profiles for weather, climate, and space weather	LEO	GPS receiver	150
2013-2016				
XOVWM	Sea-surface wind vectors for weather and ocean ecosystems	LEO, SSO	Backscatter radar	350

NOTE: Colors denote mission cost categories as estimated by the committee. Green and blue shading indicates medium-cost ($300 million to $600 million) and small-cost (<$300 million) missions, respectively. The missions are described in detail in Part II of NRC (2007), and Part III provides the foundation for their selection. LEO, low Earth orbit; SSO, Sun-synchronous orbit.

SOURCE: NRC (2007).

NASA Progress from ESAS 2007

For NASA, ESAS 2007 recommended 15 missions (including one joint with NOAA) for implementation. As stated in the National Academies' Midterm Assessment, issued 5 years after publication of the survey (NRC, 2012),

> *NASA responded positively to the decadal survey and its recommendations and began implementing most of them immediately after the survey's release. Although its budgets have never risen to the levels assumed in the survey, NASA's Earth Science Division (ESD) has made major investments toward the missions recommended by the survey and has realized important technological and scientific progress as a result. Several of the survey missions have made significant advances, and operations and applications end users are better integrated into the mission teams. . . . At the same time, the Earth sciences have advanced significantly because of existing observational capabilities and the fruit of past investments, along with advances in data and information systems, computer science, and enabling technologies.*

However, the Midterm Assessment authors also found that, for several reasons, the survey vision was being realized at a far slower pace than was recommended.[2]

Changing priorities and directions from the president and Congress also altered the expected program, notably requiring that NASA restructure its climate observing role. NASA responded to these requests and constraints by designing the *Climate-Centric Architecture Plan* (NASA, 2010; OIG, 2016), which also provided further guidance for implementing the ESAS 2007 recommendations and augmenting them with other high-priority observations.[3] One result of the delayed implementation, and significantly higher costs,

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[2] From the report: "Although NASA accepted and began implementing the survey's recommendations, the required budget assumed by the survey was not achieved, greatly slowing implementation of the recommended program. Launch failures, delays, changes in scope, and growth in cost estimates have further hampered the program."

[3] The plan (NASA, 2010) summarized this as follows: "In addition to building the Orbiting Carbon Observatory-2 mission for launch in 2013, NASA will: accelerate development of the four NRC Decadal Survey Tier 1 missions so that they are all launched by 2017; accelerate and expand the Venture-class line of competed, innovative small missions; initiate new space missions to address

of ESAS 2007 missions is that the Midterm Assessment recommended that NASA ESD should implement its missions via a cost-constrained approach, requiring that cost partially or fully constrain the scope of each mission such that realistic science and applications objectives can be accomplished within a reasonable and achievable future budget scenario.[4]

Consistent with recommendations from the Midterm Assessment, NASA has since included cost-constraints as part of mission definition. The Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission was rescoped as a demonstration on the International Space Station (ISS). Pre-Aerosol, Clouds, and ocean Ecosystem (PACE), a mission from the Climate-Centric Architecture initiative, is being implemented as a directed cost-capped mission.[5] As a result, the current number of missions flying and under implementation is different from that noted in the Midterm Assessment (OIG, 2016).

Table 2.3 shows those missions already flying, as well as the anticipated launch dates for missions under implementation. Missions that have a legacy in the ESAS 2007 recommended missions or were selected through the ESAS-recommended Earth Venture program are shown with an asterisk and foundational missions (those that were planned prior to ESAS 2007 and were assumed would be flown) are shown with a double asterisk. Missions in preformulation are not listed. In addition, a number of joint NOAA/NASA missions as well as other "legacy" missions have either launched or are scheduled for launch, but are not listed here. Finally, as noted in Chapter 3 (Table 3.10), the science objectives of several 2007 survey missions are being realized either partially or via an implementation that differs from that originally envisioned. For example, the repeat-pass Interferometric Synthetic Aperture Radar (InSAR) planned for the survey's Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission will now be realized via NISAR (NASA-ISRO SAR), a dedicated U.S. and Indian InSAR mission scheduled for launch in 2021, and the GEDI Lidar (Global Ecosystem Dynamics Investigation Lidar) planned for launch to the International Space Station in 2019. Together, these missions will substantially contribute to the high-resolution observations envisioned for DESDynI.

Finding 2.1: The NASA ESD program has made important progress during the decade, partially recovering from the underfunded state it was in a decade ago, and extending the progress noted in the ESAS Midterm Assessment's conclusion that "NASA responded favorably and aggressively to the 2007 decadal survey."

- Since the ESAS Midterm Assessment, NASA has adeptly responded to changing requirements and maintained a healthy cadence of Venture suborbital, instrument, and mission opportunities, managed with an improved focus on cost constraints.
- The Earth system science community has benefited from strong international partnerships and satellites exceeding their expected design lifetimes.
- Implementation of pre-decadal and ESAS 2007 missions has been slowed by budgetary constraints, increases in mission costs and scope, and launch failures.

NOAA Progress from ESAS 2007

NOAA's capability to implement the recommendations of the 2007 decadal survey was hampered by budgetary and programmatic challenges to core elements of its satellite programs, specifically the devel-

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continuity of high-priority climate observations; and bring two decadal survey Tier 2 missions forward to allow launch by 2020."

[4] See "Establishing and Managing Mission Costs," in NAS (2012, pp. 57-59). While not recommending "missions," the present survey follows a similar approach to constrain the costs of addressing its recommended targeted observables.

[5] The PACE mission, directed by NASA's Goddard Spaceflight Center (GSFC), is defined as a "Design to Cost" development. Details on this type of development may be found in Jeremy Werdell, PACE Project Scientist, "Project Update," PACE Science Team meeting, January 20-22, 2016, https://pace.oceansciences.org/docs/sci2016_werdell.pdf.

TABLE 2.3 Status of Pre-ESAS 2007 NASA Missions Planned for the 2007-2017 Decade, and Those Entering Implementation or Operations Since ESAS 2007

Mission	Geophysical Variables	Status
OSTM/Jason-2**	Ocean surface topography	Launched 2008, operating
OCO**	CO_2	Launch failure
Glory**	Aerosol and cloud particle size and optical thickness	Launch failure
Aquarius**	Sea-surface salinity	Mission ended
Suomi NPP**	Multiple variables (ATMS, VIIRS, CrIS, OMPS, CERES)	Launched 2011, operating
LDCM**	Land use and land-surface temperature	Launched 2013, operating
GPM**	Precipitation (rain and snow)	Launched 2014, operating
OCO-2	CO_2	Launched 2014, operating
CYGNSS*	Hurricane winds	Launched 2016, operating
SMAP*	Soil moisture; freeze/thaw state; surface salinity	Launched 2017, operating
SAGE-III (on ISS)	Stratospheric O_3, aerosols	Launched 2017, operating
GRACE-FO	Changes in gravitational field	In development (2017)
ICESat-2*	Ice-sheet elevation change, sea-ice thickness, vegetation canopy height	In development (2018)
ECOSTRESS*	Plant temperature and water stress	In development (2018)
GEDI*	Ecosystem structure and dynamics	In development (2018)
TEMPO*	Air pollution (O_3, NO_2, . . .)	In development (2018)
MAIA*	Aerosols	In development (2021)
TROPICS*	Precipitation and storm intensity	In development (2021)
GeoCARB*	Carbon exchanges between land and atmosphere	In development (TBD)
PACE	Phytoplankton communities	In development (2022)
NISAR*	Surface changes from ice-sheet collapse, earthquakes, tsunamis, volcanoes, and landslides	In development (late 2021)
SWOT*	Ocean (and freshwater) high-resolution elevation, providing water storage and ocean circulation	In development (2021)
CLARREO-Pathfinder on the ISS*	High-accuracy spectral reflectance with on-board calibration	In development (2021 time frame)
OCO-3 (on ISS)	CO_2	In development (2018)

NOTE: Missions that have a legacy in the ESAS 2007 recommended missions, or were competed through the ESAS-recommended Earth Venture Program, are shown with an asterisk. Foundational missions are shown with a double asterisk. For future missions, expected launch dates are given in parentheses. Acronyms are defined in Appendix G.

opment of next generation geostationary and polar-orbiting operational environmental satellites, GOES-R and the National Polar-orbiting Operational Environmental Satellite System (NPOESS), respectively.[6] Cost growth and delays occurred in both programs; for the polar program, this led to utilization of NASA's Suomi-NPP for operational data, and the initiation of the Joint Polar Satellite System (JPSS) to replace NPOESS.[7]

ESAS 2007 recommended that NOAA should restore several key climate, environmental, and weather observational capabilities to its planned NPOESS, now Joint Polar Satellite System (JPSS), and Geostationary Orbit Environmental Satellite-R Series (GOES-R) missions, following descopes to those systems.[8] NOAA, with NASA, was able to continue the Clouds and Earth's Radiant Energy System (CERES)[9] time series and restore OMPS for JPSS; however, it was unable to do so for Conical-Scanning Microwave Imager/Sounder (CMIS; microwave imager sounder). NOAA was unable to include a temperature and humidity profiling capability for GOES-R (as described in more detail in Box 4.7, in Chapter 4).

Eventually, as a result of the unanticipated technical problems that led to delays and cost growth, NOAA significantly reduced the scope of the nation's future polar operational environmental satellite series. This reduction included omitting observational capabilities assumed by ESAS 2007 to be part of NOAA's future capability and being unable to to implement the three new missions recommended for NOAA implementation by ESAS 2007 (the Operational GPS Radio Occultation Mission,[10] the Extended Ocean Vector Winds Mission, and the NOAA portion of CLARREO).

ESAS 2007 also recommended that NOAA should increase investment in identifying and facilitating the transition of demonstrably useful research to operational use. This recommendation was met with mixed results. NOAA was unable to secure funding for an Extended Ocean Vector Winds Mission (XOVWM) for flight on the Japan Aerospace Exploration Agency GCOM-W1 satellite, but it was successful in securing funding for the U.S. contribution to Jason-3 (and launching it on January 17, 2016).[11] However, while NOAA will continue to be involved and play a support role, overall U.S. responsibility for continuing the series beyond Jason-3 is reverting back to NASA. The descope of CMIS from JPSS and the lack of follow-on Advanced Microwave Scanning Radiometer (AMSR) are contributing to the potential gap in microwave coverage (this gap is discussed in detail in Box 4.4, in Chapter 4).

Finding 2.2: NOAA progress during the decade was hampered by major programmatic adjustments, as summarized in the ESAS Midterm Assessment's conclusion that "NOAA's capability to implement the assumed baseline and the recommended program of the 2007 Decadal Survey have been greatly dimin-

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[6] See, for example, GAO (2007, 2010).

[7] The first of the GOES-R satellites was successfully launched on November 19, 2016, and is performing well. At the time of this writing, JPSS-1 is scheduled for launch in late 2017. Notably, throughout the period of planning and development of GOES-R and NPOESS/JPSS, which overlapped the decade since publication of the 2007 decadal survey, and despite technical and budgetary challenges, the recent report by the NOAA National Environmental Satellite, Data, and Information Service Independent Review Team stated, "During this multi-year period, the U.S. weather forecasting and severe storm warning capability has functioned at a high level of performance" (NOAA, 2017, p. 14).

[8] See "NOAA Satellite Programs" in NRC (2012, Appendix D).

[9] The measurements of Earth's radiation budget provided by CERES instruments since 1998 will now be continued by (1) CERES on the Joint Polar Satellite System-1 (JPSS-1) and (2) the Radiation Budget Instrument (RBI), a scanning radiometer capable of measuring Earth's reflected sunlight and emitted thermal radiation. RBI will fly on the JPSS-2 mission planned for launch in November 2021, as well as JPSS-3 and JPSS-4. See Georgieva et al. (2015).

[10] Many of the objectives of the Operational GPS Radio Occultation Mission were addressed by the FORMOSAT-3/COSMIC mission jointly implemented by NOAA and Taiwan National Space Organization and launched in 2006. A follow-on mission, FORMOSAT-7/COSMIC-2 is scheduled to launch in two phases, with the first launching in 2017. As this report was going to press, NOAA announced it would no longer pursue the second phase of COSMIC-2.

[11] The ESAS 2007 report did not explicitly recommend Jason-3; it considered Jason-2 and the NPOESS altimeter series as part of the program of record. When the NPOESS altimeter was descoped as part of the Nunn-McCurdy process, a follow-on NRC report in 2008, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft* (NRC, 2008), identified Jason-3 as a first-tier priority to ensure climate-quality continuity of the altimetry record.

ished by budget shortfalls and cost overruns and by sensor descopes and sensor eliminations on both JPSS and GOES-R." NOAA's responsibilities have since evolved to focus on those satellite programs that directly contribute to weather forecasting and warnings and, consequently, it has transferred responsibility for many climate observations to NASA.

USGS Progress from ESAS 2007

The USGS role in space-based observation during the last decade has been significant, built around the 40+ year Landsat program and reinvigoration of this program through the new long-term Sustainable Land Imaging (SLI) partnership with NASA[12] and the decision in 2008 to make the Landsat standard data products freely available through the Internet.[13] At the time of ESAS 2007 publication, continuity of the Landsat program was a serious concern. Landsat 5 was over 20 years old; Landsat 6 had failed; Landsat 7, launched in 1999, was well beyond its expected lifetime and had been operating since 2003 with a failed scan line corrector;[14] and planning for Landsat 8 was not proceeding as needed. The Landsat program had a long history of moving from one agency to another and unsuccessfully changing business models. Building on a National Research Council (NRC) report (NRC, 2013), an interagency study led to a commitment from the administration for a NASA-USGS partnership creating the SLI program and extending the plan for Landsat by two decades. As a result of this attention, the situation has stabilized. Landsat 8 launched in 2013, and Landsat 9 is planned to launch in 2020+.

Finding 2.3: USGS has transformed the Landsat program via the SLI program by operating Landsat, connecting the scientific/user communities and the developers of new measurement technologies, and archiving/distributing data products. This has placed the Landsat measurements on a more operational footing. As long as it is funded and managed as an operational program, the SLI program will support and motivate widespread usage, benefiting both the operational and scientific communities.

Policy Progress from ESAS 2007

The 2007 decadal survey recommended that "the Office of Science and Technology Policy[OSTP], in collaboration with the relevant agencies and in consultation with the science community, should develop and implement a plan for achieving and sustaining global Earth observations. This plan should recognize the complexity of differing agency roles, responsibilities, and capabilities as well as the lessons from the implementation of the Landsat, EOS, and NPOESS programs."[15] The 2014 *National Plan for Civil Earth Observations*, produced by the National Science and Technology Council (NSTC) and chaired by the Director of OSTP, responds to this recommendation and provides a framework for determining when

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[12] See NRC (2013). SLI is also described in Tim Newman, Land Remote Sensing Program Coordinator, U.S. Geological Survey, "USGS Land Remote Sensing Program Update: Briefing for the National Geospatial Advisory Committee," April 7, 2016, https://www.fgdc.gov/ngac/meetings/april-2016/landsat-program-update-ngac-apr-2016.pdf.

[13] The benefit of a free archive of Landsat data is discussed in the National Geospatial Advisory Committee paper "Landsat Advisory Group Statement on Landsat Data Use and Charges" (NGAC, 2012). See also Miller et al. (2013).

[14] The scan line corrector (SLC) compensates for the forward motion of the satellite. Without an operating SLC, the sensor's line of sight traces a zigzag pattern along the satellite ground track and an estimated 22 percent of any given scene is lost. A number of methods have been employed to fill the gaps in Landsat 7 data (see USGS, "Landsat 7," https://landsat.usgs.gov/landsat-7), although for some applications this approach is still not adequate (e.g., see Zhu et al., 2012).

[15] See NRC (2007), p. 14. This same recommendation was echoed in a 2008 follow-on report, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft* (NRC, 2008), which further explored in its Chapter 4 the elements needed for a long-term climate strategy.

experimental Earth observations should be transitioned to sustained observations for research or for the delivery of public services. However, executing the transition remains problematic.

As noted earlier, NOAA's response to the 2007 decadal survey, which included recommendations to sustain a number of measurements, was greatly diminished by budget shortfalls; by cost overruns and delays, especially those associated with the NPOESS program prior to its restructuring in 2010 to become the JPSS; and by sensor descopes and sensor eliminations.[16] In 2010, NASA released a Climate-Centric Architecture plan (NASA, 2010) that included a set of "continuity" missions. Further illustrating a much-expanded role for NASA in sustaining observations, the fiscal year 2014 budget of the Obama administration directed NASA to assume responsibility for a suite of climate-relevant observations for the purpose of continuing a multidecadal data record in ozone profiling, Earth radiation budget, and total solar irradiance. This added responsibility, however, has not been accompanied with resources necessary to offset the increased associated expenses. As a result, other activities at NASA are impacted.[17]

The United States has become increasingly reliant upon the international Earth observing community for maintaining long-term data records essential to understanding the Earth system and how it changes over time. In the 1970s and 1980s, NASA was essentially the sole agency with Earth observing satellites.[18] The Europeans and Japanese soon followed. In the 1990s NASA led the way in Earth system science with the Earth Observing System (EOS). Since that time, additional space agencies have developed Earth observing capabilities, and the Committee on Earth Observation Satellites (CEOS)—the primary forum for international space-based Earth observations—has grown to include 32 member organizations. Within the past decade, China and India have both developed ambitious programs. And today, the Europeans—the European Space Agency (ESA), the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), and the European Union (EU; with its commitment to its Copernicus program)—have become strong and capable organizations, and have established international leadership in implementing sustained global Earth observations.

Finding 2.4: The 2013 National Strategy for Civil Earth Observations and the 2014 National Plan represent progress toward a strategy for achieving and sustaining Earth observations, as recommended by ESAS 2007. However, the United States has not committed the resources to collect the broad range of sustained observations needed to monitor and understand Earth as a system, leaving critical gaps in the implementation of this National Plan and a dependency on non-U.S. sources.

Science and Applications Progress

Scientific and applications progress as a result of the ESAS 2007 report has been substantial. The report articulated challenges in the context of both a general vision for improving science and applications knowledge and specific goals associated with particular science, applications, or societal benefits. Specific progress was anticipated in the areas of (1) Improving Weather Forecasts, (2) Protecting Against Solid-Earth Hazards, (3) Ensuring Water Resources, (4) Maintaining Healthy and Productive Oceans, (5) Mitigating Adverse Impacts of Climate Change, (6) Protecting Ecosystems, and (7) Improving Human Health. Looking back, progress over the last decade has been substantial in these as well as other areas, as a result of continuing access to space-based observations.

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[16] See Table 3.1, "Summary of Decadal Survey Related NOAA Developments," in NRC (2012).

[17] NRC (2012), p. 7.

[18] Russia has had Earth-observing satellites since the 1970s, but access to their data, for all practical purposes, has not been feasible.

Mission Science Example

Scientific progress resulting from the specific missions listed in Table 2.3 is just now being realized, as these missions have been launched and early research results published. The accomplishments of the OCO-2 mission provide an illustrative example.

The OCO-2 Project science objectives include quantifying variations in the column averaged atmospheric carbon dioxide (CO_2) dry air mole fraction, X_{CO2} with the precision, resolution, and coverage needed to improve our understanding of (1) surface CO_2 sources and sinks (fluxes) on regional scales (≥1,000 km) and (2) the processes controlling their variability over the seasonal cycle. OCO-2 was launched in July 2014, and these goals are now being addressed. For example, the OCO-2 mission data have now been characterized and calibrated (Crisp et al., 2017; Eldering et al., 2017), and OCO-2 data have been merged with data from the Greenhouse Gases Observing SATellite (GOSAT, now called Ibuki) to provide a more comprehensive data product (Nguyen et al., 2017). Further progress using these data should include improved understanding of the sources and sinks of CO_2.[19]

Highlighted Progress

Scientific progress enabled by satellite observations during the last decade extends far beyond what this committee, in this short review, can assess and communicate. Rather than a comprehensive assessment, we have chosen to provide examples that demonstrate both the progress of the last decade and the opportunity for the next decade.[20] To start, *eight important examples of progress in the last decade are described in a series of sidebars (boxes) later*. The examples and corresponding boxes are as follows:

- Scientific improvements that advanced weather prediction skill (Box 2.1).
- Understanding of air/sea fluxes of sensible and latent heat (Box 2.2).
- Tracking extreme precipitation to reduce disaster risk (Box 2.3).
- Enhanced monitoring to support improvements in U.S. air quality (Box 2.4).
- Tracking sea-level rise and its sources (Box 2.5).
- Monitoring and understanding of stratospheric ozone (Box 2.6).
- Increasing global availability of satellite-based emergency mapping (Box 2.7).
- Satellite ocean color and marine ecosystems—revolutionizing our understanding of life in the sea (Box 2.8).

In addition to these examples highlighted in sidebars, *seven other noteworthy examples of progress during the last decade* are listed here:

1. *Quantifying worldwide emissions and concentrations of air pollutants, and their trends.* Satellite retrievals from the multi-angle imaging spectroradiometer (MISR) and Moderate-Resolution Imaging Spectroradiometer (MODIS) instruments have been used by Zhao et al. (2017) to document regional trends in Aerosol Optical Depth (AOD) between 2001 and 2015, showing decreases over the Eastern United States and Western Europe. In Eastern and Central China, aerosol AOD increases prior to 2006, fluctuates between 2006 and 2011, and then decreases. These trends appear to be consistent with emissions estimates of aerosol, precursors, and other industrial pollutants.

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[19] See the 2017 *Science* special issue on remote sensing at http://science.sciencemag.org/content/358/6360 (Volume 358, Number 6360).

[20] It is also important to recognize that progress in the last decade—and certainly in the earliest part of that decade—is the result of investments made prior to the completion of the decadal survey.

BOX 2.1 *PROGRESS IN THE LAST DECADE:* SCIENTIFIC IMPROVEMENTS THAT ADVANCED WEATHER FORECAST SKILL

While numerical weather prediction (NWP) has improved over the last four decades, the more rapid increases in forecast skill can be attributed to more accurate initial conditions due to better data assimilation methods, more observational data, advances in understanding and modeling of physical processes, and increased computational resources (Bauer et al., 2015; Buizza and Leutbecher, 2015).

The forecast skill increase for the European Centre for Medium-Range Weather Forecasts (ECMWF) model from 1981 to present is shown in Figure 2.1.1 (see http://www.emc.ncep.noaa.gov/gmb/STATS_vsdb/longterm/ for a multimodel comparison that includes the NOAA Global Forecast System [GFS]). Forecast skill is measured here by the correlation between the forecasts and the verifying analysis of the 500 hPa height, expressed as the anomaly with respect to the climatological height. Values greater than 60 percent indicate useful forecasts, while those greater than 80 percent represent a high degree of accuracy. The predictive skill in the Northern and Southern Hemispheres is nearly equal today, due to the effective assimilation of satellite data that provides global coverage. The convergence of the curves for the Northern Hemisphere and Southern Hemisphere after 1999 represents the breakthrough associated with the more effective assimilation of satellite data through the use of variational data assimilation (Simmons and Hollingsworth, 2002). The improvement of weather forecast in lead time between 3 and 10 days has been about 1 day per decade. However, the 10-day and longer lead time has not yet reached the 50 percent level.

Over the past decade, there have been significant advances in the community's capabilities for subseasonal forecasting, and several operational centers have implemented model-based subseasonal forecast systems that provide a bridge between the medium-long-range weather and seasonal forecasts and outlooks (e.g.,

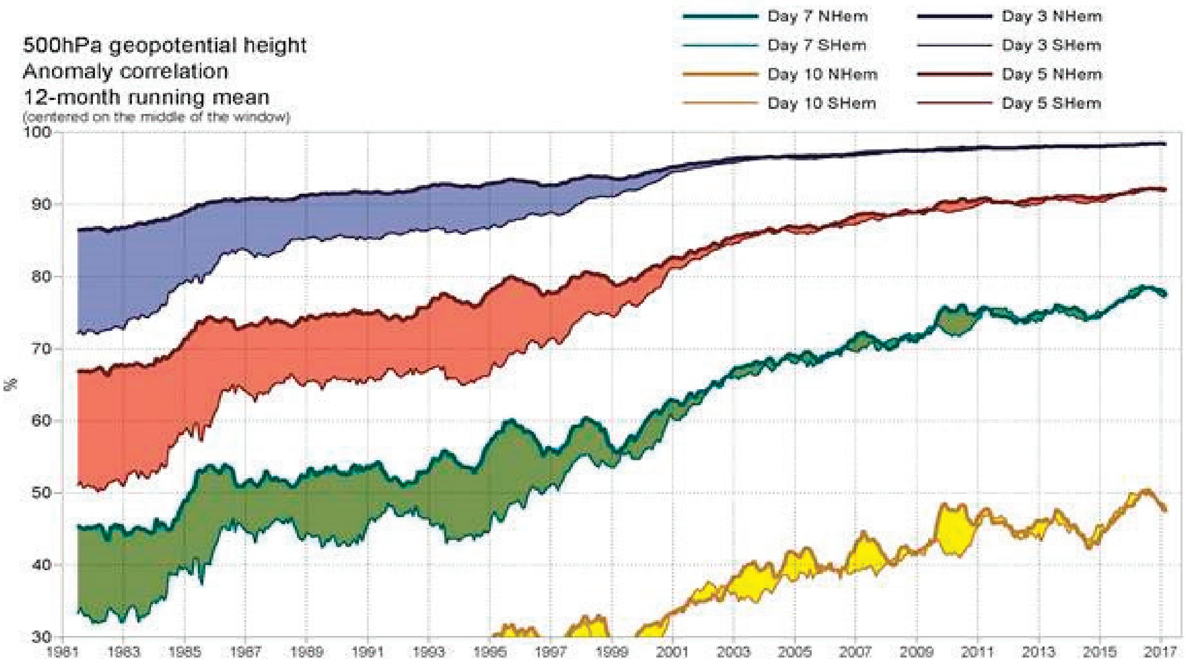


FIGURE 2.1.1 Northern and Southern Hemisphere anomaly correlations for 500 hPa geopotential height forecasts, reflecting the European Centre for Medium Range Weather Forecasts (ECMWF) numerical weather prediction (NWP) skill increase from 1981 to present. SOURCE: European Centre for Medium-Range Weather Forecasts, "Anomaly Correlation of ECMWF 500hPa Height Forecasts," https://www.ecmwf.int/en/forecasts/charts/catalogue/plwww_m_hr_ccaf_adrian_ts?time=2017101100.

BOX 2.1 Continued

s2sprediction.net; Vitart et al., 2017). Extending the useful range of forecasts beyond 2 weeks through the use of probabilistic forecasting is a priority for many operational NWP centers over the coming decade.

A significant advance in the past decade has been realized with the improved agreement between infrared (IR) radiance measurements and radiances simulated from NWP model input. This can be attributed to the advent of spectrally resolved well-calibrated IR measurements as well as better physics (line strengths, widths, mixing) in radiative transfer model calculations. These advances have, in turn, increased the impact of low Earth orbiting (LEO) IR high spectral resolution sounders (Atmospheric Infrared Sounder [AIRS], Infrared Atmospheric Sounding Interferometer [IASI], Cross-track Infrared Sounder [CrIS]) on reducing NWP model errors (Menzel et al., 2016; Hilton et al., 2012). For most NWP centers, the combined contribution to the reduction of 24-hour global forecast error for these IR sounders is now similar to combined contribution from microwave sounders (Advanced Microwave Sounding Unit [AMSU], Advanced Technology Microwave Sounder [ATMS], Microwave Humidity Sounder [MHS]; Auligné et al., 2016; WMO, 2016). In addition, the high spectral resolution IR measurements have enabled surface emissivity estimation, boundary layer probing, and higher vertical resolution temperature and moisture profile determinations.

BOX 2.2 *PROGRESS IN THE LAST DECADE:* BREAKTHROUGH IN UNDERSTANDING AIR/SEA FLUXES OF SENSIBLE AND LATENT HEAT

The rate of heat exchange between the atmosphere and ocean is represented by air-sea heat fluxes. Most applications necessitate fluxes with accuracies of at least 5 to 10 W/m^2 (e.g., Bourassa et al., 2013). This is a challenging target, and in the past flux products disagreed substantially, often by more than 20 to 40 W/m^2 (Bourassa et al., 2013). An important breakthrough of the last decade is the development of improved satellite-based estimates of air-sea fluxes of sensible and latent heat, including better uncertainty information and physical understanding of remaining issues with the existing satellite system (Figure 2.2.1; Clayson et al., 2017). Systematic and especially random errors are still higher than fluxes measured from in situ platforms like buoys (e.g., Smith et al., 2012), but with the greater spatial coverage of the satellite fields and improved retrieval methodologies, uncertainties vary spatially, but in the global mean they are beginning to approach the 10 W/m^2 target. Determining the structural character of the uncertainties and the relation of these to other aspects of the Earth system is also important for understanding how these error sources might be addressed

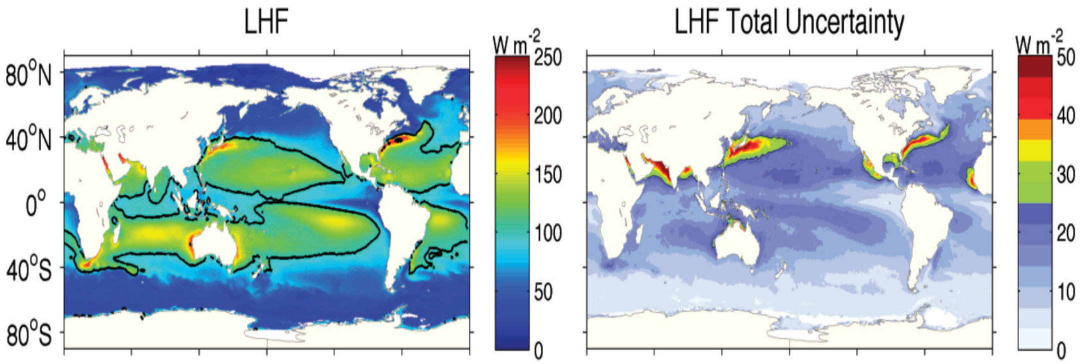


FIGURE 2.2.1 The annual mean distribution of latent heat flux and the estimated total uncertainty based on the SeaFlux. SOURCE: Curry et al. (2004).

BOX 2.2 Continued

and overcome. One important source of uncertainty in estimating latent heat flux is the difference between the saturation humidity value and its near-surface value, denoted ($Q_s - Q_a$). The error characteristics of $Q_s - Q_a$ closely correlate to the cloudy sky weather states that are defined by a combination of mostly clear and shallow boundary-layered clouds. These analyses, and our improved ability to estimate latent and sensible heat fluxes, have led to improvements that now allow for the use of the satellite flux fields for studies of extreme weather (e.g., Liu et al., 2011); regional process studies and water budgets (Brown and Kummerow, 2014); and global water and energy budget studies (L'Ecuyer et al., 2015; Rodell et al., 2015). Future advances in this area could come from sensors with greater boundary layer sensitivity, satellite retrieval algorithm improvement, increased spatial sampling, and optimized ensembles of satellite products with increased synergy between the modeling and satellite communities.

BOX 2.3 *PROGRESS IN THE LAST DECADE:* TRACKING EXTREME PRECIPITATION TO REDUCE DISASTER RISK

In the past decades, many advances in satellite remote sensing algorithms for estimating precipitation have been made. Among these are Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA; Huffman et al., 2007); Hydro-Estimator (H-E; Scofield and Kuligowski, 2003); Global Satellite Mapping of Precipitation (GSMaP; Okamoto et al., 2005); CPC Morphing (CMORPH; Joyce et al., 2004): Integrated MultiSatellite Retrievals for GPM (IMERGE; Huffman et al., 2014); and the Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN) family of systems (Hsu et al., 1997; Sorooshian et al., 2000; Hong et al., 2004; Ashouri et al., 2015). These algorithms utilize a variety of geostationary Earth orbit (GEO) IR and LEO passive microwave (PMW) sensors for the measurement of precipitation. Furthermore, various outputs generated by these algorithms are produced with different spatial and temporal resolutions and time latency.

From the perspective of emergency disaster management including flash flooding, the availability of observations with the shortest possible time latency is critical. The following is an example of the PERSIANN—Cloud Classification System (PERSIANN-CCS), with approximately 30 to 90 minutes with high resolution of 0.04 degree, from 60 degrees N to 60 degrees S, in capturing Typhoon Haiyan.

Typhoon Haiyan, with a 10-minute sustained wind speed of 230 km/hr, struck Southeast Asia in November 2013. It is one of the strongest storms on record, resulting in significant damage and many casualties. Real-time monitoring of such large storms with the least time latency is becoming invaluable for disaster early-warning applications. A visualization tool that displays satellite-based precipitation estimates offers a real-time tracking of the immense rainfall delivered by Haiyan Super Typhoon. One such tool is known as the Water and Development Information for Arid Lands—A Global Network (G-WADI) PERSIANN-CCS GeoServer (see http://hydis.eng.uci.edu/gwadi).

The G-WADI PERSIANN-CCS GeoServer has been under development since 2005 through collaboration between the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine, and the United Nations Educational, Scientific, and Cultural Organization (UNESCO) International Hydrological Program (IHP). The core algorithm of this system, supported by NASA and NOAA, extracts local and regional cloud features (coldness, geometry, and texture) from the international constellation of GEO satellites capturing IR imagery and estimates rainfall at 0.04 degrees × 0.04 degrees spatial resolution (roughly a 4-km square) every 30 minutes. Information from LEO satellites is used to then adjust the initial precipitation estimation from the artificial neural network (ANN) algorithm.

BOX 2.3 Continued

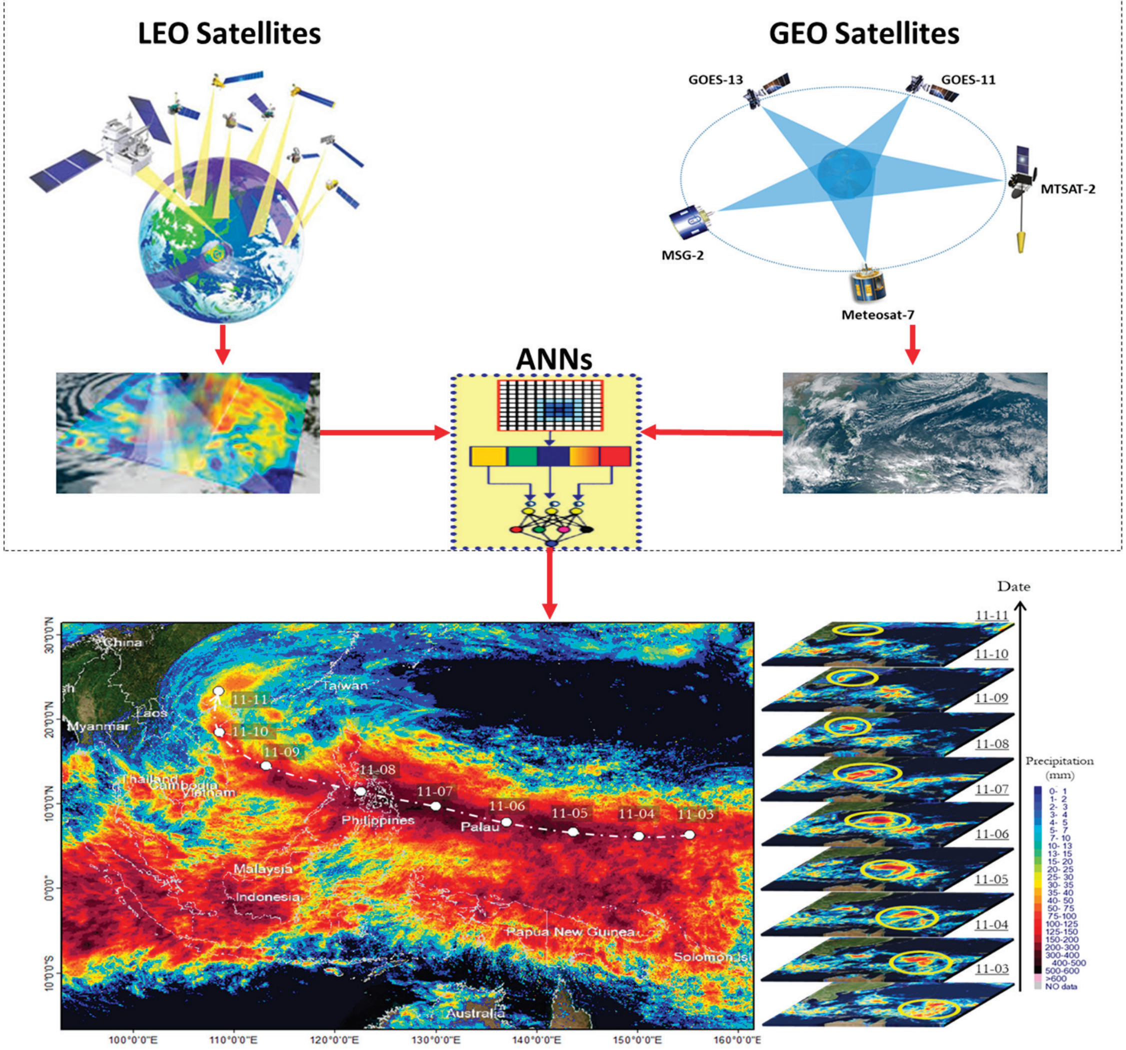


FIGURE 2.3.1 State-of-the-art real-time global space-based precipitation estimation systems using multiple satellites and advanced machine learning techniques (artificial neural networks—ANNs) are reaching the level of maturity to monitor and capture extreme precipitation events. This figure provides an example of tracking precipitation of Super Typhoon Haiyan using PERSIANN-CCS with approximately 30-minute latency at 0.04-degree resolution. SOURCE: Nguyen et al. (2014).

In the case of Haiyan Super Typhoon, PERSIANN-CCS captured the maximum precipitation intensity of approximately 361 millimeters per day reached on November 7, while the storm was approaching the Philippines (Figure 2.3.1). The following days show rainfall rates steadily decreasing with the weakening of the storm as it entered the South China Sea, struck Vietnam, and then finally dissipated on November 11.

This tool provides an example of how the confluence of machine learning algorithms and the ever-increasing capabilities of high-performance computers can process vast amounts of observations from multiple satellites in a timely manner to allow for real-time monitoring and issuance of warning of extreme precipitation in flood-prone areas and for use by engineers and operators managing water resources systems (Nguyen et al., 2014).

BOX 2.4 *PROGRESS IN THE LAST DECADE:* NASA SATELLITE OBSERVATIONS REVEAL DRAMATIC IMPROVEMENTS IN U.S. AIR QUALITY OVER THE PAST DECADE

Starting in 2003, the U.S. Environmental Protection Agency (EPA) has acted to vigorously control fuel combustion emissions of nitrogen oxide radicals ($NO_x \equiv NO + NO_2$) through the NO_x Budget Trading Program and other measures. NO_x is a major source of ozone pollution, particulate pollution, acid deposition, and ecosystem eutrophication.

Ozone Monitoring Instrument (OMI) observations of NO_2 aboard the Aura satellite have provided a vivid demonstration of the success of these emission control policies (Lu et al., 2015). Figure 2.4.1 shows the trends

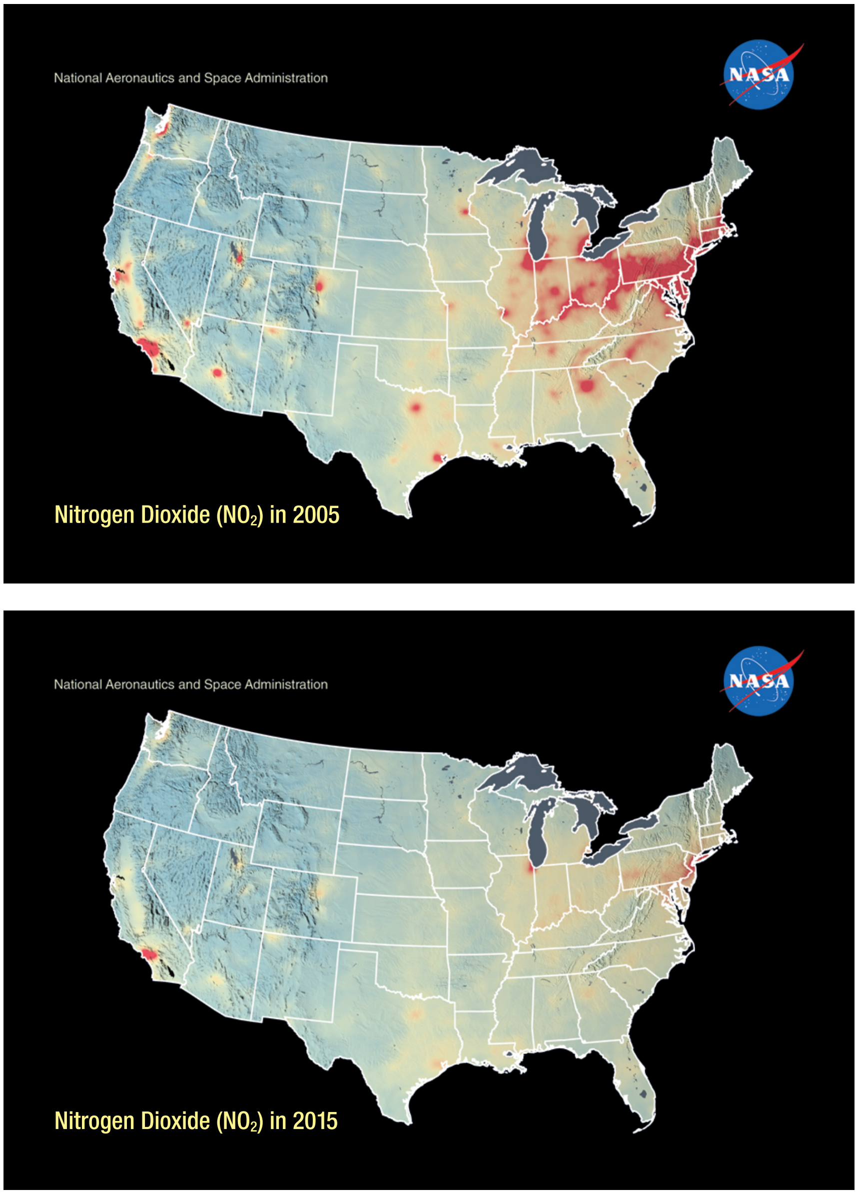


FIGURE 2.4.1 Decreasing U.S. air pollution over the past decade. The figure shows annual mean tropospheric columns of nitrogen dioxide (NO_2) observed by the Ozone Monitoring Instrument (OMI) satellite instrument in 2005 and 2015. SOURCE: Courtesy of NASA.

BOX 2.4 Continued

in NO_2 concentrations measured by OMI over the United States from 2005 to 2015. These satellite images have been critical to communicate to the public that the air over the United States is indeed getting cleaner in response to policy action. The quantitative NO_2 trends observed from space and their spatial distribution are consistent with the emission trends reported by the EPA, verifying compliance with the control measures but also demonstrating the value of the satellite observations for monitoring NO_x emissions and their trends worldwide. OMI observations have thus documented rapid increases in NO_x emissions over the past decade in the Middle East, India, and China, and a leveling off in China over the past few years in response to new air pollution control measures. Satellite observations of air quality extend also to sulfur dioxide (SO_2), formaldehyde, ammonia, ozone, and particulate matter. These observations are now providing a sustained global monitoring system for air quality and are a crucial trusted resource for air quality managers. The observations have also been crucial in identifying air pollution as one of the top environmental killers in the world (OECD, 2012).

BOX 2.5 *PROGRESS IN THE LAST DECADE:* GLOBAL SEA-LEVEL RISE AS AN INTERDISCIPLINARY PROBLEM

Global sea-level rise is an interdisciplinary issue with immense societal impact. Sea-level rise is the combined result of thermal expansion as water warms and the addition of mass as land ice (glaciers and ice sheets) melts. Since the advent of satellite altimetry in 1992, measurements of the absolute sea level from space indicate an average global rate of sea-level rise between +2.6 ± 0.4 mm/yr and +2.9 ± 0.4 mm/yr (depending on the choice of vertical land motion applied), more than twice the average rate for the entire 20th century (Watson et al., 2015). This rate is consistent with measurements of the thermal structure of the upper ocean by Argo floats, and of the mass loss of ice sheets and the associated ocean mass increase by the Gravity Recovery and Climate Experiment (GRACE) satellite; they demonstrate that the contribution from melting ice now exceeds that from thermal expansion. This rate is increasing due to increased warming of the oceans and melting of glaciers and ice sheets. Furthermore, the rate of global sea-level rise within the past two decades has been increasing, with the largest contribution coming from increased melting of the Greenland ice sheet (Chen et al., 2017). The largest source of uncertainty in projections is the response of the Antarctic ice sheet, which contains 56 m of sea-level rise equivalent, and the contribution from that ice sheet is accelerating (Harig and Simons, 2015).

The estimated 146 million people worldwide living along the coast within 1 m or less above mean high tide—about 2 percent of the global population—are at direct risk this century depending on how fast global sea level continues to rise in their region. The largest impacts will be associated with storm surge and intense rainfall, which are exacerbated by changes in local relative sea level, tidal amplitudes, local subsidence, and the nature of extreme meteorological forces. The Intergovernmental Panel on Climate Change (IPCC) in its 5th Assessment Report (2013) projects anywhere from ~25 cm to 1 m by 2100, depending on which model scenario is used for carbon concentration. More recent projections (Kopp et al., 2014) for 2100 adopted by California are larger, ranging from 0.5 to 1.2 m. Still others project higher values that could exceed 2 m (Oppenheimer and Alley, 2016).

Sea level does not rise uniformly over the whole ocean, and different climate scenarios give a range of average global sea-level rise values. Moreover, coastal sea-level rise depends on the relative rate of sea-level rise, as opposed to the absolute rate. Critical to that determination is the subsidence and uplift of the coastal lands. Thus, accurate geodetic measurements (e.g., from Global Positioning System [GPS]) as well as surface displacement measurements (as can be derived from Interferometric Synthetic Aperture Radar [InSAR]) are two critical contributions to understanding local rates of sea-level rise. Addressing the impact of local sea-level rise (due to the combination of the absolute height change of sea level itself and the corresponding coastal vertical motion) requires an assessment of the implications for coastal facilities. The most important metric needed for

BOX 2.5 Continued

individual cities to plan to adapt to sea-level rise is a prediction for when local sea level will meet or exceed a particular height on the land at that location under various climate scenarios. Planners and engineers urgently need projections of geographically varying sea-level rise as far into the future as possible, they need margins of error associated with the projections (Griggs et al., 2017), and they need to know local rates of vertical land motion. The uncertainty in projections of sea-level rise directly impacts how fast and how much the coast must be hardened, how high streets and piers should be raised, where airports and other infrastructure should be relocated, and/or which neighborhoods should be abandoned.

In many communities, the most dramatic impacts of sea-level rise result from increased vulnerability to coastal flooding. Contributing factors include not only the local sea-level rise, but also storm surges and intense rainfall (e.g., Houston after Hurricane Harvey) and their dependence upon changes in local relative sea level, tidal amplitudes, local subsidence, and the nature of extreme meteorological forces. Coastal flooding manifests itself in the increasing frequency of *nuisance floods*, such as shown for the city of Boston in Figure 2.5.1.

Evaluating future risks from coastal flooding and inundation—and reducing uncertainties in projections—involves an understanding of how storm frequency and intensity, offshore ocean currents, and decadal variability in the ocean is changing. This in turn depends on maintaining continuing satellite observations of the variables that determine global sea-level rise (changes in ocean heat and land-ice mass), as well as observations of the variables that determine the strength of storm surges (winds, wave height, and tides), intensity of rainfall, and any local subsidence.

Coastal cities and regional governments across the United States—Seattle (Seattle Office of Sustainability and Environment, 2013), San Francisco (City and County of San Francisco, 2016), San Diego (City of San Diego, 2005), Southeast Florida (Southeast Florida Regional Climate Change Compact, 2015), and New York City (City of

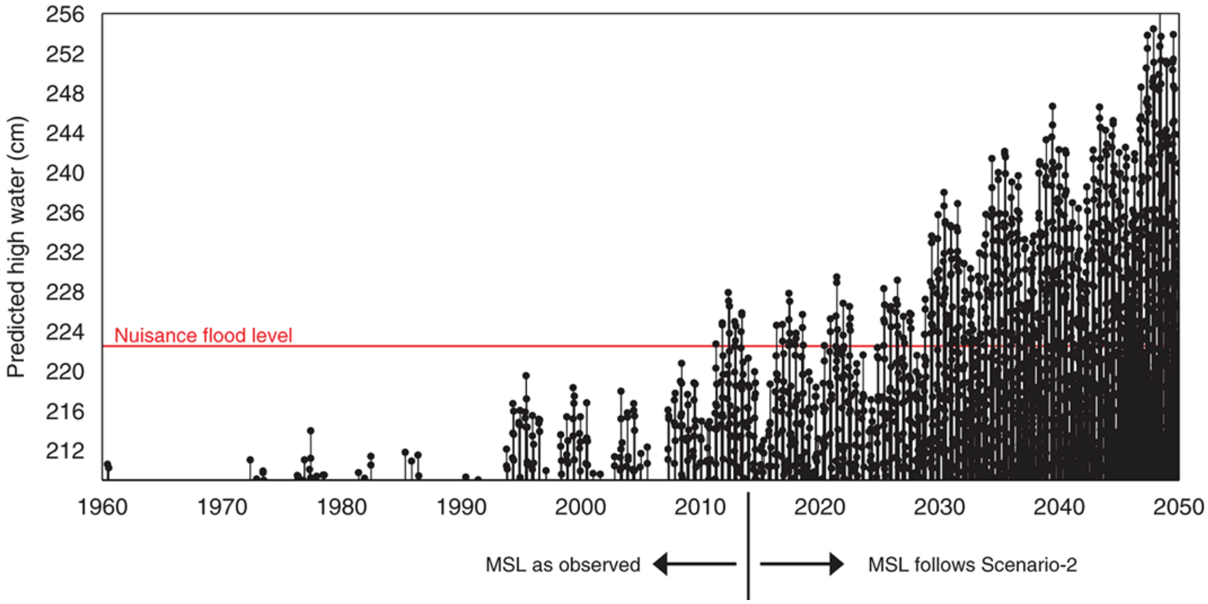


FIGURE 2.5.1 Predicted high tides at Boston near or exceeding the *nuisance flood* level of 68 cm above mean high water, and their relationship to sea-level rise. Before 2010, the tides alone never exceeded flood levels; from 2011 onward, and likely into a future climate, sea level has risen and will rise sufficiently that tides alone can produce nuisance flooding. Catastrophic flooding can occur if a storm occurs on top of a high tide. NOTE: In this figure, MSL = mean sea level, and Scenario-2 refers to the "Intermediate-High" scenario of the U.S. National Climate Assessment, which is available at https://cpo.noaa.gov/sites/cpo/Reports/2012/NOAA_SLR_r3.pdf. SOURCE: Kruel (2016).

BOX 2.5 Continued

New York, 2015), among others—have developed Climate Action Plans that evaluate concerns about sea-level rise. Reducing uncertainties provides for improved community adaptation and mitigation planning, leading to stronger overall resilience to disasters. As an example of the urgency of this issue, a number of coastal communities are now moving beyond the planning stage to implementation. For example, Miami Beach has embarked on a $100 million flood prevention project in the face of sea-level rise. This effort will raise roads, install pumps and water mains, and redo sewer connections over the next 2 years in the Mid-Beach area (Flechas, 2017).

BOX 2.6 *PROGRESS IN THE LAST DECADE:* MONITORING AND UNDERSTANDING OF STRATOSPHERIC OZONE

Satellite observations of atmospheric ozone began in 1979 with the Total Ozone Mapping Spectrometer (TOMS). Observations over the past decade from the Ozone Monitoring Instrument (OMI), the Microwave Limb Sounder (MLS), and the Tropospheric Emission Spectrometer (TES) aboard NASA Aura have sustained the long-term satellite record and provided further insights into the vertical distributions of ozone. The satellite record has been critical for understanding of the complex interplay between dynamic, physical, and chemical processes driving the formation of the Antarctic ozone hole. Satellite observations have enabled the monitoring of interannual variability and potential ozone depletion in the Arctic, and provided understanding of the differences between the Arctic and the Antarctic. The satellite record has also enabled tracking of ozone trends at northern midlatitudes with sufficient information to relate these trends to their causes.

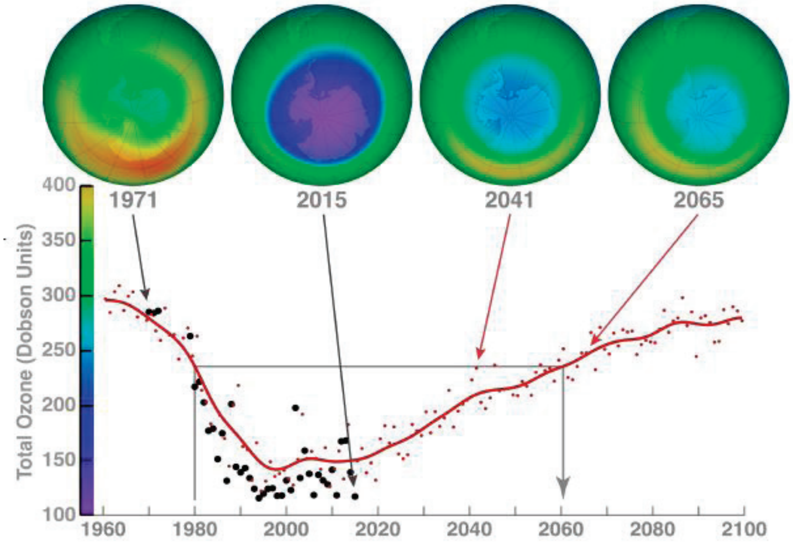


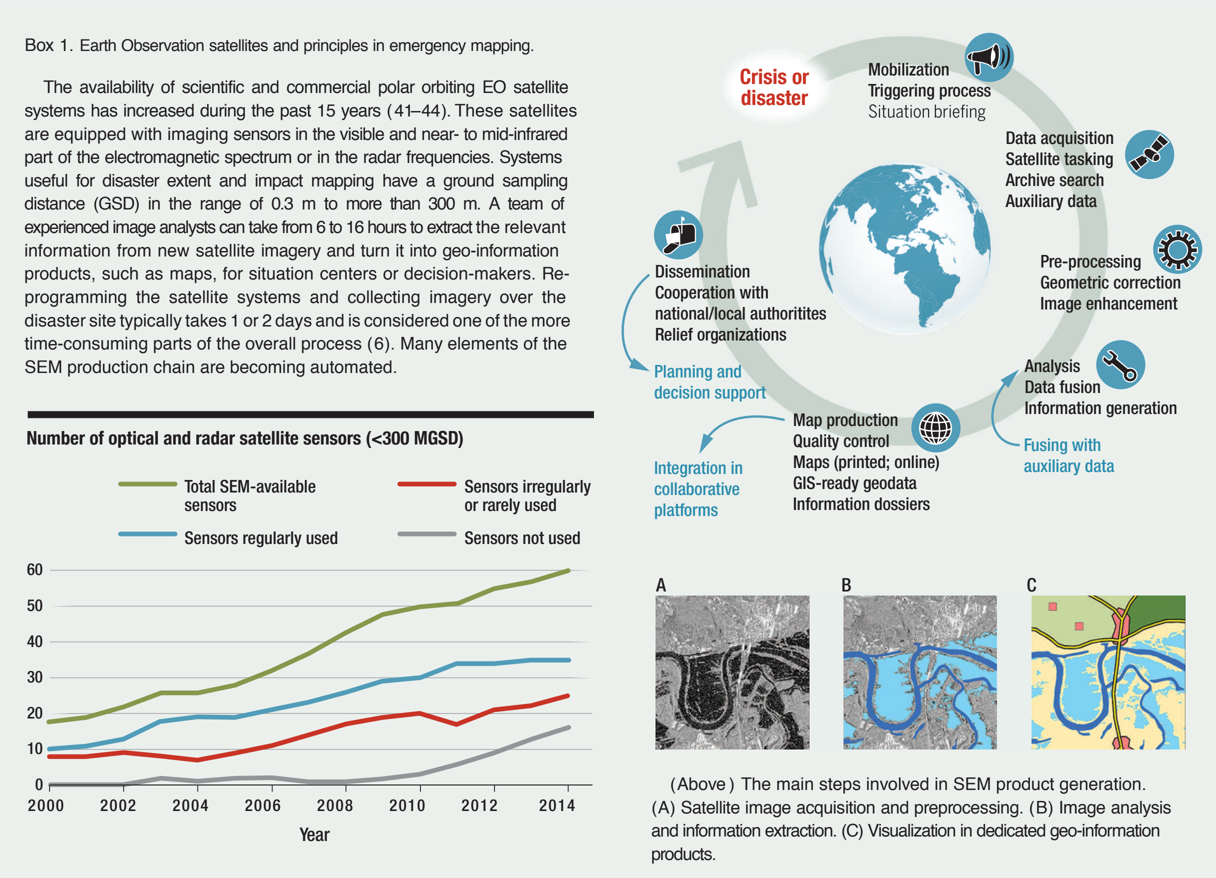
FIGURE 2.6.1 *Top panels:* False color images of October average total column ozone (Dobson units). The 1971 and 2015 panels are observations derived from the NASA Nimbus-4 BUV instrument and the NASA Aura Ozone Monitoring Instrument (OMI, KNMI), respectively. The 2041 and 2065 panels are from a NASA/Goddard Space Flight Center (GSFC) Goddard Earth Observing System Chemistry-Climate Model (GEOSCCM) simulation using projections of ozone-depleting substances (ODSs) and greenhouse gases (GHGs). The color scale for total ozone is on the left side. High ozone values are in red/yellow, while low values are blue/purple. *Bottom panel:* The lowest values from the October average over Antarctica. The black dots are observations from the BUV instrument, the Total Ozone Mapping Spectrometer (TOMS), and the OMI instrument. The red dots are from NASA/GSFC GEOSCCM model simulation. The red curve shows the smoothed values of the red points (10-year Gaussian filter). SOURCE: NASA, "Aura: Informing Policy Makers," https://aura.gsfc.nasa.gov/informing_policy_makers.html.

BOX 2.6 Continued

Observations from satellites have provided guidance to international policies to protect the ozone layer, starting with the Montreal Protocol, and resulting in the total ban on halocarbon production as of the late 1990s. As illustrated in Figure 2.6.1, satellite observations of ozone over the past decade show that the depletion of the ozone layer has been halted and there are some early signs of recovery. The satellite observations have provided the basis for the development of advanced models to simulate the chemistry of the stratosphere, and model projections for the future are also included in Figure 2.6.1. Satellites will play a central role in the coming decades for monitoring the expected recovery of ozone and the complications associated with climate change.

BOX 2.7 *PROGRESS IN THE LAST DECADE:* INCREASING GLOBAL AVAILABILITY OF SATELLITE-BASED EMERGENCY MAPPING (SEM)

Over the past few decades, satellite observations have been used effectively for warnings and assessments of high-impact natural hazards such as hurricanes, severe winter storms, and wildfires (e.g., Clark et al., 2003; Gillespie et al., 2007; CEOS, 2015). Enabled by advances in satellite remote sensing capability and information



Box 1. Earth Observation satellites and principles in emergency mapping.

The availability of scientific and commercial polar orbiting EO satellite systems has increased during the past 15 years (41–44). These satellites are equipped with imaging sensors in the visible and near- to mid-infrared part of the electromagnetic spectrum or in the radar frequencies. Systems useful for disaster extent and impact mapping have a ground sampling distance (GSD) in the range of 0.3 m to more than 300 m. A team of experienced image analysts can take from 6 to 16 hours to extract the relevant information from new satellite imagery and turn it into geo-information products, such as maps, for situation centers or decision-makers. Re-programming the satellite systems and collecting imagery over the disaster site typically takes 1 or 2 days and is considered one of the more time-consuming parts of the overall process (6). Many elements of the SEM production chain are becoming automated.

(Above) The main steps involved in SEM product generation. (A) Satellite image acquisition and preprocessing. (B) Image analysis and information extraction. (C) Visualization in dedicated geo-information products.

FIGURE 2.7.1 An example of the transition of integrative science to applied use. NOTE: The references cited in this figure include the following: (6) Ajmar et al. (2015); (41) Belward and Skøien (2015); (42) University of Twente (2015); (43) ESA (2015); and (44) CEOS (2015). SOURCE: Voigt et al. (2016).

BOX 2.7 Continued

technology, more sophisticated global and regional mapping systems based on rapid assessments of flooding, earthquake damage, and other natural and man-made disasters are being developed. For example, the International Working Group on Satellite-based Emergency Mapping (IWG-SEM; http://www.unspider.org/network/iwg-sem) was established after the Haiti earthquake and Pakistan flood in 2010 to improve information sharing and cooperation across the international community.

Figure 2.7.1 (Voigt et al., 2016) provides a summary of how increased satellite availability has improved our ability to provide mapping for decision makers in response to emergencies such as typhoons and earthquakes. Response capacity is improving rapidly. In some cases the creation of disaster-related products has been accelerated to just a few hours or less through capabilities such as crowdsourcing, machine learning, satellite constellations, and use of day/night all-weather sensors such as radar.

BOX 2.8 *PROGRESS IN THE LAST DECADE:* SATELLITE OCEAN COLOR AND MARINE ECOSYSTEMS—REVOLUTIONIZING OUR UNDERSTANDING OF LIFE IN THE SEA

Satellite measurements of ocean color have revolutionized our understanding of life in the sea. Ocean color tracks variations in microscopic phytoplankton in the upper ocean that form the base of the marine food web supporting invertebrates, fish, marine mammals, seabirds, and valuable commercial and recreational fisheries. Continuous global satellite ocean color coverage has been available from mid-1997 since the launch of the Sea-viewing Wide Field of View Sensor (SeaWiFS) followed more recently by Moderate-Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) (McClain, 2009). The amount of phytoplankton chlorophyll, the key pigment in photosynthesis, is derived by measuring light backscattered from the upper ocean in different spectral bands. Chlorophyll estimates can then be combined with information on sea-surface temperature, light, nutrients, and mixed layer depth to quantify variations in photosynthesis or primary productivity. The large-scale geographic and seasonal variations in surface ocean chlorophyll, well known in large part because of satellite observations, are strongly influenced by ocean circulation patterns. Elevated chlorophyll values and highly productive marine ecosystems occur in upwelling regions along the equator, in high latitudes, and in coastal eastern boundary current regions such as off California, Oregon, and Washington State (Figure 2.8.1).

Over the past decade, major scientific advances occurred along several fronts facilitated by the continuity of the growing global ocean color time series and development of new methods for estimating novel biological variables from ocean color sensors. Examples include mapping long-term natural variability in surface chlorophyll and phytoplankton biomass (Siegel et al., 2013); constraining seasonal phytoplankton blooms and improved understanding of the underlying mechanisms (Behrenfeld and Boss, 2014; Blondeau-Patissier et al., 2014); and improved estimates of phytoplankton primary production, functional type, and size (Lee et al., 2015; Kostadinov et al., 2016; Mouw et al., 2017).

A key finding is that surface chlorophyll in the tropical ocean (bounded by the black lines in Figure 2.8.1) is linked closely with interannual climate variations such as El Niño, with lower chlorophyll found during periods with warmer sea-surface temperatures as a possible indicator of responses to future climate change (Siegel et al., 2013). This climate signal reflects primarily physiological reductions in the amount of chlorophyll to carbon biomass in cells, likely due to nutrient stress under more stratified upper-ocean conditions. Other new satellite algorithms are opening windows on particle size and phytoplankton community composition, important ecological attributes for connecting plankton dynamics to the carbon cycle, food webs, and fisheries (e.g., Siegel et al., 2014). Pilot studies using Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) lidar data are showing great promise for observing plankton deeper in the water column than passive ocean color sensors as well as resolving the vertical structure of plankton communities (Behrenfeld et al., 2017).

BOX 2.8 Continued

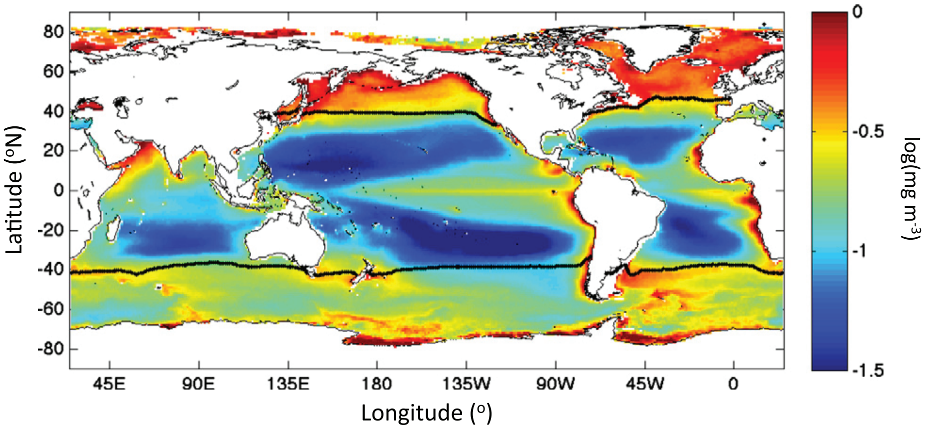


FIGURE 2.8.1 Mission mean chlorophyll concentration from Sea-viewing Wide Field of View Sensor (SeaWiFS) from August 1, 1997, to December 14, 2010. The black lines indicate the boundary between warm tropical waters and the cooler extra-tropics. Surface chlorophyll exhibits larger geographic variations of over a factor of 100 from low chlorophyll open-ocean regions to highly productive coastal zones. To capture this wide range in values, the color bar uses a standard logarithmic scale, where each unit of variation (e.g., from −1 to 0) reflects a factor of 10 increase in chlorophyll concentration. SOURCE: Siegel et al. (2013).

The wealth of satellite ocean color data is being integrated with other remote sensing data—for example, on ocean physics and circulation—and with ship and robotic ocean observations using sophisticated data science approaches and numerical models (Kavanaugh et al., 2014) for applications to marine biodiversity and fisheries.

Satellite surface ocean color and temperature provide synoptic maps for locating physical fronts and phytoplankton blooms that are often hotspots for fish (and marine mammals and seabirds), information that is used by fisherman and recreational and commercial fishery forecasting services as well as ocean conservation managers. On larger scales, primary productivity derived from satellite data helps explain geographic and temporal variations in potential fish catch and is central to models being developed for assessing climate change impacts on fisheries (e.g., Stock et al., 2017). More broadly, satellite ocean color and other remote sensing data underpin key applications related to evaluating water quality and ocean ecosystem health (e.g., McCarthy et al., 2017), and NOAA produces a number of routine products for the public and natural resource managers.

Examples of valuable ocean monitoring and ecological forecasting products include data on ocean turbidity, land pollution, and runoff events to assess possible threats to coral reef health (NOAA Coral Reef Watch[1]); the presence of harmful algal blooms (HABs) in coastal waters and the Great Lakes that can endanger aquaculture, recreational and commercial fisheries, and human health;[2] and the magnitude of low oxygen dead zones in coastal waters and the potential for coral bleaching.[3] Synoptic information from satellites also creates a framework that greatly enhances the value of in-water physical, chemical, and biological data from the U.S. Integrated Ocean Observing System as illustrated in the new U.S. Marine Biodiversity Observation Network.[4]

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[1] NOAA Coral Reef Watch, "Satellite Ocean Color Product Development," https://coralreefwatch.noaa.gov/satellite/research/oceancolor.php.

[2] NOAA National Ocean Service, "Harmful Algal Blooms: Tiny Organisms with a Toxic Punch," https://oceanservice.noaa.gov/hazards/hab/.

[3] NOAA National Ocean Service, "NOAA Ecological Forecasting: Protecting Human Health and Coastal Economies with Early Warning," https://oceanservice.noaa.gov/ecoforecasting/.

[4] NOAA Integrated Ocean Observing System, "Marine Biodiversity Observation Network (MBON)," https://ioos.noaa.gov/project/bio-data/.

2. *Use of satellite data in health impact assessment.* The application of satellite retrievals in health impact assessment has been revolutionary and growing rapidly since 2007, relying largely on MODIS, MISR, and related retrievals (Chudnovsky et al., 2013; Kloog et al., 2012, 2014; Liu et al., 2007a, 2007b; Snider et al., 2015). This has been facilitated by both the global coverage from satellites and the improved resolution of estimates of particulate matter (PM)-related properties. Satellite-based estimates of PM exposures are now finer than 1 km, allowing for improved estimates of pollutant health interactions, and the (albeit limited, at present) information from satellites on PM properties is providing information on how specific sources are impacting health.
3. *Monitoring land-use change due to both human and natural causes.* The primary measurements in the SLI suite (Landsat, MODIS, and VIIRS) have sparked substantial research productivity on understanding both processes and features of the land surface, due to both human and natural influences (e.g., Cai et al., 2014). For example, there is newly derived quantification of the global distribution of irrigated and nonirrigated cropland, and of the fact that increased agricultural productivity (ca. 50 percent over the past 50 years) explains up to 25 percent of the observed changes in seasonality of atmospheric CO_2 (Gray et al., 2014; Salmon et al., 2015).
4. *Tracking variations in ocean plankton and land vegetation as well as primary production.* SeaWiFS and MODIS-Aqua data were used to provide significant advances in understanding the interannual variability and long-term trends in marine plankton biomass and primary productivity on a global scale as well as the relationship of regional biological variations in plankton biomass and physiology to ocean physical factors such as warming (e.g., Siegel et al., 2013). Similar progress also occurred for quantifying variations in land vegetation greenness and primary production combining satellite multispectral imagery and ecosystem models (Zhu et al., 2011; Anav et al., 2015) as well as the development of new primary production estimation approaches using measurements of solar induced fluorescence (Frankenberg et al., 2014).
5. *Seeing the rain formation process for the first time on a global scale.* Combinations of A-Train observations (the A-Train series of satellites is described in Box 2.9, below) have provided a unique glimpse into one of the important processes of the Earth system—how rain forms (e.g., Suzuki et al., 2010; Takahashi et al., 2017). This revealed many surprises both with respect to how frequently it rains on Earth (Stephens et al., 2010) and exposed significant deficiencies in the way this rain formation process is represented in Earth system models (Golaz et al., 2013; Suzuki et al., 2015), which further underscored the way this process fundamentally shapes the cloud aerosol interactions.
6. *Cloud feedbacks contributing to the decadal cooling in the eastern tropical Pacific.* Zhou et al. (2016) used geostationary satellite observations of clouds and climate model simulations to show how the slowdown in global mean warming that occurred from 1998 to 2013 (Yan et al., 2016) was contributed to by a positive cloud feedback on localized tropical cooling.
7. *Observation of a slowdown in sea-level rise associated with flooding in Australia.* Fasullo et al. (2013) used altimetry, gravity, and color imaging observations from three satellite instruments. It demonstrated that monitoring of sea level and gravity from space is necessary in order to detect a rapid increase in sea-level rise and attribute its causes, consistent with what is expected to happen eventually as the ice sheets begin to decline faster.

Transitioning to the Coming Decade

With Earth science and applications, scientific needs and societal needs are tightly coupled. Curiosity-driven science often leads to significant societal benefits. Science driven by societal needs often reveals new intellectual challenges of a purely scientific nature. This productive coupling between curiosity-driven science and applications-driven research is a hallmark of Earth system science.

Discipline-specific advances based on observations from space have enabled fundamental discoveries across the natural sciences. In addition, space-based data has provided the foundations for integrated science of the Earth system (Jacobson et al., 2000; Reid et al., 2010; Berger et al., 2012). Many of the important discoveries based on observations from space involve new insight into interactions among major components of the Earth system, for example the atmosphere and oceans (Mechoso et al., 2014), large ice sheets and the oceans (Pritchard et al., 2012; Rignot et al., 2013), ocean circulation and biogeochemistry (Siegel et al., 2014), or terrestrial ecosystems and the water cycle (Wrona et al., 2016). While some discoveries are grounded entirely on observations from space, many more depend on combining information from a range of sources, including field campaigns, laboratory experiments, computer modeling, and theoretical studies (Sellers et al., 1988, 1995; Mechoso et al., 2014). Science based on integrating information from several approaches can lead to products where the insights from the whole are much greater than the sum of the parts. As a consequence, the value of space-based observations amplifies the returns on investments across the Earth sciences.

The top science priorities for the next decade all combine opportunities to drive fundamental science advances as well as contribute to important applications for forecasting, managing, and planning. All fit into a science and technology ecosystem that involves other kinds of measurements as well as theory, with expected returns from the integrated system that amplify the value of each component. Some of the top priorities are important mainly from the perspective of one science discipline or one societal application. Others are critical for a range of disciplines and applications as well as for continued progress in understanding, predicting, and managing the Earth as an integrated system.

A DECADE'S OPPORTUNITY FOR RAPID PROGRESS

A convergence of institutional capacity, technological advance, and scientific discoveries from prior years makes possible rapid progress during the period of this decadal survey.

Institutional Capacity to Meet Scientific and Societal Needs

Since the last decadal survey, the suite of nations with commitments to space-based observation programs has expanded, and a new generation of commercial satellites (especially small commercial satellites) has emerged as a viable option for some kinds of science and applications. Close coordination can facilitate efficiency not only across nations but also between nations and the private sector. Indeed, advances in technology, coordination, and private-sector capabilities have the potential to allow for increased observation capacity within the existing budget constraints. Also, optimal implementation of space-based observation depends on effectively integrating these measurements with measurements from suborbital missions and ground-based measurements and campaigns.

Scientific and Technological Opportunities

The coming decade will present rapidly growing and increasingly challenging needs for Earth information and the science on which it is founded. At the same time, advances in Earth system science, and in other fields that Earth scientists draw from, promise new capabilities that can allow us to progress even more rapidly than we have in the past:

- *Advances in space systems technology* (such as small spacecraft and active sensing) will allow us to address critical questions in new ways, providing the tools to observe new parameters.
- *New scientific methods*, such as machine learning, will allow us to extend the reach of our science within limited resources.
- *Novel observational methodologies*, such as advanced satellite constellations (see Box 2.9), have been shown to significantly amplify the science and applications beyond that which any single satellite provides on its own.
- *Innovative project implementation approaches*, including rideshare and secondary payload opportunities, spacecraft block buys, public-private partnerships, and international partnerships offer the potential of lower cost missions and/or more frequent access to space.
- Earth process *models, data assimilation, and computational capabilities* will be sufficiently robust to the point where they can make full use of all the data (tens of terabytes per day) that satellites have to offer, a capacity we cannot currently fully exploit.
- The scientific community and the public have the capacity to effectively absorb new capabilities enabled by the availability of *new applications, data structures, and dissemination tools*.
- *Alternative sources* of observations and analytic capabilities are rapidly emerging, particularly in the commercial sector. These can augment traditional sources to enhance capability.

Supported with appropriate resources, NASA, NOAA, and USGS hold the potential to make tremendous advances *this decade* in both our scientific understanding of Earth and the use of that knowledge to benefit society. Doing so can be best accomplished with a national commitment.

Finding 2.5: This decade presents an *opportunity for rapid progress* in space-based Earth science and its application to benefit society. The recommended Earth observing system will provide previously unavailable capabilities; new modeling and analysis tools are poised to enable scientific breakthroughs; complementary capabilities are expanding in the commercial sector and other communities; and the research and user community's ability to deliver benefits is greatly enhanced by technological advances such as widespread Internet access and mobile device use.

A STRATEGIC FRAMEWORK FOR DECADAL PROGRESS

The coming decade is one in which we must not only accelerate the advance of our science and applications, but also do so within constrained resources. This perspective was summarized in the Decadal Community Challenge, as stated in Chapter 1:

> *Pursue increasingly ambitious objectives and innovative solutions that enhance and accelerate the science/applications value of space-based Earth observation and analysis to the nation and to the world in a way that delivers great value, even when resources are constrained, and ensures that further investment will pay substantial dividends.*

A visionary overall strategy is critical for responding to such a difficult challenge. Succeeding requires cost-effectively expanding the benefits of Earth science and the resulting Earth information. Doing so means addressing *strategic issues:* those high-level issues common to all programs and program elements within each agency and across agencies.

Rising to this challenge requires innovation, not just doing things the way we have in the past but aggressively implementing new means to be efficient and effective in how we work. This ensures we both

BOX 2.9 THE A-TRAIN CONSTELLATION—HOW OBSERVING SYSTEM ARCHITECTURE INNOVATION ENABLES BREAKTHROUGH SCIENCE

One of the most successful demonstrations of an integrated approach to observe the Earth system is the A-Train satellite constellation, shown in Figure 2.9.1. The constellation provides multiple perspectives on many Earth system processes.

On April 28, 2006, two active sensors carried by the NASA CloudSat and the NASA/Centre National d'Études Spaciales (CNES) Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellites were added to the constellation. Together these sensors provided a much deeper understanding of the combination of cloud, precipitation, and aerosol processes and the critical role of vertical profiles in understanding the effects of clouds and aerosol on Earth's radiation balance (L'Ecuyer et al., 2009; Han et al., 2017). The radar and lidar observations mutually complement each other, offering a powerful means to interpret and evaluate other information from the passive sensors of the constellation.

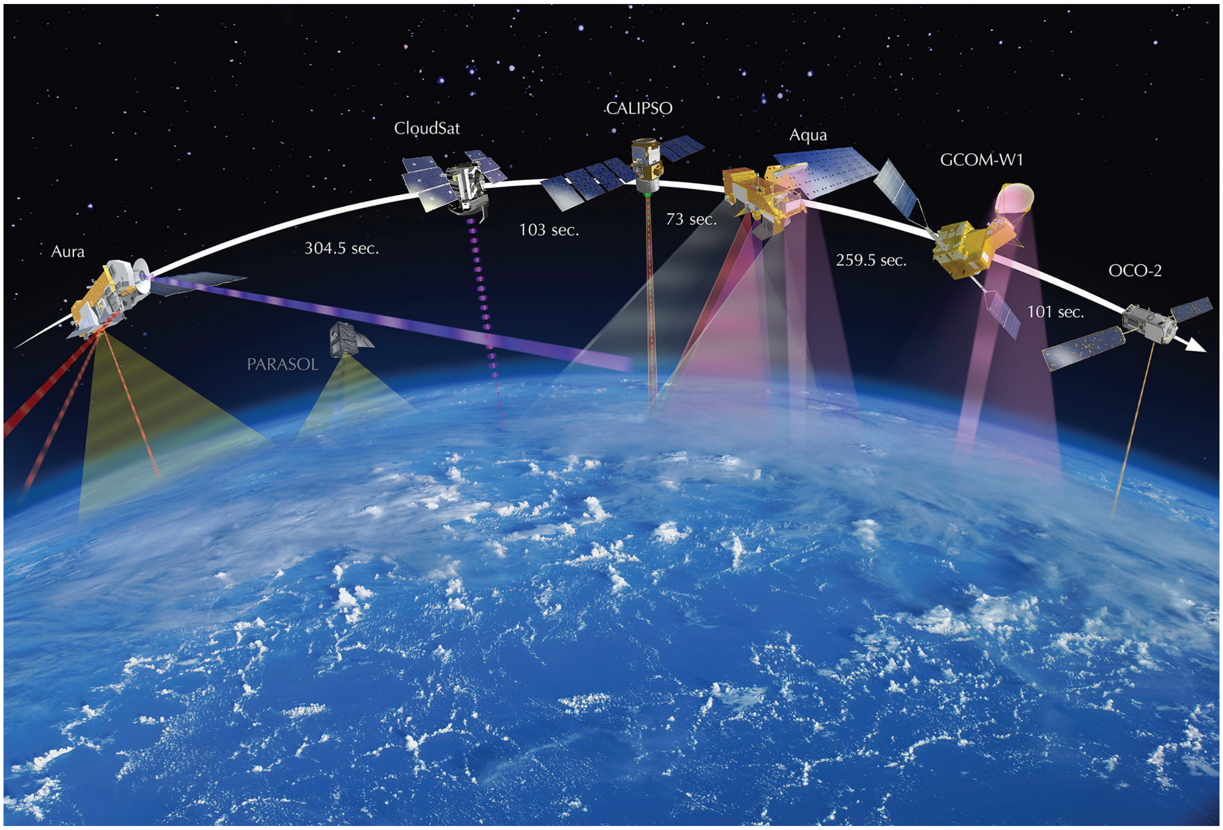

FIGURE 2.9.1 The A-Train constellation of satellites as of 2014. This constellation pioneered an integrated approach for observing Earth, advancing our understanding of Earth's atmosphere. The A-Train offered a clear demonstration of both the value of constellation flying and the viability of tightly aligning observations from different spaceborne platforms.

address shortfalls in how things are done today and anticipate opportunities to improve given a changing context for the future. As a result, the committee endorses a strategic approach to the U.S program of Earth observation, as summarized in the following recommendation and detailed in the following text.

Recommendation 2.1: Earth science and applications are a key part of the nation's information infrastructure, warranting a U.S. program of Earth observations from space that is robust, resilient, and appropriately balanced. NASA, NOAA, and USGS, in collaboration with other interested U.S. agencies, should ensure efficient and effective use of U.S. resources by strategically coordinating and advancing this program at the national level, as also recommended in the 2007 Earth Science and Applications from Space (ESAS) decadal survey.

Implementation of this recommendation is discussed in the following two sections of the report.

Toward a National Strategy

To promote national leadership and to develop a national strategy for Earth observation, the inaugural decadal survey report—ESAS 2007—included the following key recommendations:

- The U.S. government, working in concert with the private sector, academe, the public, and its international partners, should renew its investment in Earth-observing systems and restore its leadership in Earth science and applications.
- OSTP, in collaboration with the relevant agencies and in consultation with the scientific community, should develop and implement a plan for achieving and sustaining global Earth observations. This plan should recognize the complexity of differing agency roles, responsibilities, and capabilities as well as the lessons from implementation of the Landsat, EOS, and NPOESS programs.

While considerable progress has been made toward the national strategy envisioned in ESAS 2007, challenges remain and progress needs to continue in order to serve critical national and societal interests. As an example, the nation's economic and security interests in the applied use of Earth information have been poorly articulated within U.S. policy. Consequently, U.S. agency responsibilities remain unclear in many areas, and the value of the nation's investments in Earth observation are not being fully realized. This is particularly the case with regard to climate. While the most recent National Space Policy in 2010 emphasized "climate change research and sustained monitoring" to be carried out within NASA, and "climate monitoring" to be carried out within NOAA,[21] shifting responsibilities and budgets continue to buffet both agencies.

However, the committee also recognizes the important progress made under the leadership of the National Science and Technology Council, which produced the 2013 *National Strategy for Civil Earth Observations* and the ensuing 2014 *National Plan for Civil Space Observations*. These documents defined categories of observations, identified the important observation types within each category, and codified the agency roles for implementing them. To be effective, the U.S. civil strategy needs to be further coordinated with strategies in the defense and intelligence agencies, and supported with adequate funding.

Additional clarification regarding various aspects of the civil strategy has occurred through the budgeting and legislative processes, notably with regard to responsibilities and budgets for climate research

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[21] See Executive Office of the President (2010).

and monitoring. The President's FY 2011 Budget Request reallocated many climate-related observing responsibilities from NOAA to NASA as part of an administration initiative called the NASA Climate-Centric Architecture, but without concomitant budget shifts. Budget-driven clarification on the roles of NASA and NOAA was included in the President's FY 2016 Budget Request[22] and in the 2016[23] and 2017[24] Senate and House Appropriations Committee Reports. Most recently, the Weather Research and Forecasting Innovation Act of 2017 requires NOAA to "prioritize improving weather data, modeling, computing, forecasting, and warnings for the protection of life and property and for the enhancement of the national economy" in the conduct of its research.

Other budget-driven policy constrains possible international partnerships. The 2011 Department of Defense and Full-Year Appropriations Act began an annual process of restricting NASA from bilateral collaboration with China (Hester, 2016), whereas bilateral collaboration between NOAA and China is allowed under the Atmosphere Protocol of the U.S.-China Agreement for Science and Technology originally signed in 1979.[25]

By its nature, a national strategy for Earth observation involves collaboration with other nations and international coordinating bodies. Among the prominent coordinating bodies are the Coordination Group for Meteorological Satellites (CGMS), the Committee on Earth Observation Satellites (CEOS), and the Global Earth Observing System of Systems (GEOSS). Some, such as the Committee on Space Research of the International Council for Science (COSPAR), even produce their own decadal Earth-system science plans (Simmons et al., 2016). The United States both receives data from other satellites through these collaborations and has obligations to provide its satellite data to other nations. The Program of Record (Appendix A) considered by this committee to represent the foundation of the next decade's observing system includes a significant set of international satellites formally relied on by the United States within its national Earth observing strategy. Despite successes in international collaboration, access to data from non-U.S. satellites in many cases still presents challenges for U.S. science and applications uses for reasons of policy (as described earlier) or data quality.

In addition, various nongovernmental advisory bodies provide strategic guidance that is valuable to a U.S. national strategy. A 2009 report addressing the entire breadth of U.S. civil space activities (NRC, 2009) listed one of its six strategic goals as "reestablish leadership for the protection of Earth and its inhabitants through the use of space research and technology." A 2011 report addressed the impediments to interagency collaboration on Earth observation satellites (NRC, 2011), and a 2012 report (NRC, 2012) provided guidance to the National Weather Service regarding actions it should take to progress.

Finally, engagement of the U.S. aerospace and defense industry is essential to accomplishing the priority measurement of this Earth science decadal survey. The use and leveraging of industry provides extensive advantages to the agencies involved and to the U.S. economy (NRC, 2009), and was one of the three major thrusts of the 2012 NRC recommendation for advancing the National Weather Service (NRC, 2012). Beginning with the first Earth weather and observational satellites, U.S. industry has been a reliable and constructive partner and implementing agent for the execution of a wide variety of Earth science mis-

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[22] "The FY 2016 President's Budget supports NOAA's broad environmental mission and redefines NASA and NOAA Earth observing responsibilities whereby NOAA will be responsible for satellite missions that directly contribute to NOAA's ability to issue weather and space weather forecasts and warnings to protect life and property (Executive Office of the President, 2010).

[23] Senate Report 114-66 accompanying FY 2016 CJS Appropriations: "NOAA is directed to prioritize satellite programs directly related to weather forecasting and that result in the greatest reduction of risk to lives and property." House Report 114-130 accompanying CJS Appropriations for NOAA: "The Committee recommendation focuses limited resources on the Joint Polar Satellite System (JPSS) and Geostationary Operational Environmental Satellite (GOES) program in light of their role in ensuring accurate and timely weather forecasts and warnings."

[24] Similar to the 2016 language, the 2017 House (114-605) and Senate (114-239) CJS Appropriations Reports both direct NOAA to prioritize satellite programs directly related to weather forecasting.

[25] See NOAA, "Developing Partnerships," last modified July 18, 2017, http://www.nesdisia.noaa.gov/developingpartnerships.html.

sions. Greater industry participation, including an increasing emphasis on commercialization within the Earth science enterprise, is expected in coming decades. These benefits are expected over a wide range of scales as a result of increased competition, and from expanded use of public-private partnerships, data buys, and other innovative acquisition models. New entrants and the industrial capabilities in the commercial marketplace are also expected to bring increasing opportunities for technology infusion and cost savings. As these opportunities become increasingly available, governmental agencies need to ensure that commercial data meet the quality standards required for scientific analyses and operational applications, particularly in the area of climate observations for which accuracy, precision, and stability are critical to characterizing and understanding change.

Strategic Challenges and Shortfalls

Each decade presents new opportunities and issues. For the coming decade, optimizing the nation's investments to achieve a successful Earth observation program, in the expected context of constrained resources, means we must do some things differently from the past. The current programs of NASA, NOAA, and USGS reflect several *strategic shortfalls* regarding issues that are not being adequately addressed. As long as the following challenges remain unresolved, we will not be able to achieve the full value for the nation of space-based Earth observations.

- *Observations continuity (scientific and applications).* The 2013 *National Strategy for Civil Earth Observations* and the 2014 *National Plan for Civil Space Observations* clearly define the category of "sustained observations," the important observations within that category (including those related to climate), and the agency roles for implementing them. Despite these recent policy clarifications, a national commitment to implementing sustained observations is lacking[26] and funding is insufficient to match needs. Overall, it is not clear what roles NASA, NOAA, and USGS play in sustaining long-term space-based observations. Shifting responsibilities, particularly for climate observations, have exacerbated the confusion over agency roles. The commitment in Europe provides a strong contrast; the EU formally committed in 2014 to Copernicus,[27] a long-term, user-driven Earth observation and monitoring program focused on the delivery of near-real-time products and services to meet a broad range of societal needs (see Box 3.2, in Chapter 3). This is a commitment not just by a nation, but by the EU, recognizing that the investment is returned many times over in the value it provides to its population and business community.[28]

  NASA and NOAA participate in Copernicus as partners together with ESA, EUMETSAT, and the EU in Sentinel-6, a series of satellites to continue the climate record of sea-level rise. NASA, NOAA, and USGS should continue to interact with ESA, the EU, and other international space agencies to identify shared interests in the continuity of observations as the basis for further collaborative implementation, building on a framework such as that established by Copernicus. It is not just an operational meteorological and land imaging program, but an operational Earth observation program. The United States has no comprehensive equivalent beyond individual elements such as Landsat.

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[26] See further discussion in Chapter 4.

[27] European Parliament, "Securing the Copernicus Programme—Why EU Earth Observation Matters," Briefing, April 2017, http://www.copernicus.eu/sites/default/files/library/EPRS_BRI_Copernicus_matters.pdf. Copernicus includes a space component, and six series of Sentinel missions are expected to be fully operational by 2023, collecting continuous, consistent observations of the Earth for at least a decade.

[28] See European Space Agency, "Copernicus: Overview," http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Overview4.

- *Fragmentation.* This report addresses three separate U.S. agencies that manage civil Earth observations from space. Other U.S. agencies utilize Earth observation for civilian, military, and intelligence purposes. Even within agencies, Earth observation can be fragmented. In NOAA, for example, observation is mostly separated from the research and operational users of the data, and weather is organized separately from oceans. Improving research-to-operations and research-to-end-use have historically faced significant challenges resulting from institutional stove-piping (NRC, 2000). Fragmentation of roles and responsibilities with U.S. civil Earth observation is a growing issue that will impede progress if not addressed.
- *National commitment.* A U.S. commitment to Earth observation in support of economic and security progress would provide the stability and prioritization required for efficient long-term planning. ESAS 2007 recommended that Earth information be elevated to a national strategy, a recommendation that has been only partly implemented and deserves further attention (NRC, 2007). Today, such commitment remains inconsistent across agencies, incomplete within agencies, and lacking long-term perspective.
- *Managing within resources.* While NASA has done an excellent job in developing a program to address the highest priority science needs and objectives, the U.S. civilian space program has insufficient resources to appropriately serve the needs of the nation (for the example of NASA, see Figure 1.4). The resource limitations force a trade between sustained observations needed to characterize and understand changes in the Earth system, and new capabilities aimed at understanding key Earth system processes that directly impact national and societal interests. While restoring appropriate resources is the first choice, the realism of budget constraints implies a need for strategies targeted to greatest success, including new ways of doing business, in the face of inadequate resources.
- *Promoting innovation.* Government agencies have many requirements and constraints that limit their ability to innovate. While some constraints may be appropriate, in today's environment innovation has become central to progress. Strategies that break down barriers to innovation are needed, and leveraging of external innovation must be embraced.

Programmatic Impediments and Vulnerabilities

Strategic challenges are often related to tactical, more immediate issues having direct impact on effective program implementation. Of particular importance are institutional and cultural impediments or vulnerabilities that either currently exist or may arise during the next decade. Some of these are internal to the programmatic structure, with strong potential for improvement given recognition of the issue and attention to solutions. Others are external and require planning that anticipates events or decisions outside of programmatic control. Important examples include the following:

- Funding that is insufficient to address program priorities;
- Lack of mechanisms to effectively restructure the overall program, in a manner that faithfully reflects community priorities, when changes are required;
- Changes to the Program of Record due to changes in funding or direction by Congress, or due to changes in partner plans (in particular, the United States is heavily reliant on the ongoing European investment in the Copernicus program, which has become an increasingly important complement to the U.S. program);
- Policy-mandated limitations on collaboration and/or data exchange with potential international partners or data providers;
- Lack of committed resources to collect the specific sustained observations needed to monitor and understand Earth as a system (summarized in general Finding 2.4);

- Institutional and cultural impediments to interagency cooperation;
- Policy, regulatory, and budgetary barriers to integration of commercial technologies and data sources;
- Overreliance on unproven and unlikely technology advances that introduce risk and cost growth;
- Cost growth due to project or mission scope creep or poor cost control; and
- Unanticipated launch or on-orbit failures that lead to reflight decisions and potentially additional budget obligations.

These issues are relevant to development of strategies for the decade, as discussed in this chapter. Equally important, however, is addressing or overcoming specific impediments to more effective programmatic implementation. The new programmatic approaches proposed in Chapter 3 and Chapter 4 are specifically designed to accomplish that, consistent with the Decadal Community Challenge presented in Chapter 1.

Strategic Innovation

This section describes a strategic framework, employing eight elements (Table 2.4), which can help the community meet our ambitious Decadal Community Challenge. It is intended to achieve three objectives: (1) overcome strategic shortfalls from the past; (2) help avoid new strategic shortfalls (cross-agency and cross-program) that threaten to emerge during the decade; and (3) ensure readiness to take advantage of unplanned opportunities for advance and improvement that arise during the decade.

Strategy Element 1—Commit to *Sustained Science and Applications*

Science generally progresses initially by a first step of exploration that leads to discovery. Often, this is a *time-limited* process: define and pursue an exploration (such as a space-based mission), publish the resulting science, seek any societal benefits that emerge from the science, and move on to new scientific exploration areas. With this time-limited approach, societal benefits are often ad hoc spin-offs of this process, not explicitly planned but achieved through after-the-fact efforts once the societal value is recognized.

Today, we have come to recognize the important additional discoveries that are obtained when Earth science proceeds beyond initial exploration and commits to *sustained* science and applications, enabled by

TABLE 2.4 Elements of a Decadal Strategic Framework

ELEMENTS OF DECADAL STRATEGY
1. Commit to *Sustained Science and Applications.*
2. Embrace *Innovative Methodologies* for Integrated Science and Applications.
3. Amplify the *Cross-Benefit of Science and Applications.*
4. Leverage *External Resources and Partnerships.*
5. Institutionalize *Programmatic Agility and Balance.*
6. Exploit *External Trends* in Technology and User Needs.
7. Expand Use of *Competition.*
8. Pursue *Ambitious Science and Applications*, Despite Constraints.

continuous observing over periods requiring multiple generations of observing spacecraft.[29] For example, continuous space-based observations enable the understanding of change in the Earth system occurring over longer timescales than a single spacecraft lifetime. With sustained science and applications, the outcome of an initial exploration (such as a space-based mission) is reviewed for the potential that follow-on missions could produce valuable additional science and applications. In some cases, the additional science involves new discoveries. In others, new science and/or applications emerge as a consequence of extending the length of the observation over multiple years and decades.

By further ensuring that sustained science involves planned implementation of applications, the latency between performing science and achieving societal benefits is reduced. Among NASA's science portfolio, Earth science is unique in the benefits that can be obtained from commitment to sustained science and applications. Sustained observations are central to the progress of Earth science, and integral to the long-term achievement of societal benefits. As noted earlier, the European Union has embraced sustained science and applications, through its Copernicus program and the underlying Sentinel space-based observations (also described in more detail in Box 3.2, in Chapter 3).

To achieve the needed commitment to sustained science and applications, and to achieve the greatest value from the nation's investments, *roles and responsibilities* need to be better defined and implemented for each agency, and *resources* need to be included in the budgeting process to allow the fulfillment of continuous observations.

The importance of sustaining a growing list of measurements for science and applications (see, for example, Box 4.5, in Chapter 4) and the lack of accompanying growth in the budget suggests that international collaboration must play a key role in any strategy for sustained observations. ESA, EUMETSAT, the European Commission, NASA, and NOAA have recently agreed to ensure the measurement record of global and regional sea-level change through at least two future missions via the Sentinel-6 missions within the Copernicus Program. A systematic approach to identifying measurements requiring long-term continuity (e.g., following NRC, 2015) and which of those are of interest to potential international partners should be undertaken to determine whether similar agreements and/or frameworks are viable as the basis for collaboration on implementation sustained measurement programs.

Recommendation 2.2: NASA—with NOAA and USGS participation—should engage in a formal planning effort with international partners (including, but not limited to ESA, EUMETSAT, and the European Union via its Copernicus Program) to agree on a set of measurements requiring long-term continuity and to develop collaborative plans for implementing the missions needed to satisfy those needs. This effort to institutionalize the sustained measurement record of required parameters should involve the scientific community, and build on and complement the existing domestic and international Program of Record.

Strategy Element 2—Embrace *Innovative Methodologies* for Integrated Science and Applications

One means to accelerate progress is to seek fundamental methodological advances that are shared across disciplines and pursuits. These hold the potential to advance the field or organization as a whole. Examples include, but are not limited to:

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[29] The multidecadal Landsat (now Sustainable Land Imaging, or SLI) program is one example. Its 30+ year continuous data set has proven critical for understanding the evolution of Earth's surface, and for managing resources on that basis. Many examples of the need for sustained science and applications emerged from the Earth Observing System (EOS) program starting in the 1990s, including policy-critical areas such as sea-level rise, water availability, and transport of pollutants.

- *Advanced cost-effective observation methodologies*. Low-cost observations and methodologies can be used to enhance and/or augment investments in space-based data. Examples include (1) citizen science and community-based observations, (2) ad hoc and distributed observations, as from existing ground networks, automobile sensors, and mobile phones, and (3) observational sampling using compressive sensing (see Box 2.10).
- *Advanced analysis methodologies*. Investments in innovative analysis capabilities accelerate the ability to convert observations into scientific knowledge. Candidates include (1) data science, including big data analytics and other techniques emerging in the commercial world, (2) a more integrated data analysis system that includes advances in modeling; and assimilation of in situ data and data from multiple satellite sensors.
- *Accelerated applications*. Accelerating the conversion of science to societal benefits amplifies the societal impact. Candidates include (1) applications included from the early stages of observation planning and development, (2) rapid applications prototyping, (3) rapid transition from science to applications, and (4) promoting the science of applications, to advance applications methodologies (Dozier and Gail, 2009).

Strategy Element 3—Amplify the *Cross-Benefit of Science and Applications*

Curiosity-inspired science will always be central to Earth observation and analysis. But a growing portion of our science is use-inspired or closely related to the applications it enables. The traditional paradigm for integrating science and applications can be described as pursuing high-quality and innovative science, and then assuming it will somehow find a path to applications. Sometimes referred to as the *valley of death* between science and end-use (for example, NRC, 2000), or between research and applications, the issue is widely recognized even as this paradigm has been slow to evolve.

Inspiration goes both ways: science inspires applications scientists and engineers, and end-use needs can inspire research scientists and engineers. Embedding science in the applications process often reveals new and inspirational scientific questions driven by those end-uses not well-recognized by research scientists. While we often select our pursuits by using this science-applications thinking in an implicit way, doing so more explicitly can lead to improved outcomes, particularly when resources are constrained.

Among NASA's diverse and inspirational scientific elements, Earth Science is special in the extent and breadth of its practical benefits to society. To its credit, NASA has increasingly integrated applications into flight programs and research, with results that have been embraced by both the science and applications communities. The SMAP mission has been used as a prototype for a more integrated science/applications team, with positive results. Extending and expanding on this trend will strengthen both science and applications. To accomplish this, programs with both science and applications elements need to explicitly identify the connection, and define opportunities to amplify the cross-benefit, and organization structures and processes need to be adapted when possible to integrate, rather than segregate, science and operations/applications.[30]

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[30] Through its Earth Venture-Instruments solicitation, NASA recently announced its first competitively selected mission with societal benefit as its primary objective. The Multi-Angle Imager for Aerosols (MAIA), will investigate the connections between aerosols and human health. From the very beginning, MAIA has involved collaborations with the Environmental Protection Agency (EPA), National Institutes of Health (NIH), Centers for Disease Control and Prevention (CDC), NOAA, and World Health Organization (WHO). See Lin and Diner (2017).

BOX 2.10 LESS-COSTLY OBSERVING SYSTEMS THROUGH OPTIMIZED SAMPLING

One example of a promising observational methodology that could reduce system cost or improve performance is "compressive sensing." This is a technique for utilizing data processing to reconstruct relatively complete observational data sets from sparse measurements of those data sets. If this, or other techniques, can be used to reduce the number of space-based observations needed to adequately sample some aspect of the Earth system, it might be possible to build satellite systems with fewer satellites or less complex instruments.

The technique has been applied to medical data, such as Magnetic Resonance Imaging (MRI) (Lustig et al., 2008), using wavelet transforms to compress the very large MRI data volumes by large amounts and translating that reduction into reduced scan times that benefit patients. MRI imagery is naturally compressible because it is not acquired in the domain of the spatially oriented image itself but rather in a domain that is readily transformed using wavelets. Artifacts associated with data recovery need to be assessed on the basis of the sensitivity of each end-use case.

Remote sensing imagery shares some of the characteristics that make compressive sensing a candidate technique for MRI. This potential has been explored by the Department of Defense (Jason, 2012) for a variety of remote sensing data sets with different characteristics (see example in Figure 2.10.1). Recently, it has been explored as a means for reducing data volume in Earth observation data sets (Ebtehaj et al., 2015), such as global observations of temperature and humidity fields from AIRS and AMSU, since they admit nearly sparse representations in the wavelet domain. If fields such as this can be reproduced with fewer space-based observations, simplified observing systems may be possible. Things are often more complicated in the real world of Earth remote sensing. For example, different observations will be more or less amenable to sampling methods. Without further work, this technology should be considered a promising example of how new observing approaches are still possible, even if it cannot yet be considered a proven solution.

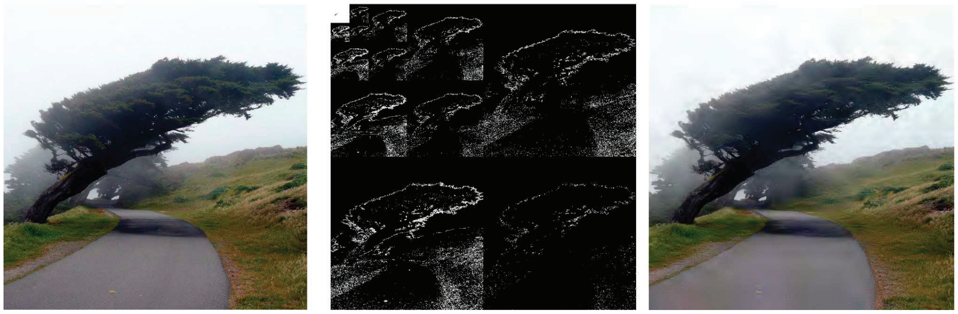

FIGURE 2.10.1 An uncompressed image (*left*), its wavelet coefficients (*center*), and a JPEG-2000 recovered image (*right*) made using compressive sensing with only 10 percent of the wavelet coefficients (from Jason, 2012). Although this laboratory example is not fully applicable, the ability to nearly reproduce original data with far fewer samples holds the potential for lower cost observing systems.

SOURCE: M. Davenport, M. Duarte, Y. Eldar, and G. Kutyniok, 2012, "Introduction to Compressed Sensing," pp. 1-64 in *Compressed Sensing* (Y. Eldar and G. Kutyniok, eds.), Cambridge University Press, Cambridge and New York, available at http://webee.technion.ac.il/Sites/People/YoninaEldar/files/ddek.pdf.

Strategy Element 4—Leverage *External Resources and Partnerships*

In a constrained resource environment, much can be done by leveraging resources. NASA, NOAA, and USGS have long-established partnerships with non-U.S. space agencies and other organizations, which have already proven highly valuable in bringing additional resources to address their missions (further discussion is included in Chapter 4). In many cases, they also enable access to regional and global observations that would simply be unavailable to U.S. agencies any other way.

Today, there is a strong need to build on and extend those partnerships, and to bring in innovative new partnerships such as commercial data sources. In particular, there is a need to (1) extend and strengthen the already strong international partnerships and (2) leverage the availability of commercial providers for resources traditionally supplied by governments. Specific suggestions for accomplishing that are addressed in this report.

Strategy Element 5—Institutionalize *Programmatic Agility and Balance*

The demands we will face in the coming decade, and the problems to be solved in order to address them, will arrive at an ever-increasing pace as populations grow, human impacts on the environment continue to increase, and society's digital information use broadens. NASA, NOAA, and USGS will need to make both large and small programmatic adjustments over short time periods. *Agility* in programmatic structures, and in the authorities of staff who implement programs, is essential to respond to new discoveries and emerging needs, particularly in the context of resource constraints. At the same time, achieving and maintaining *programmatic balance* is critical to successful programs.

Agility and balance do not emerge naturally in organizations. They must be explicitly built into the cultures and processes or they risk being overcome by bureaucracy. For example, the software industry moved from the traditional preplanned "waterfall" model to agile software management techniques to more rapidly and effectively advance their products (Kettunen and Laanti, 2008).

With NASA, NOAA, and USGS, the development cycle for space-based observations can be as long as a decade and more, impeding the ability to be responsive to changing needs and emerging science. NOAA and USGS, in their portion of the committee's statement of task, have specifically sought suggestions for being more agile in terms of integrating new science and technology. This agility is achieved in part through a balanced portfolio that incorporates both long-lead missions and activities as well as shorter-term efforts that can be more responsive to and take advantage of emerging capabilities and opportunities.

Strategy Element 6—Exploit *External Trends* in Technology and User Needs

Successful organizations formally review and track key enabling trends and proactively incorporate them in their activities.[31] Within NASA, NOAA, and USGS, success at anticipating and leveraging trends has been episodic;[32] the agencies have been slow at times to leverage external capabilities that could have enhanced their capabilities.

For NASA, NOAA, and USGS, a successful process for exploiting external trends might include, at minimum, a survey of (1) advances in scientific methodologies from outside these agencies; (2) commer-

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[31] The importance of anticipating trends in the rapidly moving Internet field is well known. A source widely cited is industry analyst Mary Meeker, currently at the venture capital firm Kleiner Perkins, who has publicly released an annual report on Internet trends for many years. See Meeker (2017).

[32] There are notable exceptions. NASA has invested for many years in technology advances through the Earth Science Technology Office (ESTO) program, seeking to leverage technology progress within the community, and has embraced use of small satellites and funded advances in small launch vehicles.

cial methods for characterizing the diverse applications and information end-uses of data; (3) observation technology advances in the commercial sector; (4) computing and data methodologies and tools that enable new data analysis approaches; (5) community science, such as crowdsourcing and distributed observations, which has the potential to augment space-based observations; (6) nontraditional partnerships such as philanthropists and nonprofits; (7) innovation in public-private partnerships and acquisition alternatives such as data buys, standardized spacecraft, and system block buys; and (8) human resources and education methods (such as the "boot camps" used widely today to rapidly educate software engineers) targeted at making the workforce more effective.

For example, item (2) reflects the fact that there are so many end-uses of NASA/NOAA/USGS data that the agencies no longer can simply track straightforward metrics like grants or website data requests to know how their data are used. This is the same problem faced throughout the commercial internet world, including by internet leaders such as Google, for understanding their user base. Since there is a clear financial stake in this information, companies are investing in developing solutions that involve more sophisticated metrics and tools, including big data techniques. Federal agencies with similar needs can benefit from these investments.

Strategy Element 7—Expand Use of *Competition*

Competition has already proven effective in many areas of science and procurement for NASA, NOAA, and USGS as a means of inspiring innovation and creativity and delivering cost-effective approaches to Earth observation. The committee believes these results can be extended even further for Earth science, and we have embraced the use of competition within the structure of our recommendations (see Chapter 3). Competition and collaboration (as noted in Strategy Element 4) are not necessarily in conflict, and both should be used as appropriate.

Strategy Element 8—Pursue *Ambitious Science and Applications*, Despite Constraints

Constraints do not imply a need to be timid. The committee believes that pursuing ambitious science not only leads to the greatest scientific advances, but it also ensures the greatest likelihood that substantial and often unanticipated societal benefits will emerge. NASA, NOAA, and USGS need to build on their history of pursuing ambitious programs to serve the nation, even when faced with resource challenges. While this requires appropriate scoping to respect constraints, it does not require losing the ability to think big. Maintaining ambition can be accomplished by (1) setting clear and far-reaching goals within all planning processes; (2) explicitly identifying mechanisms that might allow these goals to be pursued despite resource constraints, such as creative implementation approaches; and (3) pursuing ambitious observation system capabilities, such as active sensing systems, while ensuring acceptable risk through targeted technology development as needed.

REFERENCES

Ajmar, A., P. Boccardo, F. Disabato, and F. Giulio Tonolo, 2015, Rapid Mapping: Geomatics role and research opportunities, *Rendiconti Lincei* 26(S1):63-73.

Anav, A., P. Friedlingstein, C. Beer, P. Ciais, A. Harper, C. Jones, G. Murray-Tortarolo, et al. 2015. Spatiotemporal patterns of terrestrial gross primary production: A review. *Reviews of Geophysics* 53: 785-818.

Ashouri, H., K.-L. Hsu, S. Sorooshian, D.K. Braithwaite, K.R. Knapp, L.D. Cecil, B.R. Nelson, and O.P. Prat. 2015. PERSIANN-CDR daily precipitation climate data record from multisatellite observations for hydrological and climate studies. *Bulletin of the American Meteorological Society* 96(1):69.

Auligné, T., R. Gelaro, R. Mahajan, D. Groff, R. Langland, J. Liu, J. Cotton, L. Morgan, and Y. Ota. 2016. "Forecast Sensitivity—Observation Impact (FSOI) Inter-Comparison Experiment." http://www.wmo.int/pages/prog/www/WIGOS-WIS/reports/6NWP_Shanghai2016/WMO6-Impact-workshop_Shanghai-May2016.html.

Bauer, P., A. Thorpe, and G. Brunet. 2015. The quiet revolution of numerical weather prediction. *Nature* 525(7567):47-55.

Behrenfeld, M.J., Y. Hu, R.T. O'Malley, E.S. Boss, C. A. Hostetler, D.A. Siegel, J.L. Sarmiento, J. Schulien, J.W. Hair, X. Lu, S. Rodier, A.J. Scarino. 2017. Annual boom-bust cycles of polar phytoplankton biomass revealed by space-based lidar. *Nature Geoscience* 10:118-122.

Belward, A.S., and J.O. Skøien. 2015. Who launched what, when and why: Trends in global land-cover observation capacity from civilian Earth observation satellites. *ISPRS Journal of Photogrammetry and Remote Sensing* 103:115-128.

Berger, M., J. Moreno, J.A. Johannessen, P.F. Levelt, and R.F. Hanssen. 2012. ESA's sentinel missions in support of Earth system science. *Remote Sensing of Environment* 120:84-90.

Blondeau-Patissier, D., T. Schroeder, V.E. Brando, S.W. Maier, A.G. Dekker, and S. Phinn. 2014. ESA-MERIS 10-year mission reveals contrasting phytoplankton bloom dynamics in two tropical regions of Northern Australia. *Remote Sensing* 6:2963-2988.

Bourassa, M.A., S. Gille, D.L. Jackson, B.J. Roberts, and G.A. Wick. 2010. Ocean winds and turbulent air-sea fluxes inferred from remote sensing. *Oceanography* 23(4):36-51.

Bourassa, M.A., S.T. Gille, C. Bitz, D. Carlson, C. A. Clayson, I. Cerovecki, M.F. Cronin, et al. 2013. High-latitude ocean and sea ice surface fluxes: Challenges for climate research. *Bulletin of the American Meteorological Society* 94:403-423.

Brown, P.J., and C.D. Kummerow. 2014. An assessment of atmospheric water budget components over tropical oceans. *Journal of Climate*, 27(5):2054-2071.

Buizza, R., and M. Leutbecher. 2015. The forecast skill horizon. *Quarterly Journal of the Royal Meteorological Society* 141(693):3366-3382.

Cai, H., X. Yang, K. Wang, and L. Xiao. 2014. Is forest restoration in the Southwest China Karst promoted mainly by climate change or human-induced factors? *Remote Sensing* 6(10):9895-9910.

CEOS (Committee on Earth Observation Satellites). 2015. *Satellite Earth Observations in Support of Disaster Risk Reduction. The CEOS Earth Observation Handbook.* Special 2015 Edition for the 3rd UN World Conference on Disaster Risk Reduction. http://ceos.org/home-2/eohandbook2015/.

CEOS. 2015. "The CEOS Database." Accessed December 20, 2015. http://database.eohandbook.com/timeline/timeline.aspx.

Chen, X., X. Zhang, J.A. Church, C.S. Watson, M.A. King, D. Monselesan, B. Legresy, and C. Harig. 2017. The increasing rate of global mean sea-level rise during 1993-2014. *Nature Climate Change* 7:492-495.

Chudnovsky, A., C. Tang, A. Lyapustin, Y. Wang, J. Schwartz, and P. Koutrakis. 2013. A critical assessment of high-resolution aerosol optical depth retrievals for fine particulate matter predictions. *Atmospheric Chemistry and Physics* 13:10907-10917.

City and County of San Francisco. 2016. *San Francisco Sea Level Rise Action Plan.* March. http://sf-planning.org/sea-level-rise-action-plan.

City of New York. 2015. "Mayor de Blasio Releases NPCC 2015 Report, Providing Climate Projections Through 2100 for the First Time." Office of the Mayor: News. February 17. http://www1.nyc.gov/office-of-the-mayor/news/122-15/mayor-de-blasio-releases-npcc-2015-report-providing-climate-projections-2100-the-first.

City of San Diego. 2005. *City of San Diego Climate Protection Action Plan.* Environmental Services Department. July. https://www.sandiego.gov/sites/default/files/legacy/environmental-services/sustainable/pdf/action_plan_07_05.pdf.

Clark, J., A. Parsons, T. Zajkowski, and K. Lannom. 2003. Remote sensing imagery support for Burned Area Emergency Response teams on 2003 southern California wildfires. USFS Remote Sensing Applications Center BAER Support Summary.

Clayson, C.A., J.B. Roberts, and A. Bogdanoff. 2017. Seaflux Version 1: A new satellite-based ocean-atmosphere turbulent flux dataset. *International Journal of Climatology*, submitted.

Crisp, D., H. Pollock, R. Rosenberg, L. Chapsky, R. Lee, F. Oyafuso, C. Frankenberg, et al. 2017. The on-orbit performance of the Orbiting Carbon Observatory-2 (OCO-2) instrument and its radiometrically calibrated products. *Atmospheric Measurement Techniques* 10(1):59-81.

Curry, J.A., A. Bentamy, M.A. Bouras, D. Bourras, E.F. Bradly, M. Brunke, S. Castro, et al., 2004. Seaflux. *Bulletin of the American Meteorological Society* 85(3):409-424.

Ebtehaj, A.M., E. Foufoula-Georgiou, G. Lerman, and R.L. Bras. 2015. Compressive Earth observatory: An insight from AIRS/AMSU retrievals. *Geophysical Research Letters* 42:362-369.

Eldering, A., C.W. O'Dell, P.O. Wennberg, D. Crisp, M.R. Gunson, C. Viatte, C. Avis, et al. 2017. The Orbiting Carbon Observatory-2: First 18 months of science data products. *Atmospheric Measurement Techniques* 10(2):549-563.

ESA (European Space Agency). 2015. "Earth Observation Portal." Accessed December 1, 2015. https://directory.eoportal.org/web/eoportal/satellite-missions.

Executive Office of the President. 2010. *National Space Policy of the United States of America*. Washington, DC. June 28. https://obamawhitehouse.archives.gov/sites/default/files/national_space_policy_6-28-10.pdf.

Fasullo, J.T., C. Boening, F.W. Landerer, and R.S. Nerem. 2013. Australia's unique influence on global sea level in 2010-2011. *Geophysical Research Letters* 40(16):4368-4373.

Flechas, J. 2017. "Miami Beach to Begin New $100 Million Flood Prevention Project in Face of Sea Level Rise." *Miami Herald*. January 28.

Frankenberg, C., C. O'Dell, J. Berry, L. Guanter, J. Joiner, P. Köhler, R. Pollock, and T.E. Taylor. 2014. Prospects for chlorophyll fluorescence remote sensing from the Orbiting Carbon Observatory-2. *Remote Sensing of Environment* 147:1-12.

GAO (Government Accountability Office). 2007. *Geostationary Operational Environmental Satellites: Further Actions Needed to Effectively Manage Risks.* GAO-08-183T. October 23. http://www.gao.gov/products/GAO-08-183T.

GAO. 2010. *Polar-Orbiting Environmental Satellites: Agencies Must Act Quickly to Address Risks That Jeopardize the Continuity of Weather and Climate Data.* GAO-10-558. http://www.gao.gov/products/GAO-10-558.

Georgieva, E., K. Priestley, B. Dunn, R. Cageao, A. Barki J. Osmundsen, C. Turczynski, and N. Abedin. 2015. "Radiation Budget Instrument (RBI) for JPSS-2," poster at the Conference on Characterization and Radiometric Calibration for Remote Sensing, https://digitalcommons.usu.edu/calcon/CALCON2015/All2015Content/2/.

Gillespie, T.W., J. Chu, E. Frankenberg, and D. Thomas. 2007. Assessment and prediction of natural hazards from satellite imagery. *Progress in Physical Geography* 31(5):459-470.

Golaz, J.C., L.W. Horowitz, and H. Levy. 2013. Cloud tuning in a coupled climate model: Impact on 20th century warming. *Geophysical Research Letters* 40(10):2246.

Gray, J.M., S. Frolking, E.A. Kort, D.K. Ray, C.J. Kucharik, N. Ramankutty, and M.A. Friedl. 2014. Direct human influence on atmospheric CO_2 seasonality from increased cropland productivity. *Nature* 515(7527):398.

Griggs, G., J. Árvai, D. Cayan, R. DeConto, J. Fox, H.A. Fricker, R.E. Kopp, C. Tebaldi, and E.A. Whiteman. 2017. *Rising Seas in California: An Update on Sea-Level Rise Science*. California Ocean Protection Council Science Advisory Team Working Group, California Ocean Science Trust. April 2017. http://www.opc.ca.gov/webmaster/ftp/pdf/docs/rising-seas-in-california-an-update-on-sea-level-rise-science.pdf.

Han, B., H. Ding, Y. Ma, and W. Gong. 2017 Improving retrieval accuracy for aerosol optical depth by fusion of MODIS and CALIOP data. *Tehnički Vjesnik* 24(3):791-800.

Harig, C., and F.J. Simons. 2015. Accelerated West Antarctic ice mass loss continues to outpace East Antarctic gains. *Earth and Planetary Science Letters* 415:134-141.

Hester, Z. 2016. China and NASA: The challenges to collaboration with a rising space power. *Journal of Science Policy and Governance* 9(1).

Hilton, F., R. Armante, T. August, C. Barnet, A. Bouchard, C. Camy-Peyret, V. Capelle, et al. 2012. Hyperspectral Earth observation from IASI: Five years of accomplishments. *Bulletin of the American Meteorological Society* 93:347-370.

Hong, Y., K. Hsu, S. Sorooshian, and X. Gao. 2004. Precipitation estimation from remotely sensed imagery using an artificial neural network cloud classification system. *Journal of Applied Meteorology* 43:1834-1852.

Hsu, K., X. Gao, S. Sorooshian, and H.V. Gupta. 1997. Precipitation estimation from remotely sensed information using artificial neural networks. *Journal of Applied Meteorology* 36(9):1176-1190.

Huffman, G.J., R.F. Adler, D.T. Bolvin, G. Gu, E.J. Nelkin, K.P. Bowman, Y. Hong, E.F. Stocker, and D.B. Wolff. 2007. The TRMM Multi-satellite Precipitation Analysis: Quasi-global, multi-year, combined-sensor precipitation estimates at fine scale. *Journal of Hydrometeorology* 8(1):38-55.

Huffman, G.J., D.T. Bolvin, D. Braithwaite, K. Hsu, R. Joyce, and P. Xie. 2014. "GPM Integrated Multi-Satellite Retrievals for GPM (IMERG) Algorithm Theoretical Basis Document (ATBD)." Version 4.4. PPS. NASA Goddard Space Flight Center, Greenbelt, MD.

IPCC (Intergovernmental Panel on Climate Change). 2013. *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, eds.). Cambridge and New York: Cambridge University Press.

Jacobson, M., R.J. Charlson, H. Rodhe, and G.H. Orians. 2000. *Earth System Science: From Biogeochemical Cycles to Global Changes*. London, UK: Academic Press.

Jason. 2012. *Compressive Sensing for DoD Sensor Systems.* JSR-12-04. McLean, VA: The MITRE Corporation.

Joyce, R.J., J.E. Janowiak, P.A. Arkin, P. Xie. 2004. CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at 8 km, hourly resolution. *Journal of Climate* 5:487-503.

Kavanaugh, M.T., B. Hales, M. Saraceno, Y.H. Spitz, A.E. White, and R.M. Letelier. 2014. Hierarchical and dynamic seascapes: A quantitative framework for scaling pelagic biogeochemistry and ecology. *Progress in Oceanography* 120:291-304.

Kettunen, P., and M. Laanti. 2008. Combining agile software projects and large-scale organizational agility. *Software Process: Improvement and Practice* 13:183-193.

Kloog, I., A. Chudnovsky, P. Koutrakis, and J. Schwartz. 2012. Temporal and spatial assessments of minimum air temperature using satellite surface temperature measurements in Massachusetts, USA. *Science of the Total Environment* 432:85-92.

Kloog, I., A.A. Chudnovsky, A.C. Just, F. Nordio, P. Koutrakis, B.A. Coull, A. Lyapustin, Y. Wang, and J. Schwartz. 2014. A new hybrid spatio-temporal model for estimating daily multi-year PM 2.5 concentrations across northeastern USA using high resolution aerosol optical depth data. *Atmospheric Environment* 95:581-590.

Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss, and C. Tebaldi. 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future* 2:383-406.

Kostadinov, T.S., S. Milutinović, I. Marinov, and A. Cabré. 2016. Carbon-based phytoplankton size classes retrieved via ocean color estimates of the particle size distribution. *Ocean Science* 12:561-575.

Kruel, S. 2016. The impacts of sea-level rise on tidal flooding in Boston, MA. *Journal of Coastal Research* 32(6):1302-1309.

L'Ecuyer, T.S., W. Berg, J. Haynes, M. Lebsock, and T. Takemura. 2009. Global observations of aerosol impacts on precipitation occurrence in warm maritime clouds. *Journal of Geophysical Research: Atmospheres* 114(D9).

L'Ecuyer, T.S., H.K. Beaudoing, M. Rodell, W. Olson, B. Lin, S. Kato, and G. Huffman. 2015. The observed state of the energy budget in the early twenty-first century. *Journal of Climate* 28(21):8319-8346.

Lee Z., J. Marra, M.J. Perry, and M. Kahru. 2015. Estimating oceanic primary productivity from ocean color remote sensing: A strategic assessment. *Journal of Marine Systems* 149:50-59.

Liu, J., J.A. Curry, C.A. Clayson, and M.A. Bourassa. 2011. High-resolution satellite surface latent heat fluxes in North Atlantic hurricanes. *Monthly Weather Review* 139(9):2735-2747.

Liu, Y., and D.J. Diner. 2017. Multi-angle imager for aerosols: A satellite investigation to benefit public health. *Public Health Reports* 132(1):14-17.

Liu, Y., M. Franklin, R. Kahn, and P. Koutrakis. 2007. Using aerosol optical thickness to predict ground-level PM 2.5 concentrations in the St. Louis area: A comparison between MISR and MODIS. *Remote Sensing of Environment* 107(1):33-44.

Liu, Y., P. Koutrakis, and R. Kahn. 2007. Estimating fine particulate matter component concentrations and size distributions using satellite-retrieved fractional aerosol optical depth: Part 1—Method development. *Journal of the Air and Waste Management Association* 57(11):1351-1359.

Lu, Z., D.G. Streets, B. de Foy, L.N Lamsal, B.N. Duncan, and J. Xing. 2015. Emissions of nitrogen oxides from US urban areas: Estimation from Ozone Monitoring Instrument retrievals for 2005-2014. *Atmospheric Chemistry and Physics* 15:10367-10383.

Lustig, M., D.L. Dononho, J.M Santos, and J.M Pauly. 2008. Compressed sensing MRI. *IEEE Signal Processing Magazine* 72.

McCarthy, M.J., K.E. Colna, M.M. El-Mezayen, A.E. Laureano-Rosario, P. Méndez-Lázaro, D.B. Otis, et al. 2017. Satellite remote sensing for coastal management: A review of successful applications. *Environmental Management* 60(2):323-339.

McClain, C.R. 2009. A decade of satellite ocean color observations. *Annual Review of Marine Science* 1:19-42.

Mechoso, C., R. Wood, R. Weller, C.S. Bretherton, A. Clarke, H. Coe, C. Fairall, J.T. Farrar, G. Feingold, and R. Garreaud. 2014. Ocean-cloud-atmosphere-land interactions in the southeastern Pacific: The VOCALS program. *Bulletin of the American Meteorological Society* 95:357-375.

Meeker, M. 2017. *Internet Trends 2017—Code Conference*. Kleiner Perkins. May 31. http://www.kpcb.com/internet-trends.

Menzel, W.P., D.C. Tobin, and H.E. Revercomb. 2016. Infrared Remote Sensing with Meteorological Satellites. Pp. 193-264 in *Advances in Atomic, Molecular, and Optical Physics*, Volume 65 (E. Arimondo, C.C. Lin, and S.F. Yelin, eds.). London, UK: Academic Press.

Miller, H.M., L. Richardson, S.R. Koontz, J. Loomis, and L. Koontz. 2013. *Users, Uses, and Value of Landsat Satellite Imagery—Results from the 2012 Survey of Users*. U.S. Geological Survey Open-File Report 2013-1269. http://dx.doi.org/10.3133/ofr20131269.

Mouw, C.B., N.J. Hardman-Mountford, S. Alvain, A. Bracher, R.J.W. Brewin, A. Bricaud, A.M. Ciotti, et al. 2017. A consumer's guide to satellite remote sensing of multiple phytoplankton groups in the global ocean. *Frontiers in Marine Science* 4:41.

NASA. 2010. *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space*. June. http://pace.gsfc.nasa.gov/docs/climate_architecture_final.pdf.

NGAC (National Geospatial Advisory Committee). 2012. "Landsat Advisory Group Statement on Landsat Data Use and Charges." September 18. https://www.fgdc.gov/ngac/meetings/september-2012/ngac-landsat-cost-recovery-paper-FINAL.pdf.

Nguyen, P., S. Sellars, A. Thorstensen, Y. Tao, H. Ashouri, D. Braithwaite, K. Hsu, and S. Sorooshian. 2014. Satellite track precipitation of Super Typhoon Haiyan. *Eos, Transactions American Geophysical Union* 95(16):133, 135.

Nguyen, H., N. Cressie, and A. Braverman. 2017 Multivariate spatial data fusion for very large remote sensing datasets. *Remote Sensing* 9.2:142.

NOAA (National Oceanic and Atmospheric Administration). *NOAA NESDIS Independent Review Team Final Report 2017*. National Environmental Satellite, Data, and Information Service. https://www.nesdis.noaa.gov/sites/default/files/asset/document/nesdis_irt_report_2017_with_notes.pdf.

NRC (National Research Council). 2000. *From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death.* Washington, DC: National Academy Press.

NRC. 2005. *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation.* Washington, DC: The National Academies Press.

NRC. 2007. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond.* Washington, DC: The National Academies Press.

NRC. 2008. *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring.* Washington, DC: The National Academies Press.

NRC. 2009. *America's Future in Space: Aligning the Civil Space Program with National Needs.* Washington, DC: The National Academies Press.

NRC. 2011. *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions*. Washington, DC: The National Academies Press.

NRC. 2012. *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey.* Washington, DC: The National Academies Press.

NRC. 2013. *Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program*. Washington, DC: The National Academies Press.

NRC. 2015. *Continuity of NASA Earth Observations from Space: A Value Framework*. Washington, DC: The National Academies Press.

OECD (Organisation for Economic Co-operation and Development). 2012. *OECD Environmental Outlook to 2050: The Consequences of Inaction.* Paris, France: OECD Publishing. http://dx.doi.org/10.1787/9789264122246-en.

OIG (Office of Inspector General). NASA. 2016. *NASA's Earth Science Portfolio.* Report No. IG-17-003. Washington, DC. https://oig.nasa.gov/audits/reports/FY17/IG-17-003.pdf.

Okamoto, K., T. Iguchi, N. Takahashi, K. Iwanami, and T. Ushio. 2005. "The Global Satellite Mapping of Precipitation (GSMaP) Project." Pp. 3414-3416 in *2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS).* doi: 10.1109/IGARSS.2005.1526082.

Oppenheimer, M., and R.B. Alley. 2016. How high will the seas rise? *Science* 354:1375-1377.

Pritchard, H., S.R.M. Ligtenberg, H.A. Fricker, D.G. Vaughan, M.R. Van den Broeke, and L. Padman. 2012. Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature* 484(7395):502-505.

Reid, W.V., D. Chen, L. Goldfarb, H. Hackman, Y.T. Lee, K. Mokhele, E. Ostron, K. Raivio, J. Roskstrom, H.J. Shellnhuber, and A. Whyte. 2010. Earth system science for global sustainability: Grand challenges. *Science* 330(6006):916-917.

Rignot, E., S. Jacobs, J. Mouginot, and B. Scheuchl. 2013. Ice-shelf melting around Antarctica. *Science* 341(6143):266-270.

Rodell, M., H. Beaudoing, T. L'Ecuyer, W. Olson, J. Famiglietti, P. Houser, R. Adler, et al. 2015. The observed state of the water cycle in the early 21st century. *Journal of Climate* 28:8289-8318.

Salmon, J.M., M.A. Friedl, S. Frolking, D. Wisser, and E.M. Douglas. 2015. Global rain-fed, irrigated, and paddy croplands: A new high resolution map derived from remote sensing, crop inventories and climate data. *International Journal of Applied Earth Observation and Geoinformation* 38:321-334.

Scofield, R.A., and R.J. Kuligowski. 2003. Status and outlook of operational satellite precipitation algorithms for extreme precipitation events. *Monthly Weather Review* 18:1037-1051.

Seattle Office of Sustainability and Environment. 2013. *Seattle Climate Action Plan.* June. http://www.seattle.gov/Documents/Departments/OSE/2013_CAP_20130612.pdf.

Sellers, P., F. Hall, G. Asrar, D. Strebel, and R. Murphy. 1988. The first ISLSCP field experiment (FIFE). *Bulletin of the American Meteorological Society* 69:22-27.

Sellers, P., F. Hall, K.J. Ranson, H. Margolis, B. Kelly, D. Baldocchi, G. den Hartog, J. Cihlar, M.G. Ryan, and B. Goodison. 1995. The Boreal Ecosystem-Atmosphere Study (BOREAS): An overview and early results from the 1994 field year. *Bulletin of the American Meteorological Society* 76:1549-1577.

Siegel, D.A., M.J. Behrenfeld, S. Maritorena, C.R. McClain, D. Antoine, S.W. Bailey, P.S. Bontempi, et al. 2013. Regional to global assessments of phytoplankton dynamics from the SeaWiFS mission. *Remote Sensing Environment* 135:77-91.

Siegel, D.A., K.O. Buesseler, S.C. Doney, S.F. Sailley, M.J. Behrenfeld, and P.W. Boyd. 2014. Global assessment of ocean carbon export by combining satellite observations and food-web models. *Global Biogeochemical Cycles* 28:181-196.

Simmons, A.J., and A. Hollingsworth. 2002. Some aspects of the improvement in skill of numerical weather prediction. *Quarterly Journal of the Royal Meteorological Society* 128:647-677.

Simmons, A., J.-L. Fellous, V. Ramaswamy, and K.E. Trenberth. 2016. Observation and integrated Earth-system science: A roadmap for 2016-2025. *Advances in Space Research* 57:2037-2103.

Smith, S.R., M.A. Bourassa, and D.L. Jackson. 2012. Supporting satellite research with data collected by vessels. *Sea Technology Magazine*, June, pp. 21-24.

Snider, G., C.L. Weagle, R.V. Martin, A. Van Donkelaar, K. Conrad, D. Cunningham, C. Gordon, et al. 2015. SPARTAN: A global network to evaluate and enhance satellite-based estimates of ground-level particulate matter for global health applications. *Atmospheric Measurement Techniques* 8:505-521.

Sorooshian, S., K. Hsu, X. Gao, H.V. Gupta, B. Imam, and D. Braithwaite. 2000. Evaluation of PERSIANN System satellite-based estimates of tropical rainfall. *Bulletin of the American Meteorological Society* 81(9):2035-2046.

Southeast Florida Regional Climate Change Compact. 2015. *Unified Sea Level Rise Projection: Southeast Florida. Prepared by the Sea Level Rise Work Group.* October. https://www.epa.gov/arc-x/southeast-florida-compact-analyzes-sea-level-rise-risk.

Stephens, G.L., T. L'Ecuyer, R. Forbes, A. Gettelman, C. Golaz, A. Bodas-Salcedo, and K. Suzuki. 2010. On the dreary state of weather and climate models. *Geophysical Research* 115:D24211.

Stock, C.A., J.G. John, R.R. Rykaczewski et al 2017. Reconciling fisheries catch and ocean productivity. *Proceedings of the National Academy of Sciences U.S.A.* 114(8):E1441-E1449.

Suzuki, K., T.Y. Nakajima, and G.L. Stephens. 2010. Particle growth and drop collection efficiency of warm clouds as inferred from joint CloudSat and MODIS observations. *Journal of the Atmospheric Sciences* 67:3019-3032.

Suzuki, K., G.L. Stephens, A. Bodas-Salcedo, M. Wang, J.-C. Golaz, T. Yokohata, and T. Koshiro. 2015. Evaluation of the warm rain formation process in global models with satellite observations. *Journal of the Atmospheric Sciences* 72(10):3996-4014.

Takahashi, H., K. Suzuki, and G. Stephens. 2017. Land-ocean differences in the warm rain formation process in satellite observations, ground-based observations, and model simulations: Drizzle gap. *Quarterly Journal of the Royal Meteorological Society* 143(705):1804-1815.

University of Twente. 2016. "ITC's Database of Satellites and Sensors." Accessed January 15, 2016. http://www.itc.nl/research/products/sensordb/AllSatellites.aspx.

Vitart, F., C. Ardilouze, A. Bonet, A. Brookshaw, M. Chen, C. Codorean, M. Déqué et al. 2017. The Subseasonal to Seasonal (S2S) Prediction Project Database. *Bulletin of the American Meteorological Society* 98(1):163-173.

Voigt, S., F. Giulio-Tonolo, J. Lyons, J. Kučera, B. Jones, T. Schneiderhan, G. Platzeck, et al. 2016. Global trends in satellite-based emergency mapping. *Science* 353(6296):247-252.

Watson, C.S., N.J. White, J.A. Church, M.A. King, R.J. Burgette, and B. Legresy. 2015. Unabated global mean sea-level rise over the satellite altimeter era. *Nature Climate Change* 5: 565-568.

WMO (World Meteorological Organization). 2016. *Sixth WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction (Shanghai, China, 10-13 May 2016): Workshop Report* (Y. Sato and L.P. Riishojgaard, eds). Final Report. https://www.wmo.int/pages/prog/www/WIGOS-WIS/reports/WMO-NWP-6_2016_Shanghai_Final-Report.pdf.

Wrona, F.J., M. Johansson, J.M. Culp, A. Jenkins, J. Mård, I.H. Myers-Smith, T.D. Prowse, W.F. Vincent, and P.A. Wookey. 2016. Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime. *Journal of Geophysical Research: Biogeosciences* 121:650-674.

Yan, X.-H., T. Boyer, K. Trenberth, T.R. Karl, S.-P. Xie, V. Nieves, K.-K. Tung, and D. Roemmich. 2016. The global warming hiatus: Slowdown or redistribution? *Earth's Future* 4: 472-482.

Yueh, S., D. Entekhabi, P. O'Neill, E. Njoku, and J. Entin. 2016. "NASA Soil Moisture Active Passive Mission Status and Science Performance." Pp. 116-119 in *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. doi: 10.1109/IGARSS.2016.7729020.

Zhan, X., W. Zheng, L. Fang, J. Liu, C. Hain, J. Yin, and M. Ek. 2016. "A Preliminary Assessment of the Impact of SMAP Soil Moisture on Numerical Weather Forecasts from GFS and NUWRF Models." Pp. 5229-5232 in *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. doi: 10.1109/IGARSS.2016.7730362.

Zhao, B., J.H. Jiang, Y. Gu, D. Diner, J. Worden, K.-N. Liou, H. Su, J. Xing, M. Garay, and L. Huang. 2017. Decadal-scale trends in regional aerosol particle properties and their linkage to emission changes. *Environmental Research Letters* 12(5): 054021.

Zhou, C., M.D. Zelinka, and S.A. Klein. 2016. Impact of decadal cloud variations on the Earth's energy budget. *Nature Geoscience* 9(12):871-874.

Zhu, X., S. Liang, Y. Pan, and X. Zhang. 2011. Agricultural irrigation impacts on land surface characteristics detected from satellite data products in Jilin Province, China. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 4(3): 721-729.

Zhu, X., D. Liu, and J. Chen. 2012. A new geostatistical approach for filling gaps in Landsat ETM+ SLC-off images. *Remote Sensing of Environment* 124:49-60.

3

A Prioritized Program for Science, Applications, and Observations

The committee was charged with developing a prioritized list of top-level science and application objectives to guide space-based Earth observations over the next 10 years, and identifying gaps and opportunities in the Programs of Record (PORs) at the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and U.S. Geological Survey (USGS) in pursuit of those top-level science and application challenges. This chapter describes the process used by the committee to identify and prioritize observational needs, and defines a robust and balanced U.S. program of Earth observations from space consistent with agency-provided budget expectations. The resulting program, built on the foundation of the U.S. and international PORs, addresses exciting and societally relevant questions and challenges in Earth system science while providing the programmatic flexibility needed to leverage innovation and opportunities that occur on subdecadal time scales.

THE ESAS 2017 PRIORITIZATION PROCESS

Community Input

Prior to the start of the decadal survey, the standing Committee on Earth Science and Applications from Space (CESAS) issued the first request for information (RFI-1) to the community, soliciting white paper submissions describing key challenges in Earth system science. In addition to providing important input into the identification of major challenges that can be substantially advanced through space-based observations, the responses informed the structure of the panels that were established by the steering committee. A second RFI (RFI-2), issued by the steering committee, called for submittal of "specific science and applications targets (i.e., objectives) that promise to substantially advance understanding in one or more Earth system science themes." Approximately 300 white papers were submitted in response to the two calls, spanning all areas of Earth science.

Approach and Process

The 2017 decadal survey was led by a steering committee and supported by five interdisciplinary panels. Steering committee members were selected to represent the broad Earth system science and applications community.

Process

The steering committee, in close collaboration with the panels, developed and implemented a process for establishing Science and Application Priorities and determining the resulting Observing System Priorities required to address them. The steps that were used to converge from a large set of possibilities to a final, small set of priorities, and the roles of the community, committee, and panels are shown using the analogy of a narrowing pyramid in Figure 3.1 and are discussed further later. From the hundreds of suggestions

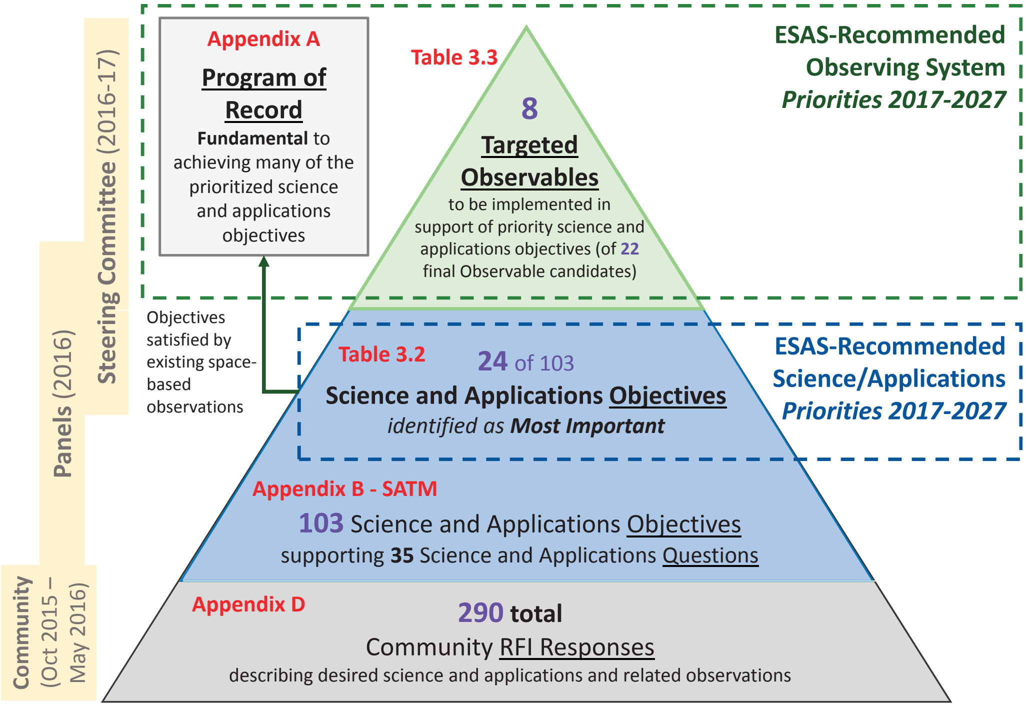

FIGURE 3.1 The steps used by the committee to incrementally establish priorities, shown using the analogy of a narrowing pyramid. The process began with two requests for information (RFIs—bottom dark gray panel) that were distributed broadly to the Earth science community. The first RFI informed the organization of the survey; the second invited the community to submit ideas for specific science and applications targets (i.e., objectives) that promised to substantially advance understanding in one or more Earth system science themes. Drawing on the RFIs, panel inputs, and key reference documents, the panels and steering committee then developed a Science and Applications Traceability Matrix (SATM) to establish and prioritize the science/applications and needed observations. Through the SATM process, 35 science/applications Questions were identified, supported by 103 science/applications Objectives, with 24 of these 103 Objectives ranked as Most Important. The steering committee then compared the observing needs associated with the 103 Objectives to the Program of Record. Unmet observation needs were then synthesized into a set of 22 Targeted Observables for consideration. The full list of 22 Targeted Observables was then prioritized and allocated to recommended flight elements, as described in Chapter 3. Consistent with assumed budgets, the recommended flight program elements support implementation of 8 Targeted Observables.

for science and applications priorities submitted through the RFI process and/or considered by the panels, only a much smaller number (103) were considered as formal priorities, and only a small portion of those (24) were ranked among the highest priorities.

Addressing the Statement of Task

As summarized in this report's preface, the committee's statement of task (SOT) requested that priorities focus on science, applications, and observations, rather than the instruments and missions required to carry out those observations. The SOT described a multistep requirements development process, diagramed in Figure 3.2, leading from science to observations through a step referred to in the SOT as "science

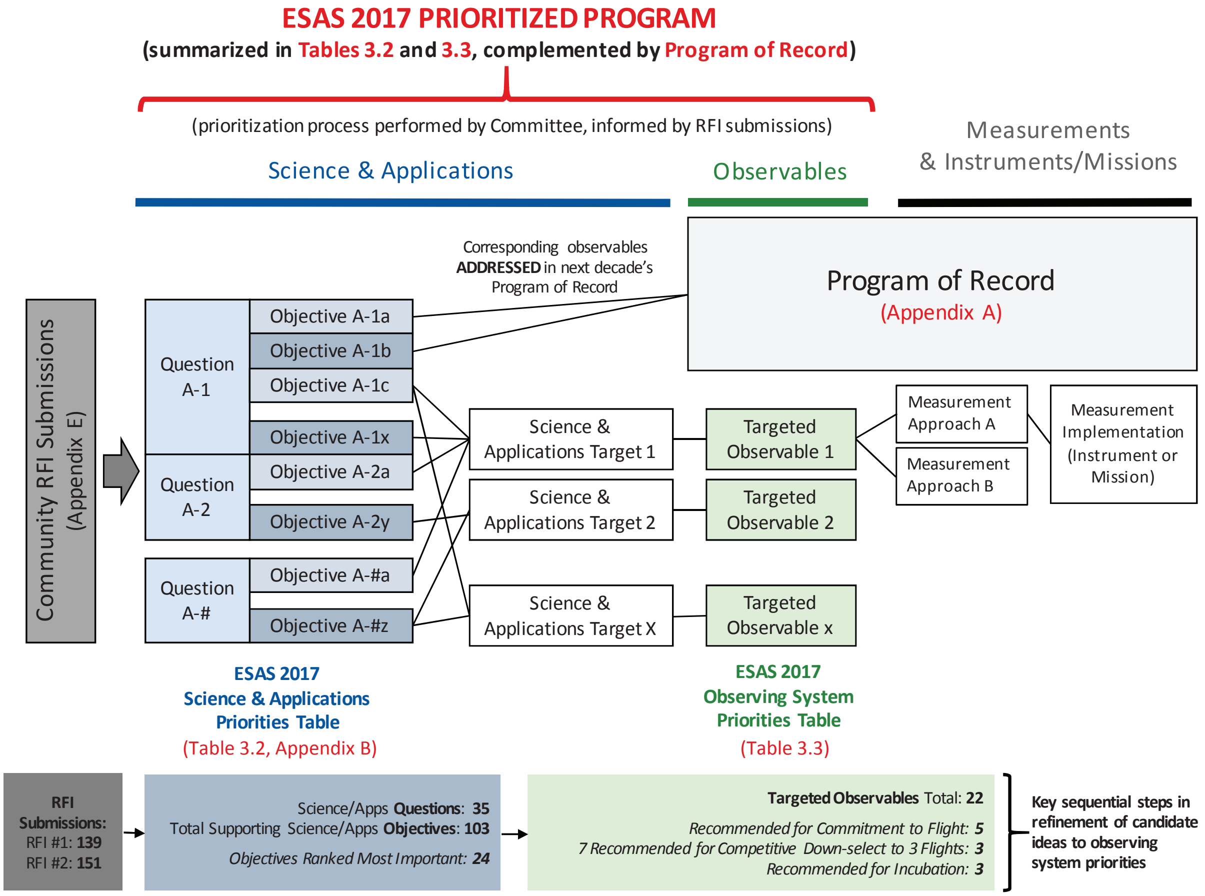

FIGURE 3.2 A notional diagram of the traceability process used by the committee to address statement of task (SOT) guidance and provide a prioritized program for (1) science and applications (blue) and (2) needed observables to fill gaps in the Program of Record (POR; green). The additional agency commitment to the POR is included (gray).

targets."[1] A science target, as defined in the SOT, is "a set of science objectives" related by a common space-based observable. The committee defined the observable associated with each science target as a Targeted Observable.

In accordance with the SOT, and with the goal of simplifying the presentation of its priorities, the committee chose to focus on two key elements of this sequence for prioritization: (1) the science and applications objectives (blue, corresponding to Table 3.2 on p. 81) and (2) the Targeted Observables (green, corresponding to Table 3.3, on page 118). Example measurements and missions were identified and evaluated only for the purpose of ensuring cost and technical readiness feasibility for Targeted Observables recommended within the NASA program, as required by the SOT.

Panels

Informed by the first RFI submission, the steering committee constructed a set of five interdisciplinary panels to facilitate community engagement in the decadal survey. Panel members were drawn from the scientific community based on their disciplinary and interdisciplinary expertise. The panels, each consisting of approximately 15 members, met three times, with the first and last of these meetings being conducted in a "jamboree" format in which all of the panels met in parallel at the same venue to identify and discuss where their science and application priorities intersected. The first panel jamboree also coincided with a meeting of the full steering committee and included joint plenary sessions to identify and discuss science priorities and areas where priorities might intersect. The second jamboree, and each of the stand-alone panel meetings, included participation by steering committee member representatives who helped facilitate communications between the steering committee and panels throughout the study. The five panels are listed here:

I. Global Hydrological Cycles and Water Resources. The movement, distribution, and availability of water and how these are changing over time.

II. Weather and Air Quality: Minutes to Subseasonal. Atmospheric dynamics, thermodynamics, chemistry, and their interactions at land and ocean interfaces.

III. Marine and Terrestrial Ecosystems and Natural Resource Management. Biogeochemical cycles, ecosystem functioning, biodiversity, and factors that influence health and ecosystem services.

IV. Climate Variability and Change: Seasonal to Centennial. Forcings and feedbacks of the ocean, atmosphere, land, and cryosphere within the coupled climate system.

V. Earth Surface and Interior: Dynamics and Hazards. Core, mantle, lithosphere, and surface processes, system interactions, and the hazards they generate.

The panel order in this list was chosen by the committee to simplify the presentation of the material and not to reflect any prioritization of the panels. This ordering is maintained throughout the discussion in this section and in various tables throughout the report. The panels developed science and applications priorities for their panel topic areas, based in large part on the input received through the RFI responses, and further informed by the expertise of the panel members and steering committee liaisons. Panel RFIs

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[1] Interpreted by the committee more broadly to be *science and applications targets*, in keeping with the nature of the report.

BOX 3.1 THE ROLE OF PANEL REPORTS

The important role of panels is identified in *The Space Science Decadal Surveys: Lessons Learned and Best Practices* report (NRC, 2015b), which notes, "The panel reports of a decadal survey have an invaluable role in tracing how the decadal survey prioritized science and identified strategies to achieve science goals and objectives. However, panel reports have no official standing; the survey report authored by the committee is the only source of consensus recommendations—panel reports typically provide context and history."

The ESAS 2017 steering committee chose to publish the panel reports as part of the same volume, consistent with the lesson learned and best practice identified in the 2015 report (p. 73):

- *Lesson Learned:* As the best and most detailed record of community input, a decadal survey's panel reports are a fundamental part of the survey's work product. It is essential that they be made public along with the final committee report. Publishing the survey committee report and the panel reports together, as has often been done, has the important advantage of providing traceability within one document of the decadal survey process of science and program prioritization.
- *Best Practice:* To make clear the utility of panel reports and to reduce ambiguity as to their use, decadal committees can choose to publish the panel reports in the same volume as the survey report, adding clear labeling that the panel reports are for reference only.

are not cited directly in this report, since the intent was to use them as guidance and not to suggest preference for particular RFIs within the report's priorities. The panels were directed to interpret their scope broadly, considering the state of science in both their encompassed traditional disciplines as well as with a broader view of Earth system science. Reports of each panel are included as chapters in Part II of this report; see Box 3.1 for further information.

Integrating Themes

The steering committee identified a set of Integrating Themes to complement the panel deliberation process by ensuring explicit consideration of broad, thematic concepts that cut across multiple panel domains. Members of the steering committee and representatives of each panel participated in an Integrating Themes Workshop during which priorities were considered in the context of advancing key aspects of Earth system science (e.g., the Carbon Cycle, the Water and Energy Cycles, Extreme Events) outside the traditional panel structure. While no separate report has been prepared from this workshop, the broad thinking of the workshop is reflected in the analysis of observation priorities and the development of the committee's recommendations.

The Integrating Themes developed at this workshop were used early in the decadal survey process to ensure important Earth system priorities were not missed by discipline-focused panels. Later, the steering committee leveraged this Integrating Themes perspective to ensure the recommended program addressed key system priorities. These themes, and their implications for the committee's priorities, are discussed throughout this chapter.

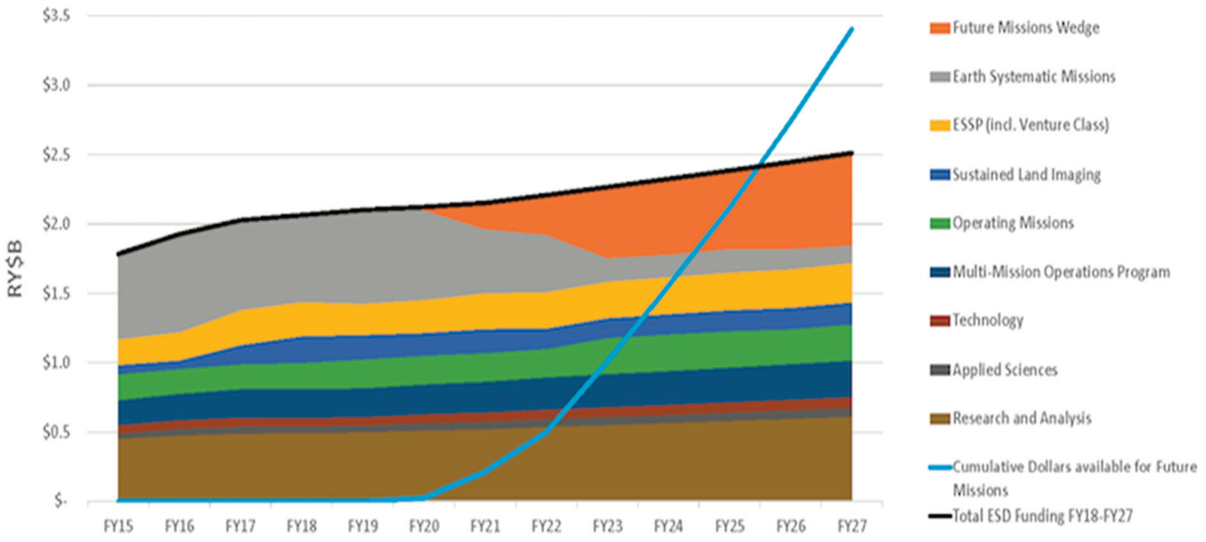

FIGURE 3.3 Baseline budget scenario assumes that the POR budget grows with inflation. Flight program funding for decadal survey priorities is unavailable until FY 2020. The cumulative total budget available for flight program investment in ESAS 2017 priorities is $3.4 billion through FY 2027. Labels shown in the legend refer to budgetary components within NASA's Earth Science Division (ESD). NOTE: ESSP = Earth System Science Pathfinder.

Budget Assumptions and Cost Assessment

Translating the committee's science and applications priorities into an observing program required that the committee assess the likely cost of the proposed observations to ensure the program can be accomplished within a budget consistent with agency expectations.[2]

In accordance with sponsor input to the decadal survey, the committee adopted a baseline NASA budget scenario that assumes that the budget provided in the Earth Science Division (ESD) POR will grow only at the rate of inflation, as shown in the "sand chart" in Figure 3.3. The cost of the flight missions in the POR (ICESat-2, NISAR, PACE, SWOT, Sentinel-6, GRACE-FO, RBI, TSIS-1/2 and CLARREO PF) from the start of fiscal year (FY) 2018 through the end of FY 2027 results in *a lien of $3.6 billion from the prior decadal interval.*[3] This baseline budget then implies a total of *$3.4 billion available to invest in the coming decadal survey's priorities* (FY 2018 through FY 2027), beyond funds already allocated and assuming existing program elements remain unchanged. This value corresponds to the orange portion of Figure 3.3. It is noteworthy that in this scenario, funding for implementing this decadal survey's flight priorities does

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[2] The statement of task says, "The survey committee will work with NASA, NOAA, and USGS to understand agency expectations of future budget allocations and design its recommendations based on budget scenarios relative to those expectations." NASA Earth Science Division (ESD) provided a budget history to the committee and indicated that large-scale changes to recent funding levels were not anticipated. The committee thus based its recommendations on the assumption that the current budget would grow with inflation. Decision rules are established in Chapter 4 to describe how the program can be tailored to accommodate modest budget shortfalls and how it can best be expanded to take advantage of any additional resources that may become available throughout the decade.

[3] See discussion in Chapter 3 of NRC (2015b, pp. 57-58).

not emerge until approximately FY 2020, as the flight program's resources are fully consumed with the POR until that time.

The committee notes that its recommendations are provided with a series of decision rules (see Chapter 4), which allow NASA to readily respond with program augmentations consistent with decadal survey priorities to take advantage of any additional funds that may be made available to support Earth system science throughout the decade. Similarly, these decision rules provide guidance on how to implement program reductions in the face of reduced resource availability.

Responsive to the study's statement of task, the committee used an independent Cost Assessment and Technical Evaluation (CATE) process to ensure concepts were credible and costs were of comparable fidelity when cost was a factor in prioritization. Drawing from the NRC *The Space Science Decadal Surveys: Lessons Learned and Best Practices* report (NRC, 2015b), the committee first used a cost "binning" approach to determine the relative scale of investment (i.e., small, medium, large) required for each potential program augmentation prior to down-selecting which program elements required more detailed cost estimation. Full CATE studies were completed by The Aerospace Corporation for explicitly prioritized program elements, which were binned as *large* (>$500 million).

Program of Record

The existing U.S. and international POR, which is summarized in Appendix A, forms the foundation upon which the committee's recommendations are established. The POR includes NASA, NOAA, and USGS missions formally planned and budgeted per input from these agencies, and those partner missions for which either NASA or NOAA explicitly expressed a commitment to this committee. This appendix also lists anticipated additional space-based observation contributions from other space agencies, but the commitments to these programs were not verified by the committee (these nonverified programs have the additional challenge that even when commitments are real, data may not be reliably available to NASA and NOAA researchers). Some items in this list (e.g., QuikSCAT) are known to currently have degraded performance, which was taken into account by the committee in its deliberations.

To identify gaps in the POR, the steering committee members and panel representatives attended a workshop during which the measurement needs to address priority science and applications objectives in the next decade as identified in the Science and Applications Traceability Matricies (SATMs) were reviewed against the POR to determine whether existing or planned measurements were adequate to meet the stated objectives. Where the POR did not adequately meet the need to address a high-priority objective, participants identified candidate augmentations to the POR to address the unmet need. Observations not in the POR were aggregated, as summarized in Appendix C, and became the starting point for the committee's deliberations regarding needed unmet observations.

The POR, and reliable funding to ensure its implementation, are particularly important. Earth system science and applications rely on long-term sustained observations of many key components of the Earth system. The POR provides many of the coming decade's needed continuity measurements, with a significant portion of that investment coming from internationally coordinated networks of operational satellites. Two such networks are the meteorological satellites coordinated by the Coordination Group for Meteorological Satellites (CGMS) and the more recent Sentinel satellites of the European Union's Copernicus Program (see Box 3.2), which together will provide continuity for a broad range of critical Earth observations.

The Sentinels will reach full operational status in 2023 and will sustain this observational capability for at least a decade. Given that the United States has no equivalent capability to this operational Earth observation and monitoring program in Europe, the committee recognizes the importance of Copernicus in general and the Sentinels in particular as a long-term, continuing source of a variety of important observations. It is clearly in the interest of the U.S. agencies and the research community for the U.S. agencies to

BOX 3.2 THE EUROPEAN COPERNICUS-SENTINEL PROGRAM: A KEY ELEMENT OF CONTINUITY IN THE PROGRAM OF RECORD

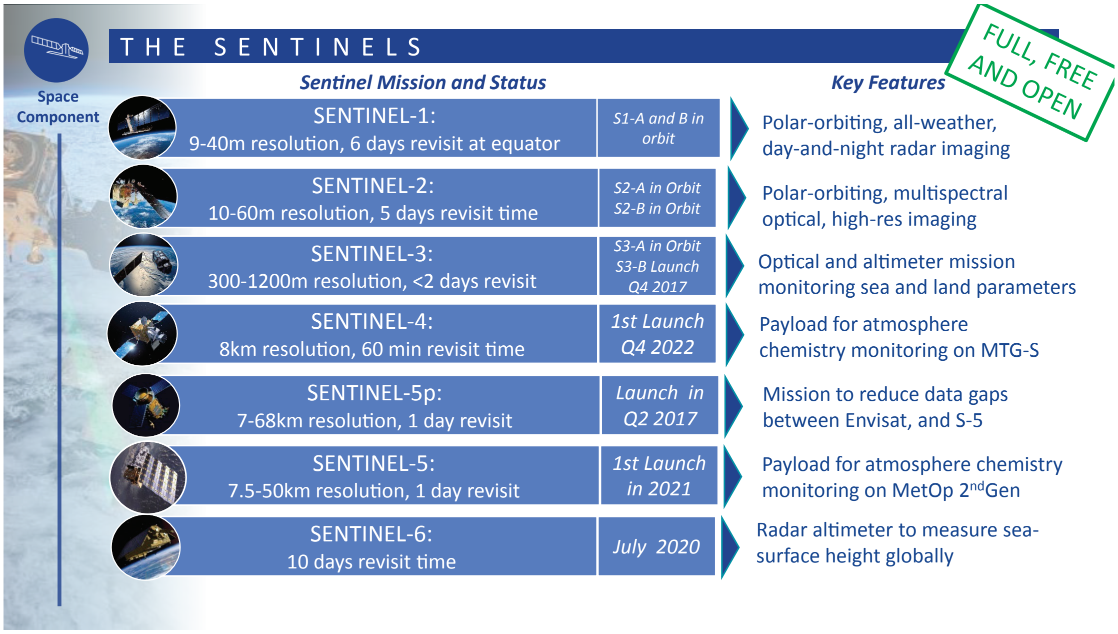
The Copernicus Program (Reillon, 2017), led and funded by the European Union (EU), represents a long-term EU commitment to deliver near-real-time products and services to better understand our planet and sustainably manage its environment.

Copernicus is supported by a family of satellites—the Sentinels—that have been designed to provide continuous, consistent global data sets on an operational basis. Copernicus Services then will transform this wealth of satellite data into value-added information by processing and analyzing the data, integrating it with data from a variety of complementary in situ sources, and validating the results.

By the end of 2017, four of the six Sentinel series should be fully deployed; all six will reach full operational status by 2023, and that capability will be maintained for at least a decade (Figure 3.2.1). (NASA and NOAA are partners in JASON-CS-A and -B, the first two satellites of Sentinel-6.) Discussions are currently under way in Europe concerning a possible expansion of the current Sentinels, as well as a long-term scenario for the next generation of Sentinels.

The Copernicus full, free, and open data policy (for which the U.S. Landsat program provided a Pathfinder example) paves the way for innovative entrepreneurs to create new applications and services to meet societal needs. Corresponding historical data sets will be made comparable and searchable, thus ensuring the monitoring of changes. By making the vast majority of its data, analyses, forecasts, and maps freely available, Copernicus contributes toward the development of new, innovative applications and services, tailored to the needs of specific groups of users.

The Copernicus Program is coordinated and managed by the European Commission. Responsibility for the development of the Copernicus Space Component is delegated to the European Space Agency (ESA), while spacecraft operations are split between ESA and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The in situ component is coordinated by the European Environment Agency (EEA) and the member states. The services component involves the European organizations listed in Table 3.2.1.



THE SENTINELS

Sentinel Mission and Status		*Key Features*
SENTINEL-1: 9-40m resolution, 6 days revisit at equator	*S1-A and B in orbit*	Polar-orbiting, all-weather, day-and-night radar imaging
SENTINEL-2: 10-60m resolution, 5 days revisit time	*S2-A in Orbit* *S2-B in Orbit*	Polar-orbiting, multispectral optical, high-res imaging
SENTINEL-3: 300-1200m resolution, <2 days revisit	*S3-A in Orbit* *S3-B Launch Q4 2017*	Optical and altimeter mission monitoring sea and land parameters
SENTINEL-4: 8km resolution, 60 min revisit time	*1st Launch Q4 2022*	Payload for atmosphere chemistry monitoring on MTG-S
SENTINEL-5p: 7-68km resolution, 1 day revisit	*Launch in Q2 2017*	Mission to reduce data gaps between Envisat, and S-5
SENTINEL-5: 7.5-50km resolution, 1 day revisit	*1st Launch in 2021*	Payload for atmosphere chemistry monitoring on MetOp 2^{nd}Gen
SENTINEL-6: 10 days revisit time	*July 2020*	Radar altimeter to measure sea-surface height globally

FIGURE 3.2.1 The structure and schedule of the European Copernicus Sentinel program.

BOX 3.2 Continued

TABLE 3.2.1 Organizational Responsibilities Within Europe's Copernicus Program

Service	Main Focus	Operator	Operational
Atmosphere monitoring	Air quality, ozone layer, emissions and surface fluxes, solar radiation, climate forcing	ECMWF	July 2015
Marine environment monitoring	Marine safety, coastal environment, marine resources, weather and climate	Mercator Ocean	May 2015
Land monitoring	Land cover, use and cover use changes, vegetation state, water cycle	JRC EEA	2012
Climate change	Climate variables, reanalyses and projections, multimodel seasonal forecasts	ECMWF	2017
Emergency management	Risk assessments of floods and forest fires, impact of natural and man-made disasters	JRC	April 2012
Security	Border surveillance, maritime surveillance, support for EU external action	Frontex-EMSA-EU SatCen	2015- early 2016

NOTE: ECMWF: European Centre for Medium-Range Weather Forecasts; JRC: Joint Research Centre; EEA: European Environmental Agency; EMSA: European Maritime Safety Agency; Frontex: European Border and Coast Guard Agency; EU SatCen: EU Satellite Centre. Mercator Ocean is a private French company. DATA SOURCE: Copernicus website: http://www.copernicus.eu/. SOURCE: Reillon, 2017.

ensure that their investigators have access to Sentinel observations in a timely manner. If the United States cannot replicate an effort like Copernicus and the Sentinels, U.S. agencies would benefit substantially from exploring options for complementing and strengthening this European effort, such as is being done by NASA and NOAA with the JASON-CS satellite partnership for Sentinel-6.

Science and Applications Traceability Matrix

Achieving traceability of both science/applications and observing system priorities was central to the committee's work. The foundation for this traceability was the SATM developed by the steering committee in conjunction with the panels, with content provided primarily by the panels. It establishes the traceability from prioritized science/applications to needed observing systems. The complete SATM is included in Appendix B. A shorter summary of the science and applications priorities within the SATM is provided as Table 3.2, below; this table provides the basis for the ESAS 2017 prioritized science and applications.

Development of the SATM was accomplished in four steps, as shown in Figure 3.2: (1) establish the priority science/applications question or goals; (2) identify a set of objectives (quantified when possible) needed to pursue those questions/goals; (3) determine the observables needed to fulfill those objectives; and (4) characterize the measurements available to make the observations.

The development of the SATM began with the committee issuing a second community RFI-2 soliciting specific science and applications needs (i.e., specific measurements/observations, or theory and/or modeling activities) that promise to advance existing or new scientific or applications objectives, contribute to fundamental understanding of Earth system science, and/or facilitate the connection between science and societal benefits (see Figure 3.1 and accompanying caption). The RFI responses provided a basis for panel deliberations, with each panel considering relevant RFI responses as it developed a set of key science and applications goals for the decade ahead. Panels then developed their SATM contributions to capture decadal goals and develop them into quantifiable objectives that might be addressed by space-based observations.

The prioritization of the Earth science/applications objectives within the SATM was accomplished using three categories:

MI—*Most Important.* Refers to objectives that are critical in order to make substantive advances in knowledge in key areas identified by the panel. These are the highest-priority objectives that should be pursued even under the most minimal of budget scenarios.

VI—*Very Important*. Refers to objectives that would contribute substantially to advances in knowledge in key areas identified by the panel and should be supported, second only to MI. Every effort should be made to accomplish these if resources are available or if they can be done opportunistically as a cost-effective add-on to an existing mission.

I—*Important*. Refers to objectives of high value that should be addressed if resources allow or if cost-effective opportunities are found to address them.

Observations often satisfy multiple objectives; therefore, some observations that are targeted at addressing MI priorities will also address VI and I priorities as well. A prioritized observing program, focused on achieving MI science and applications priorities, would be expected to achieve some (or even many) VI and I priorities at no additional cost.

Methodology for Establishing SATM Importance Ranking

The importance values ascribed to each science and applications objective within the SATM were based on the expert judgment of each panel, informed by the RFI submissions and available peer-reviewed literature. The allocation of importance into three categories was carried out by the panels and was accomplished through an iterative process by which the importance of each science and application objective was established using a score that was normalized both within and across panels. Based on these scores, the objectives were then binned into the categories of Most Important, Very Important, and Important. Because of the many possible considerations that can influence the assessment of scientific and applications importance, a rigid framework of specific considerations was not used. However, panels were encouraged to review the considerations listed in Table 3.1 to guide their discussions. Each panel, and the individual members of that panel, was free to choose its own considerations. The steering committee monitored the ranking process and concurred with the results.

During its deliberations, the committee noted that each SATM question generally involved aspects of both curiosity-driven and applications-driven science, which thus led to observations that addressed both exploratory and continuity-related needs. The fact that such basic and applied science categories have largely merged over the last decade is a tribute to a community success: restructuring our field in an integrated Earth context that balances science with applications and combines exploratory and continuity-related observations.

In developing this ranking approach, the committee reviewed the quantitative methodology described in the report *Continuity of NASA Earth Observations from Space: A Value Framework* (NRC, 2015a). While the merits of a fully quantitative valuation as recommended in the Continuity Report were attractive, the practical aspects of completing such valuation over a hundred objectives, as needed for this ESAS 2017 report, precluded that approach. It would have required reliable quantitative evaluation of five factors for these objectives, meaning thousands of quantitative assessments—each of which requires documented justification. Furthermore, the committee recognized that the factors relevant for the specific task of making continuity decisions may not be sufficient for the broader task of identifying observing system priorities.

TABLE 3.1 Considerations for the Importance Factor Used to Evaluate Science/Applications Objectives Within the SATM as Presented in Appendix B (Not in Priority Order)

Area	Description
Science Questions	Science objectives that contribute to answering the most important basic and applied scientific questions in Earth system science. These questions may span the entire space of scientific inquiry, from discovery to closing gaps in knowledge to monitoring change.
Applications and Policy	Science objectives contributing directly to addressing societal benefits achievable through use of Earth system science.
Interdisciplinary Uses	Science objectives with benefit to multiple scientific disciplines, thematic areas, or applications.
Long-Term Science and/or Applications	Objectives that can support scientific questions and societal needs that may arise in the future, even if they are not known or recognized today.
Value to Related Objectives	Science objectives that complement other objectives, either enhancing them or providing needed redundancy.
Readiness	Are we in a position to make meaningful progress to advance the objective, regardless of measurement?
Timeliness	Is now the time to invest in pursuing this objective? Examples include recently occurring phenomena that require focused near-term attention and the existence of complementary observing assets that may not be available in the future.

As a result, the committee chose to embrace the general guidance of the Continuity Report regarding a traceable (though not fully quantitative) prioritization process. Traceability is documented, to the extent possible, through the structure of the SATM (Appendix B), as discussed earlier. A prioritized assessment of the SATM's science/applications objectives was achieved through evaluating the Importance factor in the SATM, using a rigorously normalized process guided by judgment of the committee and panels.

The SATM Importance ranking (the rightmost column in Table 3.2) thus represents the committee's assessment of the pure science and applications priorities (consistent with the input provided by the panels), independent of implementation considerations such as cost. The inclusion of cost, feasibility, and readiness constraints was accomplished subsequently, when the science and applications priorities were translated into needed observations (to be ultimately implemented as instruments or missions), as discussed in the following sections. This resulted in some situations where highly ranked science and applications are not reflected in the committee's observing system recommendations when the observations proved too costly or appeared not ready for implementation. In such cases the high science and applications ranking suggests that investment in maturing the science or technology could have a substantial payoff.

The steering committee interacted directly with the panels during the development of priorities, which underwent a final review to ensure concurrence with all panel input to the ranking process. The committee is confident that the process used was comprehensive, reliable, and largely repeatable (in other words, similar results would be expected given a different committee makeup).

ESAS 2017 SCIENCE AND APPLICATIONS PRIORITIES

Using the process described earlier, the committee developed a set of science and applications priorities intended to address the breadth of the coming decade's Earth system science and applications needs.

Initial generation of the science/applications priorities list was largely the responsibility of the panels. The committee reviewed and evaluated the panel suggestions, augmenting them with integrating theme discussions in an effort to comprehensively address Earth system science and applications. These integrating themes made it possible to view Earth system science in the context of thematic areas spanning multiple panels. The goal was to ensure that the depth provided by disciplinary panel experience was appropriately complemented by a broader integrated perspective on the challenges in Earth system science.

The following sections present the science and applications assessment itself, then provide perspectives on the assessment from both interdisciplinary (panel) and cross-disciplinary (integrating theme) viewpoints.

The Science and Applications Priorities Assessment

The ESAS Integrated Science and Applications Assessment is documented in the full SATM (Appendix B) and summarized in the abbreviated version in Table 3.2, titled "Science and Applications Priorities." Table 3.2 forms the basis for all discussions in the remainder of this chapter. It describes the primary *science and applications* priorities, and it forms the basis for the *observing system priorities* discussed later in the chapter.

Recommendation 3.1: NASA, NOAA, and USGS, working in coordination, according to their appropriate roles and recognizing their agency mission and priorities, should implement an integrated programmatic approach to advancing Earth science and applications that is based on the *questions and objectives* in Table 3.2, "Science and Applications Priorities for the Decade 2017-2027."

TABLE 3.2 Science and Applications Priorities for the Decade 2017-2027—The Science and Applications Portion of the Full Science and Applications Traceability Matrix (SATM) in Appendix B

GLOBAL HYDROLOGICAL CYCLES AND WATER RESOURCES PANEL

Societal or Science Question/Goal	Earth Science/Applications Objective	Science/ Applications Importance
QUESTION H-1. How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?	**H-1a.** Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance from headwater catchments to continental-scale river basins.	Most Important
	H-1b. Quantify rates of precipitation and its phase (rain and snow/ice) worldwide at convective and orographic scales suitable to capture flash floods and beyond.	Most Important
	H-1c. Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide at scales driven by topographic variability.	Most Important

TABLE 3.2 Continued

GLOBAL HYDROLOGICAL CYCLES AND WATER RESOURCES PANEL

Societal or Science Question/Goal	Earth Science/Applications Objective	Science/ Applications Importance
QUESTION H-2. How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally, and globally, and what are the short- and long-term consequences?	**H-2a.** Quantify how changes in land use, water use, and water storage affect evapotranspiration rates, and how these in turn affect local and regional precipitation systems, groundwater recharge, temperature extremes, and carbon cycling.	Very Important
	H-2b. Quantify the magnitude of anthropogenic processes that cause changes in radiative forcing, temperature, snowmelt, and ice melt, as they alter downstream water quantity and quality.	Important
	H-2c. Quantify how changes in land use, land cover, and water use related to agricultural activities, food production, and forest management affect water quality and especially groundwater recharge, threatening sustainability of future water supplies.	Most Important
QUESTION H-3. How do changes in the water cycle impact local and regional freshwater availability, alter the biotic life of streams, and affect ecosystems and the services these provide?	**H-3a.** Develop methods and systems for monitoring water quality for human health and ecosystem services.	Important
	H-3b. Monitor and understand the coupled natural and anthropogenic processes that change water quality, fluxes, and storages in and between all reservoirs (atmosphere, rivers, lakes, groundwater, and glaciers) and the response to extreme events.	Important
	H-3c. Determine structure, productivity, and health of plants to constrain estimates of evapotranspiration.	Important
QUESTION H-4. How does the water cycle interact with other Earth system processes to change the predictability and impacts of hazardous events and hazard chains (e.g., floods, wildfires, landslides, coastal loss, subsidence, droughts, human health, and ecosystem health), and how do we improve preparedness and mitigation of water-related extreme events?	**H-4a.** Monitor and understand hazard response in rugged terrain and land margins to heavy rainfall, temperature, and evaporation extremes, and strong winds at multiple temporal and spatial scales.	Very Important
	H-4b. Quantify key meteorological, glaciological, and solid Earth dynamical and state variables and processes controlling flash floods and rapid hazard chains to improve detection, prediction, and preparedness. (This is a critical socioeconomic priority that depends on success of addressing H-1c and H-4a.)	Important
	H-4c. Improve drought monitoring to forecast short-term impacts more accurately and to assess potential mitigations.	Important
	H-4d. Understand linkages between anthropogenic modification of the land, including fire suppression, land use, and urbanization on frequency of, and response to, hazards. (This is tightly linked to H-2a, H-2b, H-4a, H-4b, and H-4c.)	Important

TABLE 3.2 Continued

WEATHER AND AIR QUALITY PANEL

Societal or Science Question/Goal	Earth Science/Applications Objective	Science/ Application Importance
QUESTION W-1. What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean, and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations?	**W-1a.** Determine the effects of key boundary layer processes on weather, hydrological, and air quality forecasts at minutes to subseasonal time scales.	Most Important
QUESTION W-2. How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months?	**W-2a.** Improve the observed and modeled representation of natural, low-frequency modes of weather/climate variability (e.g., MJO, ENSO), including upscale interactions between the large-scale circulation and organization of convection and slowly varying boundary processes to extend the lead time of useful prediction skills by 50% for forecast times of 1 week to 2 months.	Most Important
QUESTION W-3. How do spatial variations in surface characteristics (influencing ocean and atmospheric dynamics, thermal inertia, and water) modify transfer between domains (air, ocean, land, and cryosphere) and thereby influence weather and air quality?	**W-3a.** Determine how spatial variability in surface characteristics modifies regional cycles of energy, water, and momentum (stress) to an accuracy of 10 W/m^2 in the enthalpy flux, and 0.1 N/m^2 in stress, and observe total precipitation to an average accuracy of 15% over oceans and/or 25% over land and ice surfaces averaged over a 100 × 100 km region and 2- to 3-day time period.	Very Important
QUESTION W-4. Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?	**W-4a.** Measure the vertical motion within deep convection to within 1 m/s and heavy precipitation rates to within 1 mm/hour to improve model representation of extreme precipitation and to determine convective transport and redistribution of mass, moisture, momentum, and chemical species.	Most Important
QUESTION W-5. What processes determine the spatiotemporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?	**W-5a.** Improve the understanding of the processes that determine air pollution distributions and aid estimation of global air pollution impacts on human health and ecosystems by reducing uncertainty to <10% of vertically resolved tropospheric fields (including surface concentrations) of speciated particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2).	Most Important

TABLE 3.2 Continued

Societal or Science Question/Goal	Earth Science/Applications Objective	Science/ Application Importance
QUESTION W-6. What processes determine the long-term variations and trends in air pollution and their subsequent long-term recurring and cumulative impacts on human health, agriculture, and ecosystems?	**W-6a**. Characterize long-term trends and variations in global, vertically resolved speciated PM, O_3, and nitrogen dioxide (NO_2) trends (within 20%/yr), which are necessary for the determination of controlling processes and estimation of health effects and impacts on agriculture and ecosystems.	Important
QUESTION W-7. What processes determine observed tropospheric ozone (O_3) variations and trends and what are the concomitant impacts of these changes on atmospheric composition/chemistry and climate?	**W-7a.** Characterize tropospheric O_3 variations, including stratospheric-tropospheric exchange of O_3 and impacts on surface air quality and background levels.	Important
QUESTION W-8. What processes determine observed atmospheric methane (CH_4) variations and trends, and what are the subsequent impacts of these changes on atmospheric composition/chemistry and climate?	**W-8a.** Reduce uncertainty in tropospheric CH_4 concentrations and in CH_4 emissions, including uncertainties on the factors that affect natural fluxes.	Important
QUESTION W-9. What processes determine cloud microphysical properties and their connections to aerosols and precipitation?	**W-9a.** Characterize the microphysical processes and interactions of hydrometeors by measuring the hydrometeor distribution and precipitation rate to within 5%.	Important
QUESTION W-10. How do clouds affect the radiative forcing at the surface and contribute to predictability on time scales from minutes to subseasonal?	**W-10a.** Quantify the effects of clouds of all scales on radiative fluxes, including on the boundary layer evolution. Determine the structure, evolution, and physical/dynamical properties of clouds on all scales, including small-scale cumulus clouds.	Important

TABLE 3.2 Continued

MARINE AND TERRESTRIAL ECOSYSTEMS AND NATURAL RESOURCES MANAGEMENT PANEL

Societal or Science Question/Goal	Earth Science/Applications Objective	Science/ Application Importance
QUESTION E-1. What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space?[a]	**E-1a.** Quantify the distribution of the functional traits, functional types, and composition of terrestrial and shallow aquatic vegetation and marine biomass, spatially and over time.	Very Important
	E-1b. Quantify the global three-dimensional (3D) structure of terrestrial vegetation and 3D distribution of marine biomass within the euphotic zone, spatially and over time.	Most Important
	E-1c. Quantify the physiological dynamics of terrestrial and aquatic primary producers.	Most Important
	E-1d. Quantify moisture status of soils.	Important
	E-1e. Support targeted species detection and analysis (e.g., foundation species, invasive species, indicator species, etc.).	Important
QUESTION E-2. What are the fluxes (of carbon, water, nutrients, and energy) *between* ecosystems and the atmosphere, the ocean, and the solid Earth, and how and why are they changing?	**E-2a.** Quantify the fluxes of CO_2 and CH_4 globally at spatial scales of 100 to 500 km and monthly temporal resolution with uncertainty < 25% between land ecosystems and atmosphere and between ocean ecosystems and atmosphere.	Most Important
	E-2b. Quantify the fluxes from land ecosystems between aquatic ecosystems.	Important
	E-2c. Assess ecosystem subsidies from solid Earth.	Important
QUESTION E-3. What are the fluxes (of carbon, water, nutrients, and energy) *within* ecosystems, and how and why are they changing?	**E-3a.** Quantify the flows of energy, carbon, water, nutrients, and so on, sustaining the life cycle of terrestrial and marine ecosystems and partitioning into functional types.	Most Important
	E-3b. Understand how ecosystems support higher trophic levels of food webs.	Important
QUESTION E-4. How is carbon accounted for through carbon storage, turnover, and accumulated biomass. Have all of the major carbon sinks been qualified and how they are changing in time?	**E-4a.** Improve assessments of the global inventory of terrestrial carbon pools and their rate of turnover.	Important
	E-4b. Constrain ocean carbon storage and turnover.	Important
QUESTION E-5. Are carbon sinks stable, are they changing, and why?	**E-5a.** Discover ecosystem thresholds in altering carbon storage.	Important
	E-5b. Discover cascading perturbations in ecosystems related to carbon storage.	Important
	E-5c. Understand ecosystem response to fire events.	Important

TABLE 3.2 Continued

CLIMATE VARIABILITY AND CHANGE: SEASONAL TO CENTENNIAL PANEL

Societal or Science Question/Goal	Earth Science/Applications Objective	Science/ Application Importance
QUESTION C-1. How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?	**C-1a.** Determine the global mean sea-level rise to within 0.5 mm/yr over the course of a decade.[b]	Most Important
	C-1b. Determine the change in the global oceanic heat uptake to within 0.1 W/m^2 over the course of a decade.	Most Important
	C-1c. Determine the changes in total ice-sheet mass balance to within 15 Gton/yr over the course of a decade and the changes in surface mass balance and glacier ice discharge with the same accuracy over the entire ice sheets, continuously, for decades to come.	Most Important
	C-1d. Determine regional sea-level change to within 1.5-2.5 mm/yr over the course of a decade (1.5 corresponds to a ~6000 km^2 region, 2.5 corresponds to a ~4000 km^2 region).	Very Important
QUESTION C-2. How can we reduce the uncertainty in the amount of future warming of Earth as a function of fossil fuel emissions, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/ adaptation strategies?	**C-2a.** Reduce uncertainty in low and high cloud feedback by a factor of 2.	Most Important
	C-2b. Reduce uncertainty in water vapor feedback by a factor of 2.	Very Important
	C-2c. Reduce uncertainty in temperature lapse rate feedback by a factor of 2.	Very Important
	C-2d. Reduce uncertainty in carbon cycle feedback by a factor of 2.	Most Important
	C-2e. Reduce uncertainty in snow/ice albedo feedback by a factor of 2.	Important
	C-2f. Determine the decadal average in global heat storage to 0.1 W/m^2 (67% confidence) and interannual variability to 0.2 W/m^2 (67% confidence).	Very Important
	C-2g. Quantify the contribution of the upper troposphere and stratosphere (UTS) to climate feedbacks and change by determining how changes in UTS composition and temperature affect radiative forcing with a 1-sigma uncertainty of 0.05 W/m^2 over the course of the decade.	Very Important
	C-2h. Reduce the IPCC AR5 total aerosol radiative forcing uncertainty by a factor of 2.	Most Important

TABLE 3.2 Continued

Societal or Science Question/Goal	Earth Science/Applications Objective	Science/ Application Importance
QUESTION C-3. How large are the variations in the global carbon cycle and what are the associated climate and ecosystem impacts in the context of past and projected anthropogenic carbon emissions?	**C-3a.** Quantify CO_2 fluxes at spatial scales of 100-500 km and monthly temporal resolution with uncertainty < 25% to enable regional-scale process attribution explaining year-to-year variability by net uptake of carbon by terrestrial ecosystems (i.e., determine how much carbon uptake results from processes such as CO_2 and nitrogen fertilization, forest regrowth, and changing ecosystem demography).	Very Important
	C-3b. Reliably detect and quantify emissions from large sources of CO_2 and CH_4, including from urban areas, from known point sources such as power plants, and from previously unknown or transient sources such as CH_4 leaks from oil and gas operations.	Important
	C-3c. Provide early warning of carbon loss from large and vulnerable reservoirs such as tropical forests and permafrost.	Important
	C-3d. Provide regional-scale process attribution for carbon uptake by ocean to within 25% (especially in coastal regions and the Southern Ocean).	Important
	C-3e. Quantify CH_4 fluxes from wetlands at spatial scales of 300 km × 300 km and monthly temporal resolution with uncertainty better than 3 mg CH_4 m^{-2}/ day^{-1} in order to establish predictive process–based understanding of dependence on environmental drivers such as temperature, carbon availability, and inundation.	Important
	C-3f. Improve simulated atmospheric transport for data assimilation/inverse modeling.	Important
	C-3g. Quantify the tropospheric oxidizing capacity of OH, critical for air quality and dominant sink for CH_4 and other greenhouse gases (GHGs).	Important
QUESTION C-4. How will the Earth system respond to changes in air-sea interactions?	**C-4a.** Improve the estimates of global air-sea fluxes of heat, momentum, water vapor (i.e., moisture) and other gases (e.g., CO_2 and CH_4) to the following global accuracy in the mean on local or regional scales: (1) radiative fluxes to 5 W/m^2, (2) sensible and latent heat fluxes to 5 W/m^2, (3) winds to 0.1 m/s, and (4) CO_2 and CH_4 to within 25%, with appropriate decadal stabilities.	Very Important
	C-4b. Better quantify the role of surface waves in determining wind stress; demonstrate the validity of Monin-Obukhov similarity theory and other flux-profile relationships at high wind speeds over the ocean.	Important
	C-4c. Improve bulk flux parameterizations, particularly in extreme conditions and high-latitude regions, reducing uncertainty in the bulk transfer coefficients by a factor of 2.	Important
	C-4d. Evaluate the effect of surface CO_2 gas exchange, oceanic storage, and impact on ecosystems, and improve the confidence in the estimates and reduce uncertainties by a factor of 2.	Important

TABLE 3.2 Continued

Societal or Science Question/Goal	Earth Science/Applications Objective	Science/ Application Importance
QUESTION C-5. A. How do changes in aerosols (including their interactions with clouds, which constitute the largest uncertainty in total climate forcing) affect Earth's radiation budget and offset the warming due to greenhouse gases? B. How can we better quantify the magnitude and variability of the emissions of natural aerosols, and the anthropogenic aerosol signal that modifies the natural one, so that we can better understand the response of climate to its various forcings?	**C-5a.** Improve estimates of the emissions of natural and anthropogenic aerosols and their precursors via observational constraints.	Very Important
	C-5b. Characterize the properties and distribution in the atmosphere of natural and anthropogenic aerosols, including properties that affect their ability to interact with and modify clouds and radiation.	Important
	C-5c. Quantify the effect that aerosol has on cloud formation, cloud height, and cloud properties (reflectivity, lifetime, cloud phase), including semi-direct effects.	Very Important
	C-5d. Quantify the effect of aerosol-induced cloud changes on radiative fluxes (reduction in uncertainty by a factor of 2) and impact on climate (circulation, precipitation).	Important
QUESTION C-6. Can we significantly improve seasonal to decadal forecasts of societally relevant climate variables?*	**C-6a.** Decrease uncertainty, by a factor of 2, in quantification of surface and subsurface ocean states for initialization of seasonal-to-decadal forecasts.	Very Important
	C-6b. Decrease uncertainty, by a factor of 2, in quantification of land surface states for initialization of seasonal forecasts.	Important
	C-6c. Decrease uncertainty, by a factor of 2, in quantification of stratospheric states for initialization of seasonal-to-decadal forecasts.	Important
QUESTION C-7. How are decadal-scale global atmospheric and ocean circulation patterns changing, and what are the effects of these changes on seasonal climate processes, extreme events, and longer term environmental change?	**C-7a.** Quantify the changes in the atmospheric and oceanic circulation patterns, reducing the uncertainty by a factor of 2, with desired confidence levels of 67% (likely in IPCC parlance).	Very Important
	C-7b. Quantify the linkage between natural (e.g., volcanic) and anthropogenic (greenhouse gases, aerosols, land-use) forcings and oscillations in the climate system (e.g., MJO, NAO, ENSO, QBO) . Reduce the uncertainty by a factor of 2. Confidence levels desired: 67%.	Important
	C-7c. Quantify the linkage between global climate sensitivity and circulation change on regional scales, including the occurrence of extremes and abrupt changes. Quantify the expansion of the Hadley cell to within 0.5 degrees latitude per decade (67% confidence desired); changes in the strength of AMOC to within 5% per decade (67% confidence desired); changes in ENSO spatial patterns, amplitude, and phase (67% confidence desired).	Very Important
	C-7d. Quantify the linkage between the dynamical and thermodynamic state of the ocean upon atmospheric weather patterns on decadal time scales. Reduce the uncertainty by a factor of 2 (relative to decadal prediction uncertainty in IPCC, 2013). Confidence level: 67% (likely).	Important
	C-7e. Provide observational verification of models used for climate projections. Are the models simulating the observed evolution of the large-scale patterns in the atmosphere and ocean circulation, such as the frequency and magnitude of ENSO events, strength of AMOC, and the poleward expansion of the subtropical jet (to a 67% level correspondence with the observational data)?	Important

TABLE 3.2 Continued

Societal or Science Question/Goal	Earth Science/Applications Objective	Science/ Application Importance
QUESTION C-8. What will be the consequences of amplified climate change already observed in the Arctic and projected for Antarctica on global trends of sea-level rise, atmospheric circulation, extreme weather events, global ocean circulation, and carbon fluxes?	**C-8a.** Improve our understanding of the drivers behind polar amplification by quantifying the relative impact of snow/ice-albedo feedback, versus changes in atmospheric and oceanic circulation, water vapor, and lapse rate feedback.	Very Important
	C-8b. Improve understanding of high-latitude variability and midlatitude weather linkages (impact on midlatitude extreme weather and changes in storm tracks from increased polar temperatures, loss of ice and snow cover extent, and changes in sea level from increased melting of ice sheets and glaciers).	Very Important
	C-8c. Improve regional-scale seasonal to decadal predictability of Arctic and Antarctic sea-ice cover, including sea-ice fraction (within 5%), ice thickness (within 20 cm), location of the ice edge (within 1 km), timing of ice retreat, and ice advance (within 5 days).	Very Important
	C-8d. Determine the changes in Southern Ocean carbon uptake due to climate change and associated atmosphere/ocean circulations.	Very Important
	C-8e. Determine how changes in atmospheric circulation, turbulent heat fluxes, sea-ice cover, freshwater input, and ocean general circulation affect bottom water formation.	Important
	C-8f. Determine how permafrost-thaw-driven land-cover changes affect turbulent heat fluxes, above- and below-ground carbon pools, resulting GHG fluxes (CO_2, CH_4) in the Arctic, as well as their impact on Arctic amplification.	Important
	C-8g. Determine the amount of pollutants (e.g., black carbon, soot from fires, and other aerosols and dust) transported into polar regions and their impacts on snow and ice melt.	Important
	C-8h. Quantify high-latitude low cloud representation, feedbacks, and linkages to global radiation.	Important
	C-8i. Quantify how increased fetch, sea-level rise, and permafrost thaw increase vulnerability of coastal communities to increased coastal inundation and erosion as winds and storms intensify.	Important
QUESTION C-9. How is the ozone layer changing and what are the implications for Earth's climate?	**C-9a.** Quantify the amount of UV-B reaching the surface, and relate to changes in stratospheric ozone and atmospheric aerosols.	Important

EARTH SURFACE AND INTERIOR: DYNAMICS AND HAZARDS PANEL

Societal or Science Question/Goal	Earth Science/Applications Objective	Science/ Application Importance
QUESTION S-1. How can large-scale geological hazards be accurately forecast in a socially relevant time frame?	**S-1a.** Measure the pre-, syn-, and post-eruption surface deformation and products of Earth's entire active land volcano inventory with a time scale of days to weeks.	Most Important
	S-1b. Measure and forecast interseismic, preseismic, coseismic, and postseismic activity over tectonically active areas on time scales ranging from hours to decades.	Most Important
	S-1c. Forecast and monitor landslides, especially those near population centers.	Very Important
	S-1d. Forecast, model, and measure tsunami generation, propagation, and run-up for major seafloor events.	Important

TABLE 3.2 Continued

Societal or Science Question/Goal	Earth Science/Applications Objective	Science/ Application Importance
QUESTION S-2. How do geological disasters directly impact the Earth system and society following an event?	**S-2a.** Rapidly capture the transient processes following disasters for improved predictive modeling, as well as response and mitigation through optimal retasking and analysis of space data.	Most Important
	S-2b. Assess surface deformation (<10 mm), extent of surface change (<100 m spatial resolution) and atmospheric contamination, and the composition and temperature of volcanic products following a volcanic eruption (hourly to daily temporal sampling).	Very Important
	S-2c. Assess co- and postseismic ground deformation (spatial resolution of 100 m and an accuracy of 10 mm) and damage to infrastructure following an earthquake.	Very Important
QUESTION S-3. How will local sea level change along coastlines around the world in the next decade to century?	**S-3a.** Quantify the rates of sea-level change and its driving processes at global, regional, and local scales, with uncertainty <0.1 mm/yr for global mean sea-level equivalent and <0.5 mm/yr sea-level equivalent at resolution of 10 km.[b]	Most Important
	S-3b. Determine vertical motion of land along coastlines, at uncertainty <1 mm/yr .	Most Important
QUESTION S-4. What processes and interactions determine the rates of landscape change?	**S-4a.** Quantify global, decadal landscape change produced by abrupt events and by continuous reshaping of Earth's surface from surface processes, tectonics, and societal activity.	Most Important
	S4b. Quantify weather events, surface hydrology, and changes in ice/water content of near-surface materials that produce landscape change.	Important
	S4c. Quantify ecosystem response to and causes of landscape change.	Important
QUESTION S-5. How does energy flow from the core to Earth's surface?	**S-5a.** Determine the effects of convection within Earth's interior, specifically the dynamics of Earth's core and its changing magnetic field and the interaction between mantle convection and plate motions.	Very Important
	S-5b. Determine the water content in the upper mantle by resolving electrical conductivity to within a factor of 2 over horizontal scales of 1,000 km.	Important
	S-5c. Quantify the heat flow through the mantle and lithosphere within 10 mW/m^2.	Important
QUESTION S-6. How much water is traveling deep underground and how does it affect geological processes and water supplies?	**S-6a.** Determine the fluid pressures, storage, and flow in confined aquifers at spatial resolution of 100 m and pressure of 1 kPa (0.1 m head).	Very Important
	S-6b. Measure all significant fluxes in and out of the groundwater system across the recharge area.	Important
	S-6c. Determine the transport and storage properties in situ within a factor of 3 for shallow aquifers and an order of magnitude for deeper systems.	Important
	S-6d. Determine the impact of water-related human activities and natural water flow on earthquakes.	Important
QUESTION S-7. How do we improve discovery and management of energy, mineral, and soil resources?	**S-7a.** Map topography, surface mineralogic composition and distribution, thermal properties, soil properties/water content, and solar irradiance for improved development and management of energy, mineral, agricultural, and natural resources.	Important

* As noted in the text, all of the indicated measurements for Questions C-6 and C-7 would be useful, but the absence or excessive coarseness of any of the measurements would not be a deal-breaker. This question is best considered *not* as a motivation for a mission but rather as a beneficiary of measurements taken to address other questions. Indicating here which measurements are already being taken is, in a way, extraneous.

[a] "Structure" is the spatial distribution of plants and their components on land, and of aquatic biomass. "Function" is the physiology and underpinning of biophysical and biogeochemical properties of terrestrial vegetation and shallow aquatic vegetation.

TABLE 3.2 Continued

[b] The steering committee worked with the Climate Variability and Change Panel and with the Earth Surface and Interior Panel regarding their different requirements for the measurement of sea-level rise. Current altimetry missions, such as Jason-3, have a mission goal of 1 mm/yr, in order to accommodate the inherent measurement uncertainty and the effects of seasonal and interannual variations. The uncertainty in the global mean sea-level rise rate over the last 25 years has been estimated to be 0.3-0.5 mm/yr (e.g., Leuliette and Nerem, 2016; Ablain et al., 2017), and acceleration rates of 0.084 ± 0.025 mm/yr^2 have been inferred (Nerem et al., 2018). The 0.5 mm/yr sea-level rise objective reflects requirements specified by the climate panel for multidecadal sea-level rise evaluations that are derived primarily from altimetry. The Earth Surface and Interior Earth Panel has advocated a more stringent requirement of 0.1-0.3 mm/yr, which would require a multi-instrument evaluation, merging measurements from in situ observations, and multiple types of satellites.

Panel Perspectives and Priorities

Part II of this report provides the comprehensive panel inputs on the science and applications underlying the SATM (Table 3.2 and Appendix B). In the following sections, the steering committee presents a review of the panel chapters and an analysis of how the panel priorities fit within the broader context considered by the steering committee of Earth system science and applications.

Global Hydrological Cycles and Water Resources

Water is the most widely used resource on Earth. Driven by this need, humans have established engineering and social systems to control, manage, use, and alter our water environment, for a variety of uses and through a variety of organizational and individual processes. Understanding the hydrologic cycle, monitoring, and predicting its vagaries, are therefore of critical importance to society.

Remotely sensed data have been playing a key role in advancing our insight into Earth's water resources. Missions such as the Tropical Rainfall Measurement Mission (TRMM), Global Precipitation Measurement (GPM) mission, Soil Moisture Active Passive (SMAP), and Gravity Recovery and Climate Experiment (GRACE)—along with still-operating sensors from the older Earth Observing System (EOS)—have provided important measurements to understand the movement of water and energy throughout Earth at various spatial and temporal scales.

Among the most important contributions to hydrologic sciences and engineering—in addition to space-based measurements of water in its various forms—are space-based observations of shortwave and longwave radiation, as such observations provide an important ingredient for estimating fluxes of evaporation and evapotranspiration (ET), snow and glacier extent, soil moisture, atmospheric water vapor, clouds, precipitation, terrestrial vegetation and oceanic chlorophyll, and water storage in the subsurface (Box 3.3), among many others.

In its report, the Hydrology Panel recognized a number of high-level integrative science questions. To address these, the panel proposed remote sensing measurements that will enhance and continue developments needed to address critical gaps in our understanding of the movement, distribution, and availability of water and its variability and change over time and space. The four objectives identified by the panel as Most Important were associated with the following two questions:

- *(H-1) Water Cycle Acceleration.* How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?
- *(H-2) Impact of Land Use Changes on Water and Energy Cycles.* How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally, and globally and what are the short- and long-term consequences?

The panel recognized the importance of the coupling between the water cycle and energetics of the Earth system as a basis for understanding how the different water cycle facets are changing now and might change in the future. Quantifying the components of the water and energy cycles at Earth's surface, through observations with sufficient accuracy to close the budgets at river basin scales, has been an unresolved problem for many decades. Two central coupled elements of the surface water and energy balances are the precipitation that reaches Earth's surface (P) and the heat fluxes associated with evaporation from the surface and from transpiration from vegetation (ET). The surface properties, including soil moisture, also strongly influence the planetary boundary layer. It, in turn, influences surface-atmosphere exchanges, further complicating the coupling between energy and water.

The panel concluded that (1) couplings between water and energy are central to understanding water and energy balances on river basin scales; (2) ET is a net result of coupled processes; (3) precipitation and surface water information is needed on increasingly finer spatial and temporal scales; and (4) the consequences of changes in the hydrologic cycle will have significant impact on the Earth population and environment. These conclusions led the panel to identify four priority societal and scientific goals associated with the hydrologic cycle:

BOX 3.3 MONITORING GROUNDWATER USAGE WITH RADAR INTERFEROMETRY

Modern development and increases in population have placed such great demand on water resources that in many places we have now fully exploited easily accessible sources of surface water. Where surface supplies are limited, we often draw upon water stored in underground aquifers to meet our needs. Groundwater already provides half of U.S. drinking water and serves as a critical supply during times of drought. Moreover, it is essential for agriculture and industry. Large-scale exploitation of groundwater resources has led to concerns about the future availability of groundwater to meet growing needs. While surface waters can be monitored and thus managed and regulated, the stocks, flows, and residence times of groundwater are poorly known. Recently, several U.S. states have enacted laws to assess and manage groundwater reserves.

Effective water management must, over the long term, maintain sustainability of groundwater aquifers. In practice this means, for groundwater systems that drain to and support river systems, that water withdrawal does not exceed the recharge rate and does not greatly reduce stream flows. In both cases, a measurement of subterranean water pressure in the aquifer, known as hydraulic head, is the critical metric needed to decide on and monitor actions. The standard approach to monitor head in an aquifer is to record water levels in wells and surface subsidence using leveling and a precise Global Positioning System (GPS). However, these usually infrequent and sparse point measurements do not resolve seasonal variations, especially over the full extent of the reservoir.

Fortunately, changes in head often produce measurable subsidence or uplift at the surface; hence repeat-pass radar interferometry (Interferometric Synthetic Aperture Radar, or InSAR)-derived deformation over time yields head estimates at the vastly greater coverage and finer resolution of a spaceborne sensor. Thus, the

BOX 3.3 Continued

potential of a radar satellite mission is that it permits temporally and spatially denser head estimates than can be obtained using wells; moreover, it can yield such data worldwide. Once calibrated with local well-based measurements, InSAR observations assimilated into a predictive model to predict future head levels. Over the past decade InSAR has moved from a research tool to monitor all types of surface deformation into a mainstream applications tool for monitoring seasonal and secular variations in vertical ground motion associated with groundwater withdrawal and recharge. The technique is now used routinely by the U.S. Geological Survey (USGS) for regional studies (Figure 3.3.1), as well as by many state and local water authorities to help monitor groundwater resources.

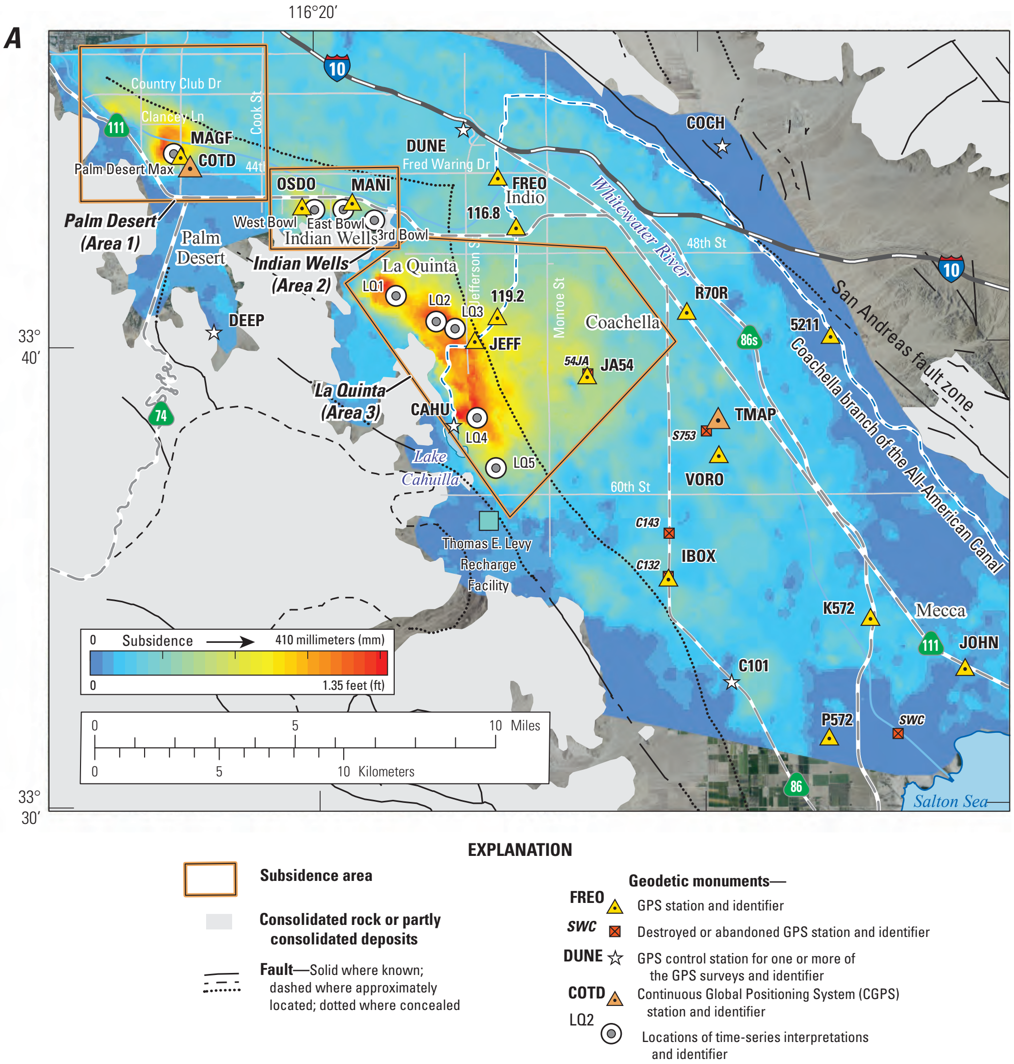


FIGURE 3.3.1 Surface subsidence of regions in the Coachella Valley caused by groundwater withdrawal between 1995 and 2010. The greatest subsidence occurred in the most developed areas of Palm Desert, Indian Wells, and La Quinta, where most of the water is used by households and to irrigate about 125 golf courses. The subsidence map is based on 93 radar interferograms constrained by GPS point measurements. SOURCE: Figure and analyses provided by USGS (Sneed et al., 2014).

1. Coupling the Water and Energy Cycles;
2. Prediction of Changes;
3. Availability of Freshwater and Coupling with Biogeochemical Cycles; and
4. Hazards, Extremes, and Sea-Level Rise.

Related to the preceding four goals, the panel identified 13 science and application questions, and within these questions ranked the following four objectives as Most Important:

- *(H-1a) Interaction of Water and Energy Cycles.* Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance from headwater catchments to continental-scale river basins.
- *(H-1b) Precipitation.* Quantify rates of precipitation and its phase (rain and snow/ice) worldwide at convective and orographic scales suitable to capture flash floods and beyond.
- *(H-1c) Snow Cover.* Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide at scales driven by topographic variability.
- *(H-2c) Land Use and Water.* Quantify how changes in land use, land cover, and water use related to agricultural activities, food production, and forest management affect water quality and especially groundwater recharge, threatening sustainability of future water supplies.

Key Points Summarized by the Steering Committee

- The Hydrology Panel's highest priorities are to develop an integrated Earth system analysis and make the measurements of rain- and snowfall, as well as accumulated snow, in order to constrain the key inputs into that analysis. In the coming decade, these advanced analysis systems will be the central framework upon which most of the water cycle remote sensing observations will be combined to deliver high-profile science and applications information about the hydrological cycle and changes to this cycle.
- This priority evolves out of the recognition that the full character of precipitation and other critical information on surface energy and water fluxes required to address critical science and application objectives is needed on much higher spatial and temporal resolutions than can be practically addressed from spaceborne observations alone.
- Many hydrological variables require such an analysis system. The multifaceted character of precipitation is one example where duration of precipitation events and total water output requires the integration of snapshot observations into a dynamic analysis system. ET is another example. This energy flux explicitly couples the water and energy cycles at the surface and is a net result of a number of complex processes that cannot be synthesized from any single remote sensing measurement alone.
- It is imperative, and an urgent challenge for the next decade, to accurately monitor the timing, amount, phase (snowfall or rain), and vertical structure of hydrometeors of precipitating systems globally and with sufficiently high space and time resolution to detect and quantify change at the river basin scale.
- In the coming decade, use of space-based observations has the potential to be revolutionized by the possibility of advancing process understanding so as to properly assimilate precipitation information in advanced high-resolution models used to forecast precipitation.

- Thus, a strong case can be made that observing variables central to key processes, like hydrometeor vertical velocities, will provide the required constraints to make high-quality model-based analyses and forecasts of precipitation at 1 km and 15-minute time steps a reality.
- Observations of all aspects of mountain hydrology are also a major challenge that has not been adequately addressed. For example, estimating the spatial distribution of the extant snow water equivalent (SWE) in mountainous terrain, which is characterized by high elevation and spatially varying topography, is an important but unsolved problem.

Weather and Air Quality: Minutes to Subseasonal

Progress over the last decade has given scientists a deeper understanding of, and capability to model and predict, the entire coupled Earth system. Satellite observations, combined with data assimilation and numerical prediction models, are now essential components in the fully coupled Earth system framework. Working from an Earth system framework is also essential for extending weather and air quality forecast skill beyond a few weeks (NASEM, 2016a). The societal benefits associated with achieving significant increases in weather skill, and extending skill to longer lead times, will be large (Box 3.4).

The panel identified and prioritized 10 science and application questions. Those with objectives ranked Most Important are listed here:

- *(W-1) Planetary Boundary Layer.* What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean, and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations?
- *(W-2) Extending Forecast Lead Times.* How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months?
- *(W-4) Convection and Heavy Precipitation.* Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?
- *(W-5) Mitigating Air Pollution.* What processes determine the spatiotemporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?

Continual increases in model resolutions enable better representation of the processes central to answering these questions and their underlying objectives. Consequently, observations central to these objectives require higher spatiotemporal resolution of the most basic atmospheric quantities, including profiles of temperature, humidity, wind, and atmospheric composition, along with quantitative surface characterization (e.g., snow, sea ice, surface temperature, soil moisture) and key physical process information. The latter includes diagnostic and validation information associated with clouds (liquid and ice phase), convection, and precipitation. In all cases better characterization of uncertainties in the observations is needed both for scientific inquiry and data assimilation purposes. Data assimilation, especially for coupled systems (e.g., atmosphere-ocean and atmosphere-land), also needs to advance in parallel to observations in order to blend model and observations delivering information on a higher time and space resolution.

Planetary Boundary Layer

The PBL has broad importance to a number of Earth science priorities. Profiles of thermodynamics and wind within it address important weather priorities. Many of the same sorts of PBL observations needed to advance weather and climate prediction would also enable improvements in our ability to track and predict the distribution of trace gases in the atmosphere. The addition of aerosol and ozone coupled to this advanced profile data would improve understanding and prediction of severe air pollution outbreaks that

BOX 3.4 KEY CHALLENGE AREAS FOR WEATHER PREDICTION

Advances in Earth science and applications will occur throughout the decadal survey interval in part due to the evolution of more sophisticated analysis systems and technology innovation. For weather forecasts, advances in the coming decade will come from scientific and technological innovation in computing, the representation of physical processes in parameterizations, coupling of Earth system components, the use of observations with advanced data assimilation algorithms, and the consistent description of uncertainties through ensemble methods and how they interact across scales. This progression is illustrated in Figure 3.4.1. The ellipses indicate key phenomena relevant for numerical weather prediction (NWP) as a function of scales between 10^{-2} and 10^{4} km resolved in numerical models and the modeled complexity of processes characterizing the small-scale flow up to the fully coupled Earth system. The boxes represent scale-complexity regions where the most significant challenges for future predictive skill improvement exist. The arrow highlights the importance of error propagation across resolution range and Earth system components.

Forecasts are central to NOAA's products and services, which affect more than one-third of U.S. gross domestic product and include daily weather forecasts and information valued at more than $600 billion (Lazo et al., 2011), navigational tools, disaster response, and science to enable the nation's $208 billion fisheries industry (National Marine Fisheries Service, 2017). Accurate weather forecasts save lives, prevent economic losses from high-impact weather, and create substantial financial revenue in many sectors of society such as energy, agriculture, transport, and recreational sectors.

Going forward, a key challenge will be developing accurate predictions for extended timeframes. As noted in a recent report from the National Academies, "as the nation's economic activities, security concerns, and stewardship of natural resources become increasingly complex and globally interrelated, they become ever more sensitive to adverse impacts from weather, climate, and other natural phenomena. Developing the capability to forecast environmental conditions and disruptive events several weeks and months in advance could dramatically increase the value and benefit of environmental predictions, saving lives, protecting property, increasing economic vitality, protecting the environment, and informing policy choices" (NASEM, 2016a, p. 17). These advances depend on progress made on the connecting elements called out in Figure 3.4.1, which, in turn, require mutual advances in models, data assimilation, and observations.

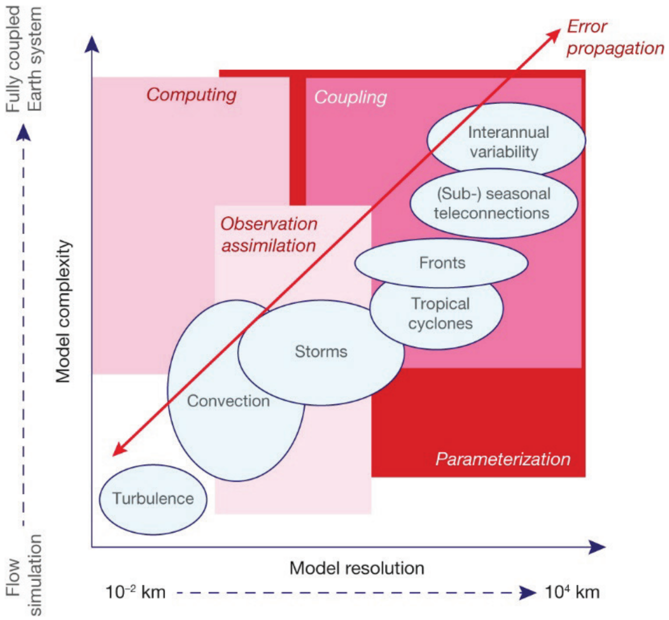


FIGURE 3.4.1 The notional process for advancing weather forecast skill. SOURCE: From Bauer et al. (2015).

affect human health, as discussed in the 2016 report *Future of Atmospheric Chemistry Research* (NASEM, 2016b). Advanced PBL measurements would improve our understanding of the exchanges between the biosphere and the atmosphere, and likewise the air-sea exchanges of chemical and energy fluxes. Better understanding of these exchange processes is critical for our understanding of biogeochemical cycles, impacts of climate change on ecological systems, and estimates of carbon storage in natural systems, among many other applications.

The profiling of thermodynamics and clouds in the boundary layer and across it into the free troposphere is relevant to low cloud feedbacks. The need for accurate, diurnally resolved, high vertical resolution in water vapor profiling in and across the boundary has now been elevated as an Essential Climate Variable by GCOS.

Accurate and high-resolution measurements and better understanding of boundary layer processes are of key importance for improving weather and climate models and predictions. As an example, recent development of the Next-Generation Global Prediction System (NGGPS) requires better understanding and modeling of the coupling among the atmosphere, surfaces waves, ocean, sea ice, and land in the integrated Earth system. The 2016 report *Next Generation Earth System Prediction: Strategies for The Subseasonal to Seasonal Prediction* (NASEM, 2016a) also identifies a number of boundary layer observations that would advance our prediction capabilities. The Weather and Air Quality Panel also identified important linkages between the PBL to other panels and Integrating Themes: (1) the PBL interacts with surface processes, which are important to the objectives of the Hydrology Panel, the Ecosystems Panel, and the Climate Panel (through near-surface atmospheric quantities such as wind speed, precipitation, aerosol and trace gases, and air-sea-land surface fluxes) and (2) subseasonal-to-seasonal prediction will bridge the weather and climate continuum and relate to hazardous event preparedness and mitigation via long-lead forecast information (e.g., floods, droughts, wildfire potential). The strategy requires a combination of space-based observations, and expansion of aircraft and ground-based observations, in conjunction with data assimilation and numerical modeling representing the 3D structure of the PBL.

Subseasonal to Seasonal Prediction

The second high-priority area reflects the goal to extend environmental predictions to seamlessly predict Earth system conditions at lead times of 1 week to 2 months. The specific objective is to improve the observed and modeled representation of natural, low-frequency modes of weather/climate variability, including upscale interactions between the large-scale circulation and organization of convection (e.g., Madden-Julian Oscillation of weather [MJO], El Niño Southern Oscillation [ENSO]) so as to reduce prediction errors by 50 percent at lead times of 1 week to 2 months. The panel identified the following steps required to advance this objective:

- Developing/improving the initialization of atmospheric variables;
- Developing optimal strategies for initializing deterministic and ensemble subseasonal forecasting systems;
- Constructing initial conditions that better utilize satellite data in cloudy and precipitating regions, where significant challenges remain in data assimilation methodology;
- Reducing systematic model errors in the underlying physical processes and subseasonal relevant phenomena that affect subseasonal forecast skill;
- Developing coupled atmosphere-land-ocean data assimilation methodologies;
- Determining optimal verification strategies, including measurements and metrics, for subseasonal forecasts; and
- Translating subseasonal forecast information into actionable information for societal benefits.

Convection

The third area of high importance is atmospheric moist convection, which exerts profound influences on our weather and climate. Life on Earth is tightly bound to the major convective storm systems that are found throughout the tropics and midlatitudes. Convective storms deliver the majority of the freshwater in the form of rain and snow and are a principal source of life-threatening severe weather. Predicting the occurrence and location of convective storms, and how they evolve into severe weather, is critical for accurate forecasting of many forms of weather and hazardous weather in particular. In addition to its role in local severe weather, convection also impacts the large-scale atmospheric circulation. The organization of convection and its coupling to the larger scale flows of the atmosphere is fundamental to understanding the principal phenomena that influence weather on subseasonal to seasonal time scales, which then influence weather across the globe.

Over the next decade, the spatial resolution of weather and climate models will increase to a point where cloud and convective processes will be explicitly resolved in varying degrees, in contrast to Earth system models of today. High-resolution weather and climate modeling is necessary to make reliable projections of rainfall extremes that are important for flood forecast risk, and hence for informing decisions regarding urban planning, flood protection, and the design of resilient infrastructure. More advanced observations about convective processes will be needed in parallel to these model advances.

Adverse Effects on Air Quality

Exposure to elevated levels of ambient air pollution is the largest environmental health risk factor globally leading to premature death. Air pollution also has a range of detrimental effects on ecosystems. Regulatory agencies charged with assessing and mitigating pollution levels need improved observing systems for air pollutants, and improved understanding of the transport and chemical processes relating emissions to impacts. This requires the establishment and maintenance of a robust, comprehensive observing strategy for the spatial distribution of particulate matter (PM; including speciation), ozone, and nitrous oxide along with a modeling strategy that quantifies how pollution is transported. It is a challenge to provide observations from space-based platforms alone, especially given this information is needed near ground level. The strategy requires a combination of space-based observations, and expansion of aircraft and ground-based observations, in conjunction with chemical transport modeling to deduce surface levels of air quality.

Key Points Summarized by the Steering Committee

- Advances in weather prediction over a range of time scales requires a comprehensive set of observations of meteorology and atmospheric composition, along with parallel advances in modeling and computation methods to assimilate data into numerical weather and air quality models.
- The PBL has broad importance to a number of Earth science priorities. Resolving the 3D structure of the PBL is an unmet but important challenge, as the PBL not only influences weather prediction and air quality forecasts but also is inherent to many other high-priority objectives connected to other panel priorities.
- The specific measurements needed to advance subseasonal prediction include either sustained observations or enhanced time-space resolution observations of (1) the 3D atmospheric state, including temperature, humidity, and winds; (2) the atmospheric boundary layer; (3) a number of surface characteristics and processes; and (4) advanced observations of atmospheric convection, including its mesoscale organization.
- Atmospheric convection exerts a profound influence on our weather and climate, influencing cloud, precipitation, atmospheric composition, and extreme weather processes.

- Accurately characterizing the levels of air pollution exposure globally, and developing effective strategies to mitigate the risks, relies on a combination of satellite information, atmospheric models, and ground-based observations, and an understanding of the dynamics of the boundary layer and atmospheric transport.

Marine and Terrestrial Ecosystems and Natural Resource Management

Land and ocean ecosystems are essential to human well-being, providing food, timber, fiber, and many other natural resources. Healthy ecosystems also help support clean air, clean water, and biodiversity among a wide range of benefits often referred to as “ecosystem services.” Ecosystems play a pivotal role in the planet’s cycling of carbon, nutrients, and water as well as energy exchange with the atmosphere. One key aspect is the removal of excess carbon dioxide by the ocean and land biosphere, acting to slow the buildup in the atmosphere of a major greenhouse gas. Ecosystem questions are thus closely related to climate, weather, hydrology, and solid Earth questions.

Information on ecosystems, and how they are changing over time, is increasingly relevant to decision making by individuals, businesses, and governments. In part, this decision-making need reflects the fact that human activities and ecosystems are so often closely intertwined. Many ecosystems are directly managed by people: croplands and rangelands for agriculture; forests harvested for timber; wetlands and coasts used for fishing, aquaculture, and protection from flooding; and coral reefs that support valuable tourism and recreation industries. The boundary between natural and managed ecosystems is becoming more blurred with time. For example, the threat of wildfires is changing with time, because of past land management decisions, because of choices about investments in suppression, and because communities commonly begin to abut forests and rangeland as they grow.

The Ecosystems Panel identified 15 science and application objectives corresponding to 5 questions. Priorities related broadly to the composition and dynamics of both land and freshwater/marine ecosystems, and how composition and dynamics are evolving with time in response to human and natural perturbations. Several of the priority ecosystem objectives spring from a growing body of evidence that ecosystem function depends in a variety of ways on vegetation and plankton composition, how the ecosystem is organized in space, and the factors governing photosynthesis or primary production. Five central interrelated objectives, four identified as Most Important and one as Very Important, are summarized here:

- *(E-1a) Distribution.* Quantify the distribution of the functional traits, functional types, and composition of terrestrial and shallow aquatic vegetation and marine biomass, spatially and over time.
- *(E-1b) Structure.* Quantify the three-dimensional (3D) structure of terrestrial vegetation and 3D distribution of marine biomass within the euphotic zone, spatially and over time.
- *(E-1c) Primary Production.* Quantify the physiological dynamics of terrestrial and aquatic primary producers.
- *(E-2a) Fluxes of CO_2 and CH_4.* Quantify the fluxes of CO_2 and CH_4 globally at spatial scales of 100 to 500 km and monthly temporal resolution with uncertainty <25 percent between land ecosystems and atmosphere and between ocean ecosystems and atmosphere.
- *(E-3a) Flows Sustaining Ecosystem Life Cycles.* Quantify the flows of energy, carbon, water, nutrients, and so on, sustaining the life cycle of terrestrial and marine ecosystems and partitioning into functional types.

Remote sensing has allowed for bulk measures of land vegetation cover (Box 3.5) and phytoplankton biomass (Box 2.8, in Chapter 2) as well as the rate of primary production. Only recently, however, has hyperspectral imaging technology advanced sufficiently to distinguish different types of plants and plankton (Devred et al., 2013; Gregg and Rousseaux, 2017). This information is critical to improve estimates of primary production, nutrient, and carbon cycling. It will also improve our understanding of how ecosystem variations propagate upward through food webs (for example, how changes in plankton influence fisheries). Similarly, new active lidar-based sensor technologies open up opportunities to characterize ecosystem properties in the vertical dimension, yielding insights on tree-canopy height and plankton distributions in and below the mixed layer.

Ecosystems are open systems that exchange material and energy with the atmosphere and other parts of the biosphere and Earth system. Better understanding of the magnitude and causes of these flows are critical for addressing many Earth system scientific questions and linking into integrative themes on the global carbon cycle. A specific example highlighted by the panel is characterizing the sources and sinks of key greenhouse gases, such as CO_2 and CH_4, with the atmosphere, as part of an effort to constrain climate forcing and develop the tools for carbon accounting.

Key Points Summarized by the Steering Committee

- Human well-being is closely tied to healthy ecosystems, which provide a wealth of direct and indirect benefits to society.
- Better information on ecosystem composition, functioning, and fluxes will support improved scientific understanding, applications, and decision making.
- Significant improvements in the characterization of ecosystems are now possible, in terms of both functional traits and vertical structure of vegetation and plankton biomass.
- Characterizing the exchange of greenhouse gases between ecosystems and the atmosphere is an essential part of understanding the global carbon cycle and climate forcing.

Climate Variability and Change: Seasonal to Centennial

The Climate Panel considered a range of processes that act across time scales: short-lived processes relevant to weather, processes that shape interannual variability, processes relevant to important modes of decadal variability, and longer time-scale processes associated with anthropogenic climate change. On decadal time scales, oceanic variations can imprint themselves on atmospheric weather patterns, leading to seasonal- and decadal-scale regional shifts and changes in the occurrence of both regularly occurring weather patterns and extremes like droughts and floods. Forecasting these shifts, and their societal impacts, is now an active area of research and one of the grand challenges of climate science.

Climate variability across these time scales has tremendous impacts on society. Understanding them requires observations for monitoring Earth, so as to quantify what changes are occurring, and to explore the mechanisms through which these changes occur. Advanced Earth system models provide an important tool for accomplishing these goals, through their ability to disentangle the interactions most responsible for the changes being observed.

The six objectives identified by the panel as Most Important were associated with the following two questions:

- *(C-1) Sea-Level Rise.* How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?
- *(C-2) Climate Forcings and Sensitivity.* How can we reduce the uncertainty in the amount of future warming of Earth as a function of fossil fuel emissions, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in

BOX 3.5 TRACKING CHANGES IN FOREST BIOMASS

Earth's forests contain a vast amount of carbon. Recent estimates put the total carbon in trees at 450-650 billion tons (Ciais et al., 2013). This is equivalent to more than half the quantity of carbon in carbon dioxide in the atmosphere, or the amount in approximately 45-65 years of industrial emissions, at current rates. Carbon emissions from the clearing of forests represent one of the largest anthropogenic sources of greenhouse gases. In recent years, forest clearing has released about 10 percent as much carbon dioxide as fossil energy and industrial activity, and fires associated with climate change are increasing. On the other hand, forests and other terrestrial ecosystems not subjected to clearing have been operating as substantial sinks, annually taking up an average of 33 percent of the carbon dioxide from fossil fuels and industry (Le Quéré et al., 2016).

Because the stocks and fluxes of forest carbon are both large, understanding their future trajectory is a central challenge in climate change science. If forests become stronger sinks for carbon in coming years, then the pressure for rapid decarbonization of the industrial sector moderates. If they become weaker sinks or transition to sources, then the opposite is true. Incomplete knowledge about the future behavior of forests is one of the largest uncertainties in setting a safe schedule for bringing carbon dioxide emissions to zero. But in addition, the emergence of a carbon economy means that forest biomass has an additional benefit beyond the traditional values of habitat and wood products. Many parts of the world have active discussions or operational programs that allow countries and individuals to make forests key mechanisms in the portfolio of strategies they use to manage their carbon emissions. The California forest offset program, for example, provides a way for landowners to realize substantial incomes from protecting or increasing forest carbon (Kelly and Schmitz, 2016).

Both the science questions and the management options require accurate quantification of forest biomass. Improving the accuracy and coverage of biomass estimates has been a major triumph of the last decade, with satellite remote sensing playing a central role. Quantifying forest carbon stocks and fluxes is always a multistep challenge, involving small-scale, ground-based measurements for detailed process studies and calibration, plus satellite data for broad coverage. Usually, mathematical models are necessary for connecting observables at different scales. Often, aircraft data are important in validating concepts at intermediate scales and for testing concepts for later deployments on satellites.

The current state-of-the-science in global forest mapping was published by Hansen et al. (2013), showing that, from 2000 to 2012, the world lost 2.3 and gained 0.8 million square kilometers of forest (Figure 3.5.1). The team used Google Earth Engine to analyze over 600,000 Landsat 7 ETM+ (Enhanced Thematic Mapper Plus) scenes, coupled with high-resolution imagery for validation, to produce global maps of tree cover at 30 m spatial resolution. Fire is one of the largest sources of forest loss and also one of the biggest unknowns for the future. A new Moderate-Resolution Imaging Spectroradiometer (MODIS)-based analysis of global fire activity (Andela et al., 2017) finds a 24 percent decrease in area burned annually from 1998 to 2015, likely contributing to the forest carbon sink during that period.

Other technologies have the potential to improve the accuracy and depth of analysis. Information on atmospheric carbon dioxide, now available from measurements from Orbiting Carbon Observatory-2 (OCO-2), can be combined with models to constrain the locations and magnitudes of carbon flux (Hammerling et al., 2012). OCO-2 and other sensors add further information with the capability of quantifying chlorophyll fluorescence, a proxy for instantaneous carbon dioxide uptake (Frankenberg et al., 2014). Imaging radar, evaluated in space on a shuttle mission in 1994, can provide detailed information on biomass (Rignot et al., 1997). One of the most powerful techniques, lidar, has been used extensively from aircraft (Gonzalez et al., 2010) and has been successfully integrated with satellite data to provide high-resolution forest biomass maps at the scale of entire countries (Asner et al., 2010). The efficacy of radar and lidar for biomass assessment are the basis for the upcoming NASA-ISRO synthetic aperture radar (NISAR) and Global Ecosystem Dynamics Investigation (GEDI) missions in the Program of Record (POR), and the European Space Agency (ESA) Biomass radar mission, also in the POR. Hyperspectral data have also been widely deployed and validated from aircraft platforms (Asner et al., 2017), establishing their utility especially in diverse forests.

BOX 3.5 Continued

As the carbon economy grows, the value of accurate satellite-based assessments of forest carbon will grow in parallel.

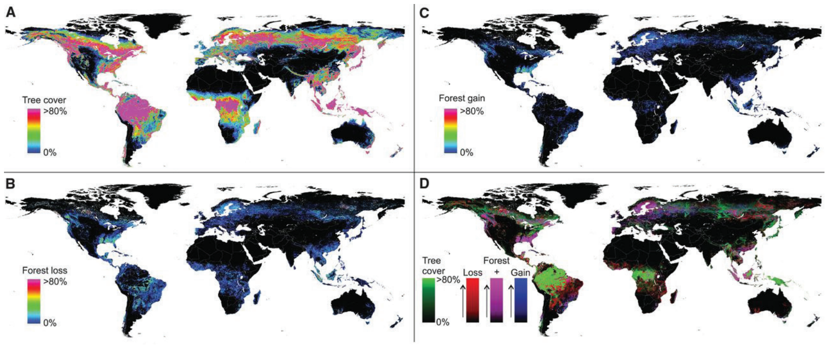


FIGURE 3.5.1 (A) Tree cover, (B) forest loss, and (C) forest gain. (D) shows a color composite of tree cover in green, forest loss in red, forest gain in blue, and forest loss and gain in magenta. In panel D, loss and gain are enhanced. SOURCE: From Hansen et al., 2013.

global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?

Sea-Level Rise: Land-Ice Contributions and Ocean Heat Storage

Global sea-level rise is one of the integrated responses of the Earth system to increased heat stored by the planet, with potentially significant impact on society's security and prosperity. Given an expected increase of approximately 25 cm to 1 m of global mean sea-level rise by 2100, and absent appropriate adaptation, 0.2 to 4.6 percent of the global population is expected to be flooded annually with expected annual losses of 0.3 to 9.3 percent of global gross domestic product (Hinkel et al., 2013). Accurate projection of sea-level rise is essential for managing these risks. Sea-level rise is tightly coupled to several aspects of the Earth system (see Figure 1.2 in Chapter 1), and advances in predicting future change require scientific progress on a complex array of poorly understood interactions. As a result, there is a wide spread in twenty-first century projections of sea-level rise.

The two main contributors to sea-level rise are (1) loss of land ice (mountain glaciers and the Antarctic and Greenland ice sheets) and (2) thermal expansion of the sea water as its temperature increases.[4] Sustained monitoring of both ice loss and heat input, in conjunction with sea-level rise monitoring, is required to quantify these two factors. Understanding the relative contributions to global sea-level change in terms of ocean warming and mass changes has been made possible by simultaneous global observations of the sea surface height from satellite altimetry (TOPEX/Poseidon and the Jason series), ocean mass from satellite gravimetry (GRACE), and ocean density from Argo floats (Box 3.6).

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[4] Changes in land water storage also contribute to change in sea level. They are the dominant contributor to sea level during El Niño Southern Oscillation (ENSO) events and have a significant contribution to the long-term trend. Contributions to sea-level rise are discussed in Chapter 3, "Contributions to Global Sea-Level Rise," in NRC (2012).

Climate Forcings

There are two basic types of aerosol forcing, aerosol *direct* effects defined by aerosol influences mostly on sunlight and aerosol *indirect* effects where aerosol affects the energy balance of Earth through their effects on clouds. Of these two forcings, the aerosol indirect effect contributes by far the largest uncertainty. The coupling of cloud, precipitation, and aerosol observations available from the A-Train (Box 2.9, in Chapter 2) and integrated into model studies has enabled a deeper understanding of aerosol indirect effects and revealed the complex nature of the problem that involves various pathways primarily determined by cloud physical and dynamical processes. Our understanding of the processes and complex interactions relevant to all aerosol cloud interactions is still rudimentary, and the cloud-aerosol impacts cannot be deciphered from observations alone because of the inherent ambiguity associated with assigning a cause to an observed effect.

Climate Sensitivity and Climate Feedbacks

The amount of warming of the Earth system that occurs due to a given level of greenhouse gases is substantially determined by the climate feedbacks that act to define the eventual response to any given radiative forcing (Box 3.6). This response is referred to as Climate Sensitivity (CS) and is defined as the amount of global average temperature change per change in effective radiative forcing (IPCC, 2013). Climate sensitivity is an aggregate result of contributions from a wide range of feedback processes including clouds, water vapor, temperature lapse rate, surface albedo, and carbon cycle. Its uncertainty is one of the largest challenges for predicted future economic impacts of future emission scenarios (SCC, 2010). Model simulations with high climate sensitivity and large (negative) aerosol forcing, as well as simulations with low climate sensitivity and small (negative) aerosol forcing, are able to fit past temperature changes but differ significantly in their prediction of future temperature (Penner et al., 2010).

Cloud feedbacks, in particular, are the largest source of uncertainty in determining this sensitivity (IPCC, 2013). Cloud processes also have far reaching influences across the climate system. They exert a significant influence on the mass and energy balances over ice sheets (e.g., Von Schuckmann et al., 2016) and sea ice (Kay and Gettleman, 2009); they are a fundamental conduit of freshwater; and in the form of convection, they are instrumental in producing weather extremes and in shaping the modes of seasonal-interannual variability. The panel's quantitative objective to "reduce the uncertainty in low and high cloud feedback by a factor of 2" (Objective C-2a) reflects the large uncertainty in feedbacks involving high and low clouds. Two measurement approaches to advance this topic were identified:

- *Development of Observational Metrics Against Which the Feedback Can Be Assessed.* This typically involves cloud observations, sustained over decades, matched to top of atmospheric radiative flux observations.
- *Quantification of Processes.* The largest cloud feedback uncertainties are those attached to low and high clouds. High cloud feedbacks are strongly shaped by convective processes and, in turn, the way convection is shaped by the atmospheric circulation (Bony et al., 2015). Low cloud feedbacks are intrinsically connected to the main branches of the atmospheric circulation and the interaction of this circulation with the planetary boundary layer.

Precipitation is an essential aspect to both feedback processes, as it shapes the life cycle of clouds, controls effects of aerosol on them, and couples to the dynamical atmosphere via the latent heating produced.

Carbon cycle feedbacks, especially over land surfaces, rival those of the physical climate system (IPCC, 2013). In reality, the feedbacks that control water and energy exchanges within the physical system on short time scales are fundamental components of the carbon feedbacks that operate over much longer time scales.

BOX 3.6 THE ENERGY IMBALANCE OF EARTH

The Earth's Energy Imbalance (EEI) is a fundamental measure of our warming planet. Earth is presently gaining energy at a rate of about 0.5-1 W/m^2, owing to increasing concentrations of greenhouse gases (GHGs). This increased heat uptake is mostly occurring in the world's oceans and is challenging to measure directly. Our current direct measurements of radiation balance at the top of the atmosphere are not accurate enough to quantify this small energy imbalance. Alternative methods are thus needed to address this fundamental property of the Earth system.

As over 90 percent of the EEI is stored in the oceans, we currently rely on in situ measurements of ocean temperature change from Argo floats to deduce this imbalance. Direct measurements, however, have some limitations, raising a number of questions about how much of the heat is stored at depths not reached by Argo. As shown in Figure 3.6.1, simultaneous global observations of the sea-surface height from satellite altimetry (the JASON series) and ocean mass from satellite gravimetry (GRACE), in conjunction with ocean density from Argo floats, have made it possible to understand the relative contributions to global sea-level change in terms of ocean warming and mass changes (and equivalently estimate the increased energy being stored in the global oceans). Altimeter and gravimetry data, when compared to Argo, agree with each other within statistical uncertainties (IPCC, 2013; Llovel et al., 2014). These data suggest that most of the heat taken up by the ocean is stored within the top 2000 m of the ocean (Llovel et al., 2014).

The approach to estimate the total heat uptake of the oceans using a combination of altimeter and gravimetry measurements is currently the most promising way of meeting the space-based monitoring needs of this very elementary property of our warming planet. This information, when combined with in situ profile data from Argo and deep Argo, offers a comprehensive way of determining both how much heat is mixed into the oceans and where this heating is stored within the water column.

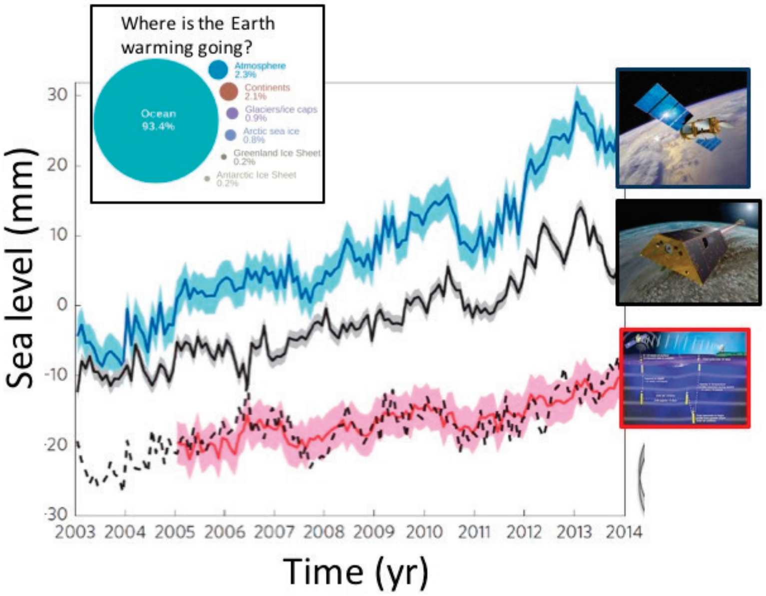

FIGURE 3.6.1 More than 90 percent of the enhanced heating by greenhouse gases is being taken up by the oceans. This heating contributes a large fraction of the observed sea-level rise. The global mean sea-level variations are observed variations by satellite altimetry (blue). The mass contributions from land sources (mostly ice sheets) are determined from Gravity Recovery and Climate Experiment (GRACE) data (solid black). The steric sea-level rise component (thermal expansion) is the difference (dashed black curve) and is independently estimated based on in situ observations (red) limited to ocean depths up to 2000 m. These data suggest that most heat uptake occurs over this depth of ocean. SOURCE: Llovel et al. (2014).

Key Points Summarized by the Steering Committee—Sea Level and Heat Content

- Although the change of the global mean sea level is now well determined from space-based measurements, maintaining and improving the sea-level measurement system is essential to understand the linkages between the ocean and the rest of the Earth system.
- A substantial amount of the uncertainty in estimating the rate of decadal change of sea level and ocean heat storage stems from the contribution of the heat storage component to the seasonal-interannual variability of the coupled atmosphere-ocean system.
- Our ability to predict the rate of sea-level rise in the future is compromised by a lack of quantitative understanding of the processes affecting sea level.
- The ice sheets account for one-third of the current trend in global mean sea level (Dieng et al., 2017). Greenland and Antarctica lose about 300 Gt/yr at present. An observational system that detects changes of the total surface mass balance at the 5 percent level (15 Gt/yr over the course of a decade) is needed to understand the interactions of ice in the Earth system at the regional scale and on a level that can test physical processes relevant to longer term change (NRC, 2015).
- Careful monitoring of Earth's radiation budget (the radiation energy in and out of Earth) continues to be essential for understanding many aspects of the changing Earth system. An important challenge is monitoring of the small energy imbalance associated with the warming of the planet, and new approaches to monitor the changes in heat content of the planet should be explored. The difference between the joint altimetric measurement of sea-level change and ocean mass change provides a direct estimate of the heat taken up by the oceans and thus represents an indirect means for monitoring change to the planetary heat content.
- Reliance on in situ Argo observations for deducing the planetary heat imbalance will continue. Improvements in these observations are needed to better represent the oceans, particularly the implementation of deep Argo to encompass the full water column to 6,000 m depth (Zilberman and Maze, 2015).

Key Points Summarized by the Steering Committee—Climate Sensitivity and Feedback

- The largest sources of uncertainty of climate sensitivity arise from feedbacks associated with low and high clouds. Improving our quantitative understanding of the connection between cloud and convection processes and clouds, water vapor, and the atmospheric circulation is essential for addressing these cloud feedback uncertainties.
- Direct observation of decadal time scale cloud feedback signals from Earth, as well as climate model predictions, requires improved accuracy and traceability to international standards for cloud property and radiative flux satellite observations.
- More rigorous approaches are needed to connect quantitative objectives for cloud process observations with specific quantitative cloud feedback objectives. A close association between observations and high-resolution cloud process models will be essential, and Observing System Simulation Experiments (OSSEs) based on these advanced model systems offer one viable approach to quantifying observational impacts. The effect of aerosols on clouds will influence the response of clouds to climate change, so quantification of this objective also requires understanding the effect of aerosols on clouds.
- Models of the Earth system are increasing in fidelity. Advances in cloud feedback will occur based on a closer coupling between observations and models to explore cloud processes over a spectrum of time scales, from weather to seasonal, and from interannual to decadal and longer.
- The coupling between carbon, water, and energy is central to understanding the carbon cycle and feedbacks that shape it.

Key Points Summarized by the Steering Committee—Climate Forcings

- The largest source of uncertainty in determining climate forcing in models is quantifying aerosol forcing, including aerosol-cloud interactions. Improving our understanding will require measurements capable of examining aerosol and cloud vertical profiles and sizes. Vertical profiles of aerosols are also essential for determining how and whether aerosols affect cloud microphysical properties.
- Because the direct aerosol impacts on radiative fluxes and ensuing climate variables are a strong function of where in the column they occur (whether high above the clouds and water vapor or lower in the atmosphere), measurement of the vertical profile of aerosol extinction is essential.
- Understanding aerosol-cloud-precipitation interactions requires observations of the aerosol-cloud-precipitation cycle. Better representation of clouds themselves in climate models is essential to advance cloud-aerosol interactions. Some progress can be expected in the coming decade because of more advanced model systems that are presently in development, but joint observations of clouds, aerosols, and precipitation will be needed to support these more advanced model systems.
- Improved aerosol measurements from space would also improve substantially our ability to determine the health impacts of aerosols (equivalently referred to as particulate matter), which are major environmental contributors to human mortality.

Earth Surface and Interior: Dynamics and Hazards

Continuous satellite observations of the solid Earth enable us to document, explain, and even anticipate Earth dynamics on an unprecedented range of spatial and temporal scales. Such dynamics include volcanic eruptions, earthquakes, landslides, ground deformation due to tectonics or large-scale groundwater extraction, changes in ice sheets and glaciers, sea-level change, erosion, large-scale tectonic uplift of mountains, and even variations in Earth's magnetic field. These phenomena motivate basic science questions and theories and also illuminate the urgent needs and opportunities for developing hazard reduction programs.

The panel identified the following key goals for sustained, high-density, space-based observation: (1) quantification of the nature and pace of solid Earth change; (2) characterization of the precursors, impacts, and key thresholds of disruptive events (e.g., volcanic eruptions or wildfires); (3) delineation of incremental change in Earth's life-sustaining surface (its "critical zone") in response to short-lived events and to sustained trends (e.g., more frequent droughts, permafrost loss, or ecological shifts); and (4) assessment of the impact of human activity on resources, environmental quality, sustainability, and habitability.

The panel identified seven science and applications questions (see Table 3.2), and within these broader questions ranked the following six objectives as Most Important:

- *(S-1a) Volcanic Eruptions.* Measure the pre-, syn-, and post-eruption surface deformation and products of Earth's entire active land volcano inventory with a time scale of days to weeks.
- *(S-1b) Seismic Activity and Earthquakes.* Measure and forecast interseismic, preseismic, coseismic, and postseismic activity over tectonically active areas, on time scales ranging from hours to decades.
- *(S-2a) Response to Disasters.* Rapidly capture the transient processes following disasters for improved predictive modeling, as well as for response and mitigation through optimal retasking and analysis of space data.
- *(S-3a) Sea-Level Change.* Quantify the rates of sea-level change and its driving processes at global, regional, and local scales, with uncertainty <0.1 mm/yr for global mean sea-level equivalent and <0.5 mm/yr sea-level equivalent at resolution of 10 km.
- *(S-3b) Coastline vertical motion.* Determine vertical motion of land along coastlines, at uncertainty <1 mm/yr.

- *(S-4a) Landscape Change.* Quantify global, decadal landscape change produced by abrupt events and by continuous reshaping of Earth's surface from surface processes, tectonics, and societal activity.

Volcanic Eruptions

Frequent satellite observations of volcanoes can be used to document changes in their shape, their emitted air chemistry, and both the temperature and composition of crater-lake or ground surfaces. Detected changes may precede eruptions by weeks to months, and thus be used in a warning system. Vertical precision of ground change detection needs to be 1 to 10 mm. Ideally, repeat frequency of observations could be adjusted to capture areas undergoing rapid change. Temperature and compositional estimates from hyperspectral observations would benefit from sampling intervals of hours to days.

Seismic Activity and Earthquakes

Earthquake prediction remains a grand challenge. Recent satellite-based observations have revealed transient slip phenomenon over periods of days to years that may shed light on the physics of earthquake cycles. Measurement of four types of phenomena will further advance the field: (1) crustal deformation between seismic events, (2) temporal variation in gravity associated with large earthquakes, (3) high-resolution bare-earth topography, and (4) high-resolution seismic activity and surface deformation (from terrestrial measurements). The length and time scale of quantification varies from 1 mm/yr, for interseismic motion, to 1mm/week for slow slip events and repeat measurements of less than 12 days over seismically active areas.

Response to Disasters

Devastating earthquakes, tsunamis, landslides, floods, and volcanic eruptions strike particular places and create a sudden local need for information to guide disaster response. Along with optical imagery, the suite of InSAR, high-resolution topography, and both hyperspectral and thermal infrared measurements from space provide an invaluable framework. This "rapid-response" objective will require the ability to redirect satellites, or the creation of a constellation of satellites to provide full Earth coverage.

Sea-Level Change

The need to quantify the rates of sea-level change and its driving processes at global, regional, and local scales is of great importance as discussed by the Climate Panel. Quantifying and understanding sea-level changes requires use of several satellite-based instruments including using radar altimeters over the oceans, and radar and laser altimeters over the ice sheets, along with GPS, InSAR, and GRACE gravity measurements. Gravity measurements provide critical information not only on the contributions of ice sheets and glacier systems to sea-level rise, but also changes and movement of mass throughout the Earth (Box 3.7).

Coastline Vertical Motion

The Earth Surface and Interior Panel identified the quantification of vertical land motion on local sea-level rise as profound but poorly constrained, and hence ranked its quantification as Most Important (S-3b). In many areas, land subsidence is the leading contributor to relative sea-level rise. Both natural and anthropogenic processes contribute to vertical land motion. GPS can be used to quantify vertical surface deformation at spatial scales on the order of 10 km or less. High-resolution (1 m horizontal and 10 cm vertical) global topography is needed to predict the path and magnitude of inundation across subsiding areas and during large storms.

Landscape Change

Earth's surface, which includes the ground surface and its vegetative mantle, is constantly changing. Many changes are slow, and even nearly imperceptible on the seasonal to yearly level. But sustained observations from space detect features such as the elevation change due to tectonics, the slow shifting of rivers, the movement of ice sheets, or the progressive change in vegetation accompanying regional climate shifts. In addition, much more abrupt changes in landscapes due to wildfire, earthquakes, landslides, floods, deforestation, urbanization, and agricultural practices can be uniquely quantified as a time series of change using sustained and continual satellite observations. Documentation of landscape change has wide application including providing insight for theory of landscape dynamics and evolution, information for hydrologic and climate models, ecosystem analysis, and data for hazard mapping and land management.

Terrestrial Reference Frame

In addition to the panel's six highest-priority objectives, there is a critical need for protecting and extending the Terrestrial Reference Frame, an observation infrastructure system that supports all satellite missions. An accurate global terrestrial reference frame provides the framework for positioning scientific satellites and aircraft, and underpins our commerce infrastructure. The reference frame must have a positional accuracy of 1 mm and a rate accuracy of 0.1 mm/yr. Such accuracy is achieved through a combination of

BOX 3.7 USING SATELLITE GRAVITY TO UNDERSTAND THE MASS CHANGE

Since its launch in 2002 the Gravity Recovery and Climate Experiment (GRACE) has provided unique insights with far-reaching benefits for understanding Earth system mass transport (Tapley et al., 2004; see Figure 3.7.1). By measuring gravity changes over the entire Earth, the GRACE mission produces monthly maps of how liquid water, ice, and solid Earth components are being redistributed within and between the ocean and the continents (Fasullo et al., 2013). This information has helped to understand and to quantify mass changes of ice sheets (Rignot et al., 2013) and mountain glaciers, water losses from lakes and underground aquifers (Rodell et al., 2015), and their overall contribution to sea-level rise. By mapping seasonal and year-to-year changes in water storage across the landscape, GRACE contributes to our understanding of the global water cycle. In addition, with a 15-year record of gravity measurements, it is possible to discern the comparatively small, but important, decadal trends associated with climate change (Johnson et al., 2013), postglacial rebound (Ivins et al., 2013), and the epoch-related mass redistribution associated with large earthquakes (Chen et al., 2007; Han et al., 2016).

Globally, sea level is changing mainly as a result of two processes: density changes due to temperature variations, and mass changes due to water mass input from ice sheets, glaciers, and changes in net land water storage. Before GRACE, it was not clear what portion each effect had on global sea-level change. GRACE gave insight into not only the magnitude of the mass component but also its sources and allowed an estimate of the heat absorbed by the ocean (Riva et al., 2010). The separation on the annual variability from the decadal trends in large underground aquifers identifies emerging problems and allows planning for resource management with regard to future water availability for agriculture and consumption.

Based on the significant advances in both measurement capability and the analytical framework during the mission life span of 15 years, GRACE data are now an essential asset for a number of operational applications, such as drought forecasting within the framework of the U.S. National Drought Monitor (Houborg et al., 2012). The ingestion of GRACE data by a Land Data Assimilation System allows significant improvement in the quality of the total terrestrial water storage estimates (higher spatial and temporal resolution). The near real-time provision of these products supports forecast and planning activities related to water use for agricultural and consumption purposes. Recent international efforts were initiated that use GRACE gravity observations for disaster

BOX 3.7 Continued

forecasting and management response (e.g., the multination European Gravity Service for Improved Emergency Management—EGSIEM). In addition to earthquake assessment and drought forecasting (http://nasagrace.unl.edu), the GRACE Total Water Column measurements provide crucial information for implementing a global early flood detection and prediction capability (http://egsiem.eu/project/introduction). These examples, which demonstrate the ability of the GRACE measurement as a unique tool to quantify Earth's mass change on a global basis as well as the ability to determine the distinct local components of the global mass change, underscore the importance of global gravity measurements in understanding the Earth system interactions.

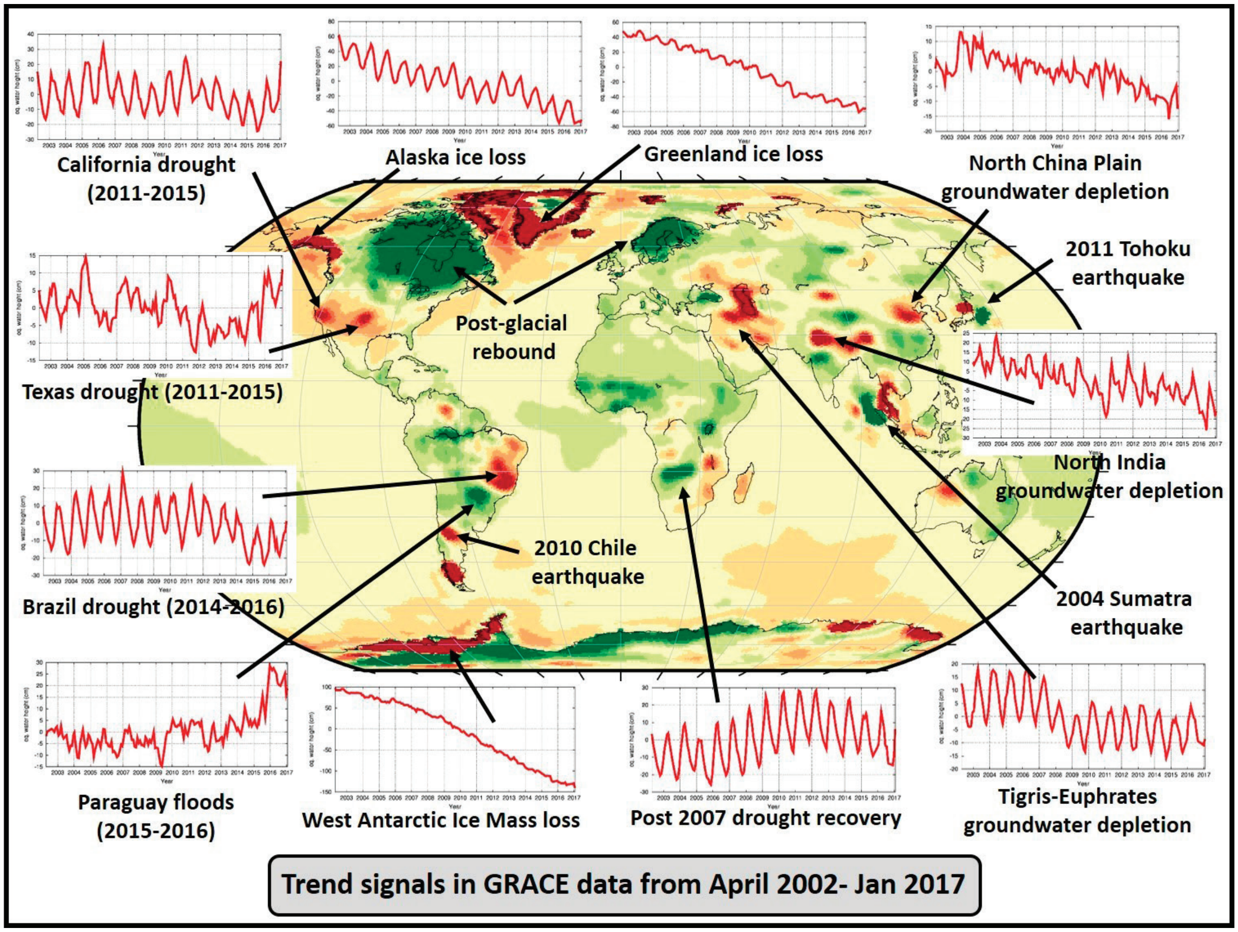

FIGURE 3.7.1 More than 15 years of gravimetric data from GRACE illustrate decadal mass change trends due to changes in total land-surface water storage and drought patterns; changes in snow, ice, and ocean mass; and changes due to post-glacial crustal rebound and large earthquakes. As shown in the local area records, each total signal involves a large annual signal with a much smaller longer-term trend. SOURCE: Prepared for the decadal survey by Byron Tapley, Himanshu Save, and Srinivas Bettadpur, 2017, from information in Save et al. (2016).

Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) (Davis et al., 2015). Sustaining this invaluable Terrestrial Reference Frame requires (1) maintaining global participation and funding support with other agencies/countries; (2) increasing capacity; (3) lowering cost; (4) upgrading older sites (some VLBI/SLR instruments are more than 30 years old); and (5) improving realtime capabilities for GPS/Global Navigation Satellite System (GNSS).

Key Points Summarized by the Steering Committee

- Key advances in understanding and predicting earthquakes, landscape evolution, landslides, volcanic eruptions, groundwater dynamics, ice sheets, sea-level rise, and other hazards and resources can be accomplished using satellite data with higher spatial resolution, expanded global Earth coverage, and higher temporal frequency of sampling.
- Measurements from space that are most important to accomplish these goals include InSAR, GPS, gravity, and hyperspectral observations.
- Satellite-derived high-resolution lidar to obtain high-resolution (1 to 5 m spatial resolution) bare-earth topography globally remains a top priority, but is not yet technically feasible.
- Maintaining and improving the global Terrestrial Reference Frame is critically important.

Integrating Themes Perspective on the Assessment

It is important to examine the science and applications priorities not only from the perspective of the five panels, but also from an Earth system science perspective, which establishes a more multidisciplinary view of the science and applications being recommended. In part, this system perspective ensures that important topics do not “fall through the cracks” between panels, that we independently assess our choice of science and applications priorities, and that we adequately address the breadth and depth of Earth system science. An Integrating Theme analysis allowed the committee to reexamine the work of the panels, reinforce the importance of key topics, and uncover new science or applications not revealed by a single thematic perspective alone.

As described earlier in this chapter, the integrating themes were addressed in a workshop attended by members of the steering committee and representatives of each of the panels. The workshop focused on four topics: (1) water and energy cycle, (2) carbon cycle, (3) extreme events, and (4) miscellaneous topics exploring other important aspects of the Earth system that do not necessarily fit under the previous three topics. The miscellaneous category included topics such as sea-level rise, tipping points, and human health.

The strategy for placing disciplinary science objectives into the broader framework of an integrating theme could have followed a number of directions. The approach adopted was to organize this discussion around the important physical cycles of the Earth system that are widely recognized as fundamental to understanding the Earth system and predicting its change. The three cycles of water, energy, and carbon served as main themes for connecting across panels. These three cycles have also served as the organizing framework of the grand Earth science challenges identified under the World Climate Research Program (Asrar et al., 2013) and as a structure for the planning of the Global Climate Observing System (Simmons et al., 2016). An additional integrating perspective was developed around the topic of extremes given the fundamental importance and visibility of extreme events to society. Though not comprehensive, these formed the basis for examining the panel priorities from a more integrated Earth system perspective.

Both the Integrating Themes Workshop and the series of panel deliberations further identified modeling of the Earth system as an important integrating theme. Models serve a fundamental basis for understanding the interactions between the subsystems that are essential in shaping the variability and changes of

Earth and its climate.[5] Observations are now increasingly being tied to modeling of the Earth system so as to disentangle the interactions and establish the causal relationships that determine them (see Modeling section in Chapter 4 for further discussion).

Extreme Events

Given the great impact and visibility of extreme events to society, the perspective of extreme events was thought by the steering committee to be an important way to consider the Earth system context of the panel's priorities. The potential for a change in the character of extreme events as the Earth system undergoes change has many important societal and economic impacts (Box 3.8). Extremes are by definition rare, and thus it takes longer time periods of monitoring and better resolution in both space and time to characterize long-term changes in extreme events. The development of high-resolution data from current archives is one important effort needed to address extremes.[6]

Carbon, Energy, and Water Cycles

The hydrological and carbon cycles of Earth and their interactions with the Earth energy balance are widely understood to be the foundation for understanding and modeling of Earth as a physical system. This view stems from the basic importance of water to life and the central and interactive role the cycling of water plays within the Earth system, as well as the seminal role of energetics as a physical basis for understanding of the evolving Earth system and partly through the widespread consequences of rising levels of carbon dioxide and methane in the atmosphere.

Water and Energy Cycle

The hydrological and biogeochemical cycles, and the energy cycle that couples to them, can no longer be considered to be changing solely due to natural variability. Anthropogenic influences on these cycles occur across a range of space and time scales. The terrestrial component of the global water cycle on the regional scale, for example, is highly managed. On the larger scale, the hydrological cycle is changing due to climate change, in ways that are not yet fully understood. One aspect of climate change is increased heat uptake by the global oceans. This heat uptake, together with an increased amount of freshwater added to the oceans associated with melting land ice, results in rising sea levels.

The water and energy cycle theme underpins a number of the most important topic areas identified across the ESAS interdisciplinary panels:

- *Global Hydrological Cycles and Water Resource Panel.* There are a number of important water-related variables that are central to the most important hydrological science challenges and to water resource applications. These include soil moisture, stream flow, lake and reservoir levels, snow cover, glaciers and ice mass, evaporation and transpiration, groundwater, water quality, and water use. High-resolution precipitation measurements, however, emerged as a high priority with the panel. Numerous discussions within the precipitation community, reflected in part by multiple white paper submissions to this decadal survey, indicate the need and desire to continue to (1) advance the

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[5] For example, the Intergovernmental Panel on Climate Change (IPCC) glossary formally considers that the inclusion of the biogeochemical carbon cycle distinguishes an Earth system model from the physical climate model, where the latter provides the coupling models of the atmosphere, ocean, land, and ice.

[6] A prioritization of the many challenges presented by extremes is given in the World Climate Research Program's Grand Challenges, available at http://www.gewex.org/about/science/wcrps-grand-challenges/.

BOX 3.8 HIGH-IMPACT WEATHER, CLIMATE, AND GEOPHYSICS EXTREME EVENTS HAVE A LARGE SOCIETAL IMPACT

High-impact weather, climate, and geophysical extreme events occur over a wide range of temporal and spatial scales (Figure 3.8.1), which have significant societal impacts (e.g., human health, food and water security, etc.). These are becoming more extreme as climate changes, with wildfires being a prominent example. We can and must advance our ability to better observe, monitor, and predict natural hazards and extreme events to meet society's needs in a changing climate.

There are common characteristics of extreme events across all time and spatial scales:

- They are usually the result of complex interactions among various processes from either within or among different components of the Earth system; and
- They are relatively rare, difficult to predict, and have high impacts on society.

Improvements in our ability to predict extreme events will come with further understanding of the fundamental physical and dynamical processes that underlie a given type of event.

Extreme events are often a result of concurrent occurrences of events from different components of the Earth system on different time scales. For example, landslides can be caused by extreme rainfall events over just minutes to hours. However, the conditions that lead to instability may develop over thousands of years as the landscapes evolve, or they can result from a recent disturbance such as deforestation that reduces the strength of the soil. Landslide predictions use topographic data (ideally high resolution), monitored and predicted precipitation, and estimates of hillslope material properties, partly controlled by vegetation. Flash floods and droughts occur from hours to seasonal and decadal time scales (Zhang, 2013). Observing and modeling the processes leading to these events requires knowledge of convective precipitation in the atmosphere, hydrological properties of soil moisture and river flow, and climate dynamic processes such as El Niño Southern Oscillation on interannual time scales.

There are many examples of using satellite observations proven to be effective in monitoring, managing, and responding to hazards and extreme events—for example, extreme lightning events (Lang et al., 2017), emergency mapping (Voigt et al., 2016), and satellite-based global landslide model (Farahmand and AghaKouchak, 2013). A wide range of high-impact extreme weather events is a focus of the international community.

The requirements for integrated Earth system observations and modeling for predicting high-impact extreme events are as follows:

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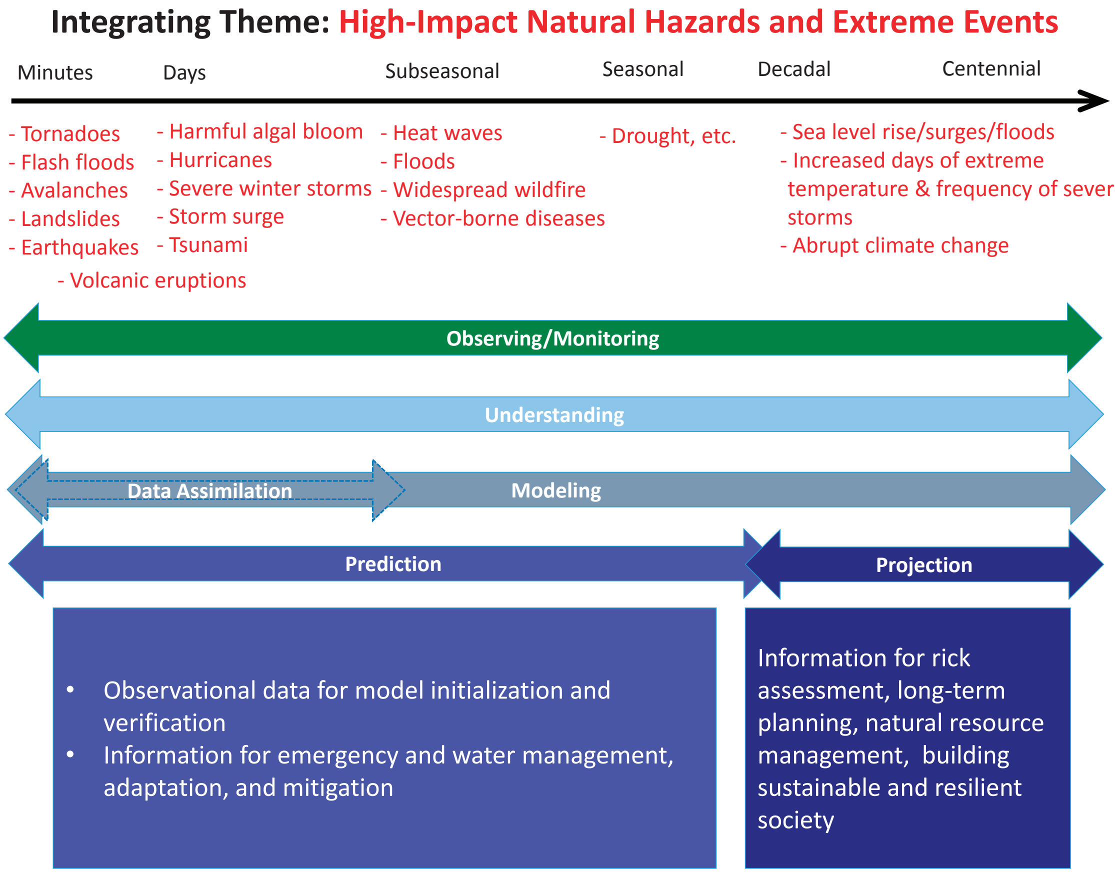
quality of space-borne instantaneous precipitation measurements not adequately covered by GPM and (2) improve the quality as well as space-time resolution of measurements of precipitation. For the latter, in particular, there is growing consensus that the key to success is better process-related observations coupled to fine-scale models. A second high-priority measurement that emerged is the surface flux of evapotranspiration, which is a flux common to both the water and energy cycles thus linking the two. The difference between surface precipitation and evapotranspiration (P-E) is considered a fundamental hydrological balance quantity being a measure of groundwater storage and surface runoff. The latent heat flux is an important component of the surface available energy and is a primary driver of the surface boundary layer that influences the coupling of the land with the atmosphere and a topic of high importance to weather and air quality.

BOX 3.8 Continued

- Observe state variables that best represent multiscale and multicomponent interactions leading to extreme events.
- Monitor global and regional trends of extreme events and impacts.
- Understand predictability of extreme events using advanced Earth system models.
- Quantify uncertainty and improve prediction and long-term projection of extreme events in a changing climate.



- Observational data for model initialization and verification
- Information for emergency and water management, adaptation, and mitigation

Information for rick assessment, long-term planning, natural resource management, building sustainable and resilient society

FIGURE 3.8.1 High-impact weather-climate extreme events occur on time scales from minutes to centuries and beyond. Observing, monitoring, and predicting these complex extreme events requires an integrated Earth system approach with interdisciplinary and transdisciplinary innovations to advance our capability to better understand and predict them and prevent natural hazards from becoming human disasters. This chart shows how Earth system observations, modeling, and data assimilation can be best used together for building a weather-climate prediction and long-term projection system to inform decision-making processes in response to natural hazards and to meet societal needs.

- *Weather and Air Quality Panel.* This panel identifies the advancement of weather prediction skill on subseasonal to seasonal (S2S) time scales as one of the most important challenges of the coming decade. The representation of physical processes in parameterizations, the coupling of Earth system components, and the use of observations with advanced data assimilation algorithms are essential ingredients for progress. Moist processes associated with atmospheric convection and the coupling of these to the atmospheric circulation largely determines the evolution of major modes of atmospheric variability on S2S time scales and principally establishes the precipitation patterns associated with these modes of variability. The PBL is also intimately connected to the water and energy cycles of Earth, as it is linked to surface processes that are important to the objectives of the Global Hydrological Cycles and Water Resources Panel, the Marine and Terrestrial Ecosystems and Natural Resource Management Panel, and the Climate Variability and Change Panel. These linkages are achieved through near-surface atmospheric quantities such as wind speed, precipitation, aerosol and trace gases, and air-sea-land surface fluxes of energy, water, and carbon.
- *Marine and Terrestrial Ecosystems and Natural Resource Panel.* Land vegetation plays a central role modulating surface energy and water fluxes. Water availability, in particular, shapes the distribution, productivity, and dynamics of terrestrial ecosystems. Different types of vegetation and the seasonal cycle of leaf cover modify the color or albedo of the surface, especially compared to bare soil or snow, and thus the fraction of solar radiation reflected back to space. Transpiration by plants strongly affects the partitioning of surface heat losses between sensible and latent heat flux and surface temperatures. Vegetation cover also influences the amount of precipitation reaching the surface, soil infiltration, and surface runoff.
- *Climate Variability and Change Panel.* Processes that couple water and energy are fundamental to the most pressing climate science challenges identified by the Climate Panel. On one scale, the increased amounts of heat being absorbed by the global oceans, together with an increased amount of freshwater added to the oceans associated with ice melt, results in the rising sea levels. Conversely, bulk measurements of the volume and mass changes of the oceans are a direct indicator of the planetary energy imbalance. Water-energy-coupled processes also shape the most influential climate feedback processes that determine the climate sensitivity through the profound and complex influences of water on energy flows within the Earth system. Water vapor feedbacks, carbon feedbacks, cryosphere feedbacks, cloud feedbacks, aerosol-cloud forcing, and precipitation are all essentially shaped by changes in the availability and state of water and the influence of these changes on the energy cycle. The two most important cloud feedbacks identified by the Climate Panel are associated with low and high clouds and how these clouds both connect to their environment and affect the radiation balance of Earth. Progress on these feedbacks requires process-scale observations of not only cloud properties, which include dynamical properties of clouds, but also convection and precipitation.
- *Earth Surface and Interior Panel.* Rainfall, snowmelt, and coastal storms drive erosional processes that evolve landscapes and generate hazards, and Earth surface characteristics—such as slopes, aspect, soil permeability, and the shape, orientation, and geometry of channels and basins—determine the terrestrial pathways of water. The Earth surface processes community is actively exploring the relationships between climate, tectonics, and topography. Higher quality precipitation observations, more resolved in space and time, will enable the advancement of mechanistic theories and hazard prediction. Landslides (see also Box 4.10, in Chapter 4) are most commonly caused by exceptional precipitation events, which lead to destabilizing pore water pressures on hillslopes, and to related issues such a gully erosion, topsoil loss, river-channel avulsion, bank erosion, and widespread flooding. Landslide warning programs have been developed that use precipitation forecasts, com-

bined with other information, to anticipate periods of potential landslide activity and landslide susceptibility, and to underpin enhanced early warning and mitigation efforts. NASA, for example, has recently launched the Landslide Hazard Assessment for Situational Awareness (LHASA) for determining regional landslide probability in near real time. LHASA provides web-based mapping of precipitation over various periods and the corresponding locations of potential landsliding.

Carbon Cycle

The natural carbon cycle and the human-driven perturbations form an integrating theme that is closely linked to water and energy cycles, biogeochemistry and the functioning of the land and ocean biosphere, and a broad range of human activities that include fossil-fuel use, industry, agriculture and forestry, and other human land uses. A central scientific focus is to document and understand the processes controlling the atmospheric levels of the greenhouse gases carbon dioxide and methane, information that is essential for improving projections of future climate forcing trends. Addressing the carbon cycle is a scientific grand challenge that requires integration across the physical, chemical, and human socioeconomic aspects of the Earth system, and the carbon cycle theme arises across a number of the most important topic areas identified by the ESAS interdisciplinary panels.

Present-day atmospheric carbon dioxide levels are nearly 45 percent higher than preindustrial conditions, acting as the single largest human factor contributing to global climate change. Currently, a little less than half of human carbon dioxide emissions stay in the atmosphere (IPCC, 2014), with the remainder removed into ocean and land reservoirs. Ocean uptake at present is predominately caused by dissolution of elevated atmospheric carbon dioxide into the surface ocean and subsequent physical transport into the deep ocean by circulation and storage through ecosystem processes. The terrestrial carbon storage sink is less well understood but reflects a mixture of carbon dioxide and nitrogen fertilization, climate change, land management, permafrost change, and forest regrowth. Looking forward in time over this century and beyond, the continued buildup of carbon dioxide in the atmosphere due to cumulative human emissions is expected to be the dominant anthropogenic climate forcing; feedbacks between climate change and the storage of carbon in land and ocean reservoirs are also important because they could amplify or dampen atmospheric carbon dioxide growth and warming. For example, the release of methane from thawing permafrost in the warming Arctic constitutes a strong positive feedback that further exacerbates warming, while increased vegetation growth at higher latitudes can increase carbon uptake, helping to reduce the rate of warming. Vegetation, however, can produce a darker surface, which in turn increases surface warming.

The carbon cycle theme underpins a number of the most important topic areas identified across the ESAS interdisciplinary panels, as follows:

- Both the Ecosystems and Climate panels prioritize science and applications related to the carbon cycle: the measurement of the fluxes of carbon dioxide (and methane, see the following) among the atmosphere, land, and ocean; the size and processes governing long-term terrestrial and ocean carbon storage; and carbon cycle-climate feedback mechanisms including possible thresholds such as carbon release from thawing permafrost.
- Other Ecosystems Panel priorities highlight observing key underlying carbon cycle dynamics, including the factors governing primary production by plants and phytoplankton and the connection of carbon fluxes to water, energy, and nutrient cycles. The direct link of carbon and water fluxes via evapotranspiration by land plants is also called out by the Hydrology and Weather and Air Quality panels, and the Hydrology Panel prioritizes characterizing the interplay of human land management practices and water quality and availability.

- Methane, an even more potent greenhouse gas than carbon dioxide on a per molecule basis, has accumulated in the atmosphere from the preindustrial era at an even faster relative rate than carbon dioxide. The causes of changes in atmospheric methane concentration are not completely understood but likely involve a combination of emissions from natural and managed wetlands, thawing permafrost, agriculture, and the natural gas industry. Methane is also linked to air quality through its importance in producing background tropospheric ozone.
- Atmospheric methane levels, fluxes with the atmosphere, and underlying natural biosphere and human methane sources are prioritized by three panels: Ecosystems, Climate, and Weather and Air Quality.

These integrating themes—(1) extreme events and (2) carbon, water, and energy cycles—provided a complementary multidisciplinary lens through which the panel priorities could be viewed. While these themes formed the core of cross- and multidisciplinary examination of the panel priorities, others were considered as well, including sea-level rise, atmospheric composition, tipping points, and human health. The recommended targeted observables, derived from the panel priorities and informed by these themes, address key priorities within and across disciplinary lines. In so doing, they focus the investments on making the most substantive advances in Earth system science possible.

The Coupled Dynamic Earth System Framework

Examination of panel priorities in the context of these sets of Integrating Themes enabled the steering committee to consider observation priorities in a broader interdisciplinary context—a critical complement to the rigorous panel prioritizations that occurred.

In the development and implementation of its programs, it is important that NASA continue to approach its Earth science missions and associated research in the context of their contributions to Earth *system* science. After all, it was the space-based perspective that brought into much sharper relief that Earth is a truly integrated system of complex dynamic interactions between the atmosphere, ocean, land, and ice across a range of spatial and temporal scales.

As a result, the Earth and our relationship with it can best be understood when we consider geophysical, chemical, and biological processes in the broader Earth system framework. Disciplinary focus remains crucial for understanding key processes in sufficient detail that their broader interactions and interfaces system can be examined, but it needs to be complemented by a broader Earth system view as a fundamental component of NASA's approach to its science activities. Such an approach will allow disciplinary phenomena to be translated to and understood in the context of matters of societal relevance.

The Integrating Themes approach provides consideration of physical, chemical, and biological processes in an Earth system context that (1) poses interesting scientific challenges; (2) integrates disciplinary elements of the Earth system into a broader framework to address larger and more comprehensive scientific challenges that are of relevance to society; and (3) provides an effective bridge between discipline-specific research and applications of direct societal relevance.

This approach is not new, but rather the culmination of progress over several decades. In the 1990s the emergence of a robust Earth Observing System (EOS) allowed us to begin viewing Earth as a system of interacting components. The space-based perspective enabled our examination of these components on global scales and allowed us to watch them evolve with time. The space-based perspective motivated characterization of their behavior, along with investigation of their interactions, with a view toward the ultimate goal of prediction or projection. Since that time, observational capabilities have improved considerably, our analytical tools such as regional and global models have advanced, our computational power to examine the vast amounts of data from satellites and other sources has become exponentially better, and our ability to examine and understand this integrated system as a whole has rapidly accelerated.

The convergence of advanced observation and analytical capabilities, as well as the three-decade evolution toward Earth system science, extends the integrated Earth system approach so that it is capable of addressing new and more complex problems. It is now possible to examine the dynamic coupling between parameters, as well as their direct and indirect interactions, which are both necessary for a full understanding of the Earth system.

These capabilities do not reduce our need to understand the underlying processes that govern individual components of the Earth system. The need for that disciplinary knowledge expands, since we can explore these fundamental Earth system elements in a framework that incorporates other detailed process knowledge, along with enhanced understanding of the couplings and interactions among those processes, how they change with time, and ultimately how they affect the trends and behavior of the Earth system. Such a system framework allows us to understand our Earth system at a level never before possible. As a result, we can better understand the mechanisms of change, the full range of impacts of change, and our role in the evolving behavior of the Earth system. The resulting understanding of the Earth system will position us to assess alternative adaptation pathways to a more resilient future.

ESAS 2017 OBSERVATION SYSTEM PRIORITIES

Following review of the science and applications priorities presented in the previous section, the steering committee proceeded to identify the requisite observations. As described earlier in this chapter, the observation needs arising from the science and applications priorities were first compared to the POR. Observation needs for the unsatisfied priorities were then aggregated and analyzed for commonalities. The resulting set of Targeted Observables—those observations needed by SATM priorities but not satisfied in the POR—is summarized in the Targeted Observables Table in Appendix C.

With limited resources, it was not possible to recommend all Targeted Observables from Appendix C for flight implementation. As described later, the committee identified those highest-priority observations that could be accomplished within the decade's available budget and defined a programmatic approach to implementing them.

The result is a comprehensive system of space-based observations, as appropriate for each sponsoring agency in accordance with the statement of task. The remainder of this section presents the proposed observation system, describes how it achieves the science and applications priorities within a realistic budget scenario, and defines existing and new agency program elements that can be used to implement the system.

A Comprehensive Observation System

The proposed observation system includes the POR,[7] which the committee assumes will be implemented as planned (and must be protected in the budget to do so), and the *additional* observations proposed in this chapter. The additional observations are relevant to all three agencies—NASA, NOAA, and USGS—from various perspectives, but all are anticipated to be implemented as instruments or missions under NASA's leadership. The extent to which NOAA or USGS participate in this NASA-implemented observing program is discussed in Chapter 4.

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[7] This system includes the ongoing operational satellite program of NOAA, to the extent that it contributes to the Program of Record (POR), as documented in Appendix A. In accordance with the statement of task (SOT), the committee did not consider changes or additions to NOAA's expected operational satellite system, except as on-ramp opportunities to augment the capabilities of that system.

TABLE 3.3 Observing System Priorities—Observations (Targeted Observables)

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Aerosols	*Aerosol properties, aerosol vertical profiles, and cloud properties* to understand their effects on climate and air quality	Backscatter lidar and multichannel/ multiangle/polarization imaging radiometer flown together on the same platform	X		
Clouds, Convection, and Precipitation	*Coupled cloud-precipitation state and dynamics* for monitoring global hydrological cycle and understanding contributing processes, including cloud feedback	Dual-frequency radar, with multifrequency passive microwave and sub-mm radiometer	X		
Mass Change	*Large-scale Earth dynamics* measured by the changing mass distribution within and between Earth's atmosphere, oceans, groundwater, and ice sheets	Spacecraft ranging measurement of gravity anomaly	X		
Surface Biology and Geology	*Earth surface geology and biology*, ground/water temperature, snow reflectivity, active geologic processes, vegetation traits, and algal biomass	Hyperspectral imagery in the visible and shortwave infrared; multi- or hyperspectral imagery in the thermal IR	X		
Surface Deformation and Change	*Earth surface dynamics* from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	X		
Greenhouse Gases	*CO_2 and methane fluxes and trends*, global and regional with quantification of point sources and identification of sources and sinks	Multispectral shortwave IR and thermal IR sounders; or lidar*		X	
Ice Elevation	*Global ice characterization* including elevation change of land ice to assess sea-level contributions and freeboard height of sea ice to assess sea ice/ocean/ atmosphere interaction	Lidar*		X	
Ocean Surface Winds and Currents	*Coincident high-accuracy currents and vector winds* to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift	Doppler scatterometer		X	
Ozone and Trace Gases	*Vertical profiles of ozone and trace gases* (including water vapor, CO, NO_2, methane, and N_2O) globally and with high spatial resolution	UV/VIS/IR microwave limb/nadir sounding and UV/VIS/IR solar/stellar occultation		X	
Snow Depth and Snow Water Equivalent	*Snow depth and snow water equivalent*, including high spatial resolution in mountain areas	Radar (Ka-/Ku-band) altimeter; or lidar*		X	
Terrestrial Ecosystem Structure	*3D structure of terrestrial ecosystem*, including forest canopy and aboveground biomass and changes in aboveground carbon stock from processes such as deforestation and forest degradation	Lidar*		X	
Atmospheric Winds	*3D winds in troposphere/planetary boundary layer (PBL)* for transport of pollutants/carbon/aerosol and water vapor, wind energy, cloud dynamics and convection, and large-scale circulation	Active sensing (lidar, radar, scatterometer); passive imagery or radiometry-based atmospheric motion vectors (AMVs) tracking; or lidar*		X	X

TABLE 3.3 Continued

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Planetary Boundary Layer	*Diurnal 3D PBL thermodynamic properties and 2D PBL structure* to understand the impact of PBL processes on weather and air quality through high vertical and temporal profiling of PBL temperature, moisture, and heights	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL (Differential Absorption Lidar); and lidar* for PBL height			X
Surface Topography and Vegetation	*High-resolution global topography*, including bare-surface land topography, ice topography, vegetation structure, and shallow water bathymetry	Radar; or lidar*			X

* Could potentially be addressed by a multifunction lidar designed to address two or more of the Targeted Observables.

Other ESAS 2017 Targeted Observables, Not Allocated to a Flight Program Element

Aquatic-Coastal Biogeochemistry	Radiance Inter-calibration	Surface Water Height
Magnetic Field Changes	Salinity	
Ocean Ecosystem Structure	Soil Moisture	

NOTE: As discussed in the text, priority observations (Targeted Observables) needed in the coming decade that are not provided via the current Program of Record are allocated as shown in the rightmost three columns of the table to one or more of three new NASA flight program elements: Designated (light green), Earth System Explorer (darker shade of green), and Incubation (darkest shade of green). Within categories, the Targeted Observables are listed alphabetically. Targeted Observables that were not allocated to a program element for implementation are listed at the bottom of the table.

Starting from the science and applications priorities jointly developed by the steering committee and panels (Table 3.2 and Appendix B), the steering committee (without panel participation) first identified a set of candidate Targeted Observables reflecting measurements needed to address the identified science and applications priorities that remained unaddressed by the POR. Appendix C provides a comprehensive table summarizing these candidate Targeted Observables.

From this candidate Targeted Observable list in Appendix C, the steering committee identified observing system priorities and developed a recommended flight program, consistent with science and applications priorities and budget constraints[8] and informed by an independent cost and technical evaluation process. The result is summarized in the ESAS 2017 Observing System Priorities Table (Table 3.3). Not all observables from the list in Appendix C were allocated to flight program elements. These unallocated Targeted Observables are listed at the bottom of Table 3.3. A description of opportunities to be considered for those listed as unallocated is described in subsequent text.

Within Table 3.3, Targeted Observables prioritized for implementation are allocated to one of three flight program elements (identified in the last three columns of the table and summarized in the above text). These flight program elements are as follows:

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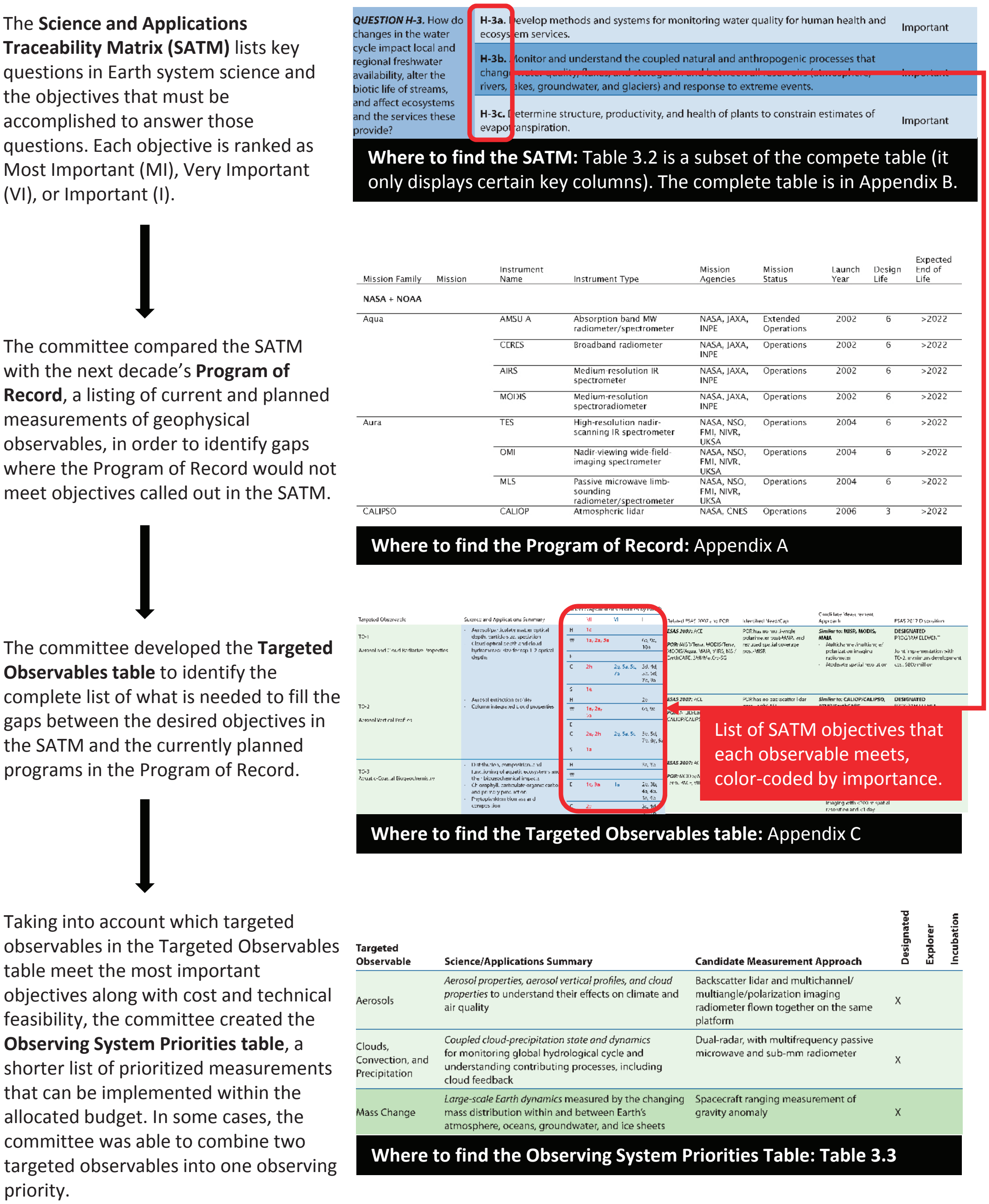
[8] All budget assumptions, and the approach to establishing a credible budget profile, were described at the beginning of this chapter.

TABLE 3.4 Summary of Newly Recommended and Existing Program Elements Referred to in This Report

Program Element	Description	Purpose
NEWLY RECOMMENDED PROGRAM ELEMENTS		
Designated	Cost-capped core elements of the program specifically recommended for implementation. Could be competed or directed.	Addresses five of the highest-priority Earth observation needs, including three large missions and two medium missions. Elements of this program are considered foundational elements of the decade's observation.
Earth System Explorer	Each competition seeks to address one of seven prespecified Targeted Observables with medium-size cost-capped missions (≤$350 million); three competition opportunities are recommended for the decade.	Addresses three key science and applications needs. The seven candidate Targeted Observables are not prioritized by importance; instead, competition is expected to drive innovation (technical and/or programmatic).
Incubation	Investments made in three Targeted Observables that are considered very high priorities for the 2027-2037 decade, but that are not currently ready for competition or directed implementation.	Focuses investments in key areas that are known to be priorities, that are not sufficiently mature for deployment at this time, but that would benefit from targeted investment. This differs from the standard NASA Earth Science Technology Office model in that it is specifically focused in three predetermined areas.
Venture-Continuity	New strand of the Venture program targeted at incentivizing low-cost continuity of existing measurements.	Provides opportunities for new and innovative ways to continue existing measurements, and seeks to address the tension between making new measurements versus continuing existing measurements by bringing forward innovative approaches to sustain measurements at lower costs.
EXISTING PROGRAM ELEMENTS		
Earth Venture Suborbital, Instrument, and Mission (EV-S, EV-I, and EV-M, respectively)	Unchanged from what was recommended in ESAS 2007, three strands targeted at new opportunities that emerge, with no prespecified science and applications area. Wide-open competition for any idea of merit.	Provide opportunities in any area of Earth science without restriction. Can potentially be used to address Targeted Observables not recommended in the three preceding categories, or any other topic that is sufficiently meritorious and viable, as deemed by the review process. Allows for agile responses to emerging science and applications topics.
Program of Record	Existing domestic and international program for which commitments are in place, with the full expectation that the missions contained in the program will fly.	Provides many needed Earth system science measurements, providing the foundation on which the recommended program is built. ESAS 2017 priorities were based on the assumption that every mission in the POR will be deployed.

1. *Designated Element.* Funding for observations identified as requiring dedicated flight opportunities, directed or competed at the discretion of NASA.
2. *Earth System Explorer Element.* Competitive opportunity for selected priority observations (identified in Table 3.2), implemented through a *new* Earth System Explorer program element.
3. *Incubation Element.* Investment for priority Targeted Observables needing technology advancement, requirements refinement, or other advances prior to cost-effective implementation, implemented through a *new* Incubation program element. This also includes a *new* Innovation Fund to enable program-level response to unexpected opportunities that occur on subdecadal time scales.

The three new NASA flight program elements, along with the existing program elements referred to in this discussion, are summarized in Table 3.4, which also illustrates their role in creating a comprehensive and robust overall observation program.



The **Science and Applications Traceability Matrix (SATM)** lists key questions in Earth system science and the objectives that must be accomplished to answer those questions. Each objective is ranked as Most Important (MI), Very Important (VI), or Important (I).

QUESTION H-3. How do changes in the water cycle impact local and regional freshwater availability, alter the biotic life of streams, and affect ecosystems and the services these provide?	**H-3a.** Develop methods and systems for monitoring water quality for human health and ecosystem services.	Important
	H-3b. Monitor and understand the coupled natural and anthropogenic processes that change water quality, fluxes, and storages in and between all reservoirs (atmosphere, rivers, lakes, groundwater, and glaciers) and response to extreme events.	Important
	H-3c. Determine structure, productivity, and health of plants to constrain estimates of evapotranspiration.	Important

Where to find the SATM: Table 3.2 is a subset of the compete table (it only displays certain key columns). The complete table is in Appendix B.

The committee compared the SATM with the next decade's **Program of Record**, a listing of current and planned measurements of geophysical observables, in order to identify gaps where the Program of Record would not meet objectives called out in the SATM.

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
NASA + NOAA								
Aqua		AMSU A	Absorption band MW radiometer/spectrometer	NASA, JAXA, INPE	Extended Operations	2002	6	>2022
		CERES	Broadband radiometer	NASA, JAXA, INPE	Operations	2002	6	>2022
		AIRS	Medium resolution IR spectrometer	NASA, JAXA, INPE	Operations	2002	6	>2022
		MODIS	Medium-resolution spectroradiometer	NASA, JAXA, INPE	Operations	2002	6	>2022
Aura		TES	High-resolution nadir-scanning IR spectrometer	NASA, NSO, FMI, NIVR, UKSA	Operations	2004	6	>2022
		OMI	Nadir-viewing wide-field-imaging spectrometer	NASA, NSO, FMI, NIVR, UKSA	Operations	2004	6	>2022
		MLS	Passive microwave limb-sounding radiometer/spectrometer	NASA, NSO, FMI, NIVR, UKSA	Operations	2004	6	>2022
CALIPSO		CALIOP	Atmospheric lidar	NASA, CNES	Operations	2006	3	>2022

Where to find the Program of Record: Appendix A

The committee developed the **Targeted Observables table** to identify the complete list of what is needed to fill the gaps between the desired objectives in the SATM and the currently planned programs in the Program of Record.

List of SATM objectives that each observable meets, color-coded by importance.

Where to find the Targeted Observables table: Appendix C

Taking into account which targeted observables in the Targeted Observables table meet the most important objectives along with cost and technical feasibility, the committee created the **Observing System Priorities table**, a shorter list of prioritized measurements that can be implemented within the allocated budget. In some cases, the committee was able to combine two targeted observables into one observing priority.

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Aerosols	*Aerosol properties, aerosol vertical profiles, and cloud properties* to understand their effects on climate and air quality	Backscatter lidar and multichannel/multiangle/polarization imaging radiometer flown together on the same platform	X		
Clouds, Convection, and Precipitation	*Coupled cloud-precipitation state and dynamics* for monitoring global hydrological cycle and understanding contributing processes, including cloud feedback	Dual-radar, with multifrequency passive microwave and sub-mm radiometer	X		
Mass Change	*Large-scale Earth dynamics* measured by the changing mass distribution within and between Earth's atmosphere, oceans, groundwater, and ice sheets	Spacecraft ranging measurement of gravity anomaly	X		

Where to find the Observing System Priorities Table: Table 3.3

FIGURE 3.4 Example of traceability from science and applications priorities (Table 3.2) to observing system priorities (Table 3.3), shown for the example of the Aerosols Targeted Observable. Each candidate Targeted Observable (in Appendix C) represents an observation need (as documented in Appendix B) not adequately addressed in the Program of Record (Appendix A). For each Targeted Observable in Appendix C, the steering committee then identified Observing System Priorities (Table 3.3) by prioritizing the Appendix C Targeted Observables based on consideration of the science and application importance and the implementation feasibility.

In addition, the committee is proposing an expansion of the Venture program elements to include a Venture-Continuity program element strand, focused on competitive opportunities for continuity observations with a goal of reducing cost. Candidates for the Venture-Continuity element could come from among Targeted Observables in Appendix C and Table 3.3, but are not explicitly identified as such. Each of these flight program elements is included in the funding wedge shown in Figure 3.4 and so can be implemented within anticipated resources. Details on these program elements, and the Targeted Observables to be implemented through them, are provided in the following text.

The seven Targeted Observables shown at the end of Table 3.3 were not allocated to any of the three program elements, but they are still considered important observations to implement in support of science and applications priorities identified in the SATMs. As the recommended flight program is implemented, it is expected that portions of the science for these unallocated observables will be addressed, particularly where similar measurement techniques are required to address both allocated and unallocated Targeted Observables. A more complete description of the disposition of these unallocated observables and the opportunities for pursuing their important underlying science is provided at the end of this section of the report.

The committee also recognizes that the focus on Targeted Observables, as opposed to missions and prespecified measurement approaches, does not lend itself to the consideration of multiple objectives being served by a single measurement technique. While this has the advantage of allowing for greater flexibility in implementation, it does not take full advantage of both the scientific and technical synergies that can develop from a more interdisciplinary framing. In particular, measurement technologies that address a particular Targeted Observable may likely also address others, and a careful evaluation of these opportunities should be built into the thinking and planning for flight program elements while respecting cost caps and guarding against mission creep leading to significant cost inflation.[9] As NASA proceeds with planning for the implementation of the recommended flight program elements, the effort will benefit from input from a wide interdisciplinary community to help identify benefits and trade-offs among different measurement approaches. Possible interdisciplinary opportunities can be identified where observing techniques are common among Targeted Observables in Table 3.3. Lidar is highlighted as a clear example.

Recommendation 3.2: NASA should implement a set of space-based observation capabilities based on this report's proposed program (which was designed to be affordable, comprehensive, robust, and balanced), by implementing its portion of the Program of Record and adding observations described in Table 3.3, "Observing System Priorities." The implemented program should be guided by the budgetary considerations and decision rules contained in this report and accomplished through five distinct *program elements*:

1. ***Program of Record.* The series of existing or previously planned observations, which must be completed as planned. Execution of the ESAS 2017 recommendation requires that the total cost to NASA of the Program of Record flight missions from fiscal year (FY) 2018 through FY 2027—October 1, 2017 through September 30, 2027—be capped at $3.6 billion.**
2. ***Designated.* A program element for ESAS-designated cost-capped medium- and large-size missions to address observables essential to the overall program, directed or competed at the discretion of NASA.**
3. ***Earth System Explorer.* A *new* program element involving competitive opportunities for cost-capped medium-size instruments and missions serving specified ESAS-priority observations.**

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[9] An example of both synergistic benefits and cost growth challenges is available through the lessons learned from the interdisciplinary scientific planning that emerged for the ESAS 2007 recommended Tier 2 Decadal Survey lidar mission known as the Aerosol/Cloud/Ecosystems (ACE) profiling lidar mission (ACE Science Study Team, 2016).

4. ***Incubation*. A *new* program element, focused on investment for priority observation capabilities needing advancement prior to cost-effective implementation, including an Innovation Fund to respond to emerging needs.**
5. ***Earth Venture*. Earth Venture program element, as recommended in ESAS 2007, with the addition of a *new* Venture-Continuity component to provide opportunity for low-cost sustained observations.**

The remaining text within this subsection, entitled "A Comprehensive Observation System," elaborates on this Recommendation 3.2, including (in sequential order) discussions on the following:

- *Prioritization Process.* Description of the prioritization process used to identify the recommended Targeted Observables.
- *Budget Considerations.* An overview of how the recommendation is structured to meet budget constraints, including guidance for how to leverage the budget for an aspirational program.
- *Observables Descriptions*. Descriptions of the Targeted Observables included within each program element (Designated, Earth System Explorer, Incubation, Venture-Continuity).
- *Opportunities for Non-Allocated Observables.* Clarification of the opportunities available for unallocated Targeted Observables, including a case study for the oceanographic community.

Prioritization Process

The Targeted Observables in Table 3.3 are responsive to the science and applications priorities (as measured by the Science/Applications Importance column) in Table 3.2, and ultimately to panel guidance addressing the science and applications as well as the needed observables. Table 3.2 was developed largely by the panels, but Table 3.3 was the responsibility of the steering committee without any direct panel consultation. Development of Table 3.3 from Table 3.2 involved two fundamental steps, listed here:

1. *Identify Observation Gaps.* Identify those gaps in the POR corresponding to observables needed to address highest-priority science and applications objectives. In practice this meant working directly with two large tables of data. The first is the Program of Record table (Appendix A). The second is the Science and Applications Traceability Matrix (Appendix B). By comparing the two tables, a list was developed detailing gaps in observing capability (i.e., needed observations not available in the next decade's POR) that are anticipated during the coming decade. The result of this effort was the Targeted Observables Table (Appendix C), which lists the 22 key unmet observation needs (referred to as Targeted Observables) in the next decade's POR, as identified by the committee.
2. *Prioritize the Observation Gaps.* Prioritization of the 22 Targeted Observables in Appendix C to derive the priorities in Table 3.3 was accomplished through extensive deliberation by the committee, with consideration of the following two factors:
    - *Scientific and Applications Priority.* The scientific and applications priority is summarized in the Science/Applications Priorities column of the Targeted Observables table (Appendix C). The entries in this column refer to lines in the Science and Applications Traceability Matrix (Appendix B). At a simple level, priority can be discerned by the total number of Science and Applications Priorities, along with the preponderance of Most Important and Very Important priorities. While the committee used this simple view for guidance, decisions were made through direct review of the original science/applications priorities in Appendix B.

- *Cost and Technical Feasibility.* With the assistance of The Aerospace Corporation, various implementations were assessed to understand the potential cost and feasibility of measuring each proposed Targeted Observable. Because the committee is recommending observations, rather than missions, the assessment performs the role of an existence proof rather than an implementation plan. Nevertheless, a comprehensive range of feasibility factors was considered, from technical readiness to flight heritage.

The committee focused on ensuring that this process is traceable and grounded in the guidance of the panels. While endeavoring to achieve objectivity to the extent possible, the process inevitably involves subtle and often subjective trade-offs among the preceding factors. The committee held discussions involving complex considerations to arrive at the priorities in Table 3.3. An important consideration for the committee was the extent of interdisciplinary (i.e., Earth system) benefit obtained from a Targeted Observable, as measured by the degree of cross-panel prioritization. In addition, the committee considered programmatic balance (see Chapter 4 for a description of balance considerations) to be a desirable aspect of the recommended program.

While an inherent subjectivity exists in any prioritization, the multiple diverse perspectives from the steering committee that led to Table 3.3, as well as the consideration of panel input as informed by RFI responses, has produced a set of recommendations that is appropriately balanced, informed, and reflective of societal and scientific needs.

As also discussed elsewhere in this section, the committee chose to not simply list the prioritized Targeted Observables but to group them according to three candidate programmatic implementations (Designated, Earth System Explorer, and Incubation), based on the suitability of each Targeted Observable for each approach. In a general sense, the size of the resource commitment is justified by the value of the science and applications, as summarized for each Targeted Observable in the Science/Applications Priorities column of the Targeted Observables table (Appendix C). The committee's overall goal was to maximize the amount and quality of the science and applications that can be achieved within constrained resources.

An example of the process is shown in Figure 3.4, illustrating the use of each of the key tables in development of the Aerosols Targeted Observable within Table 3.3.

Fitting Within a Realistic Budget

The committee had two fundamental strategic goals that guided its partitioning of the funds anticipated to be available for the Earth science program. The first goal is to achieve and preserve balance in the program portfolio by maintaining approximate ratios between each of the program elements. This is to be accomplished by application of the Decision Rules, which provide guidance on the cadence that elements in each program line should be implemented, as well as the possibility, if necessary, of modulating the schedule for development of the larger missions. The second goal is to control carryover into the next decade such that implementation of the large mission pipeline over the decadal boundary is maintained without deeply impacting the future funding wedge.

Figure 3.5 shows how the recommended program elements accomplish these two objectives and fit within the assumed profile of available funding.[10] This budget assumes spending of $3.4 billion on new

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[10] Recognizing there is a natural latency that occurs at the transition between decadal surveys, it was assumed that there would be some encumbrance beyond 2027 to complete this decadal survey's recommended program. The encumbrance equates to approximately all of the assumed available flight funding in 2028 (the first year post transition), falling to half and then less than a quarter of assumed available flight program funding in the second and third post-transition years, respectively. This approach, if followed for each successive decade, will ensure a full mission pipeline while also facilitating an earlier start for subsequent decadal surveys' priorities.

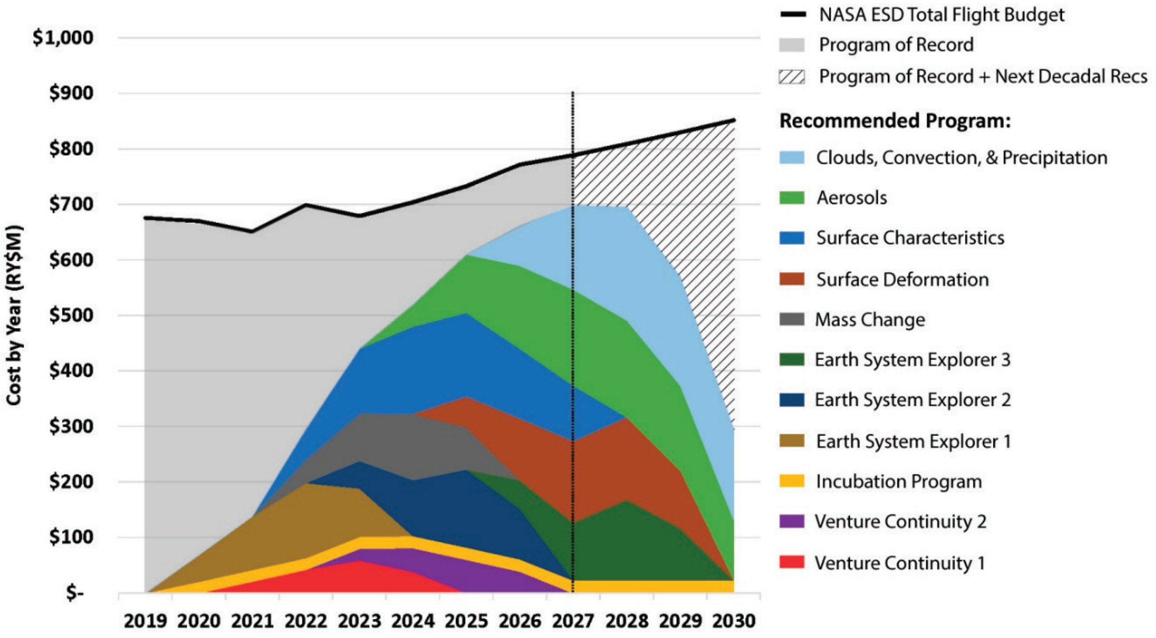

FIGURE 3.5 ESAS 2017 estimated costs (colored wedges), broken down by element, as compared to the anticipated flight budget (black line), showing how the ESAS 2017 costs fit within the available budget. The total NASA Earth Science Division (ESD) budget for flight elements assumes growth at the rate of inflation for years beyond the current budget projection. Budgets to support ESAS 2017 flight recommendations are shown for the Designated, Earth System Explorer, Venture-Continuity, and Incubation program elements described in Recommendation 3.2. ESAS 2017 estimated costs are phased to match the expected available unallocated funding wedge of $3.4 billion over the decade of 2017-2027, with a carryover of $1.7 billion into the following decade, as discussed further in the accompanying text. Only the investments related to ESAS 2017 recommendations are shown; the remainder of the ESD budget is allocated to existing projects and programs (see Figure 3.3). All values are in real-year (RY) dollars. The gap between the estimated costs and the available budget represent funds that have been committed to other mission-related activities.

programs (beyond the already allocated POR runout budget) during the coming decade, and *a lien on the following decade of $1.7 billion* due to flight programs starting late in the decade. Such liens are an accepted consequence of achieving continuity from one decadal study recommendation to the next, but minimizing the lien is desirable (NRC, 2015b). The lien proposed by ESAS 2017 is less than half of the $3.6 billion lien currently estimated to complete POR flight programs this coming decade that were started last decade.

As described in more detail in the remainder of this chapter, the recommended program includes funding for the following:

- *Designated.* Three large (two expected to be <$800 million in FY 2018, one expected to be <$650 million) and two medium (one expected to be <$300 million and the other expected to be <$500 million) cost-capped projects, directed or competed at the discretion of NASA.
- *Earth System Explorer.* Three competitively selected cost-capped (<$350 million) projects.
- *Venture-Continuity.* Two projects that are <$150 million each, selected competitively with a goal of reducing costs as compared to prior projects for the same observable.

- *Incubation.* Funded at $20 million per year to advance identified priorities for concept and technology maturation, including the Innovation Fund to enable program-level innovation.

Given the breadth of observations needed to address priorities in Earth system science and the expectation of comparatively austere budgets, the recommended program relies on competition as the core approach to controlling individual mission costs, through the use of cost caps combined with trades between performance and risk during the formulation and implementation stages of system development.

An Aspirational Program

The committee intended the proposed observing system to be realistically accomplished within nominal budget growth, with recommended investments stated in terms of the "maximum recommended NASA development cost" levels to ensure that program balance is maintained.[11]

For each program element, the included Targeted Observables were drawn from the nonprioritized list of Targeted Observables identified in Appendix C, and intended to address the science and applications priorities listed in that table. In order for implementations of Targeted Observables to remain within their respective cost caps, however, it is not expected that every science and applications priority identified in Appendix C will be achieved for each relevant Targeted Observable. Rather the implementation is expected to first target the highest currently unmet science and applications priorities, and address others as feasible.

That should not preclude NASA from trying to accomplish more, and the committee believes that NASA can and should do so. Indeed, the new Earth System Explorer program includes more than twice as many candidate observations as the committee believes will be implemented in this decade, and Appendix C suggests there are many more good candidates for flight opportunities such as Earth Venture. With an increased budget, an aspirational program could be pursued. More importantly, however, it is possible to be aspirational *within* the nominal budget—to get more done with the same amount of resources. NASA is quite adept at many of the ways this could happen, as shown here:

1. *International partnerships* that provide the same capability with reduced cost to NASA. Interest by several viable international partners was expressed to the committee regarding potential collaboration opportunities. Several of the priority observations included in the system are known to also be high priorities of these international partners, leading the committee to believe that partnering opportunities are quite promising.
2. *Technology innovation* with the potential to reduce cost for all aspects of space-based observation. The commercial sector (in addition to NASA and academia) is presently introducing a wide range of technology innovation capabilities with the potential to be leveraged by NASA for cost reduction.
3. *Programmatic innovation,* including public-private partnerships and spacecraft block buys, that accomplish the same goals with reduced resources.
4. Aggressive *cost management and requirements control* of programs being implemented.
5. *Extended operations* for continuity observations that delay the need for new missions.

A comprehensive effort within NASA focusing on these steps could reduce cost and generate the additional resources needed to expand the Earth System Explorer program element, complete the survey's high-priority observations more rapidly, or increase opportunities for continuity of key Earth system observations. Doing so would enable additional high-priority science beyond the baseline recommended

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[11] The maximum recommended NASA development cost is what is allocated from NASA's budget to cover the prelaunch (development phase) and launch vehicle cost for a mission to address the stated science and applications objectives. Development phase costs include reserves. Operations cost and associated research and analysis (R&A) funding are not included in this total.

by this committee. The key to achieving this aspirational program relies on managing costs through the approaches outlined in items 1 through 5 in the preceding list, and incentivizing mission development to be accomplished as far below the cost cap as possible.

Recommendation 3.3: NASA should manage development costs for each flight program element (including the Program of Record committed to prior to this report), and for each project within the Designated program element, so as to avoid impact to other program elements and projects.

- **Innovative cost reduction, through programmatic or technological advances and partnerships, should be sought and incentivized where possible.**
- **By the time of the Midterm Assessment, NASA should report on steps it has taken (e.g., use of innovative approaches or partnerships) to ensure cost-effective development in each program element, and if or how these steps translate to increased science opportunity across the program.**
- **NASA should consult its standing scientific advisory committees if the project cost of the Program of Record is expected to grow to consume more than $3.6 billion in the FY 2018-2027 decade, if more than one mission in this decadal survey is delayed more than 3 years, or upon premature loss of a mission in the Program of Record or one required to make the measurements of this decadal survey.**
- **When appropriate, cost-effective, and consistent with recommended cost caps, NASA should consider instrument and mission designs that can increase science/applications return by combining Targeted Observables having common measurement technologies.**

Program Element: Designated

The Designated program element represents a group of Targeted Observables believed by the committee to be of sufficiently high value to the Earth system science and applications communities to warrant designated implementation during the decade. This implementation could occur through directed guidance to the NASA Centers, through internal or external competition, or other means chosen by NASA ESD to achieve the most cost-effective solution.

Within the Designated program element, five Targeted Observables are recommended for implementation during the 2017-2027 decade. Table 3.5 lists these and indicates the maximum recommended NASA development cost, with science and implementation considerations discussed for each in the following sections. The maximum recommended development costs are not to be taken as expected development costs. Instead, the committee expects NASA to identify implementation approaches that achieve the recommended objectives for ***less than*** *the identified maximum.*

CATE Cost Confirmation

Consistent with other NASA space science decadal surveys, The Aerospace Corporation CATE process was applied to all concepts expected to cost more than $500 million, excluding operations costs.[12] For those expected to be less than $500 million, a cost analysis was performed to estimate a cost cap but no formal CATE was completed. For the three large (two <$800 million, one <$650 million) Targeted Observables in Table 3.5, notional proof-of-concept missions with the recommended capabilities were evaluated to ensure top-level technical and programmatic risks were understood. Aerospace found each of these proof-of-concept missions to be implementable within the listed cost cap.

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[12] As discussed earlier in this chapter, the Cost Assessment and Technical Evaluation (CATE) process is a formal cost and technical readiness evaluation, performed by The Aerospace Corporation. It is mandated for the decadal survey.

TABLE 3.5 Targeted Observables to Be Addressed Through the Designated Program Element, and Their Respective CATE-Confirmed or Estimated Cost Caps

Targeted Observable	Cost Cap ($FY2018)	Basis for Being Foundational
Aerosols	CATE Cap $800 million	Essential for air quality forecasting; provides critical insights into key radiative forcings, both direct and indirect (from cloud hydrometeor size and optical depth). When combined with Clouds, Convection, and Precipitation observations, enables assessment of aerosol effects on clouds and precipitation. Addresses many of the "Most Important" objectives of the Climate Panel and Weather and Air Quality Panel, along with key components of the water and energy cycle integrating theme.
Clouds, Convection, and Precipitation	CATE Cap $800 million	Critical for assessing low and high cloud feedbacks, and seasonal and interannual climate variability and its prediction, processes that are at the core of severe weather and extremes. Fundamental observations for water resource and hydrological applications. When combined with Aerosols observations, aerosol indirect effects can also be substantially advanced. Addresses many of the "Most Important" objectives of the Climate, Weather and Air Quality, and Hydrology panels, along with key components of the Water and Energy Cycle and Extreme Events integrating theme.
Mass Change	Estimated Cap $300 million	Ensures continuity of measurements of groundwater and water storage mass change, land ice contributions to sea-level rise, ocean mass change, ocean heat content (when combined with altimetry), glacial isostatic adjustment, and earthquake mass movement. Also important for operational applications, including drought assessment and forecasting, hazard response, and planning water use for agriculture and consumption. Addresses various "Most Important" objectives of the Climate, Hydrology, and Solid Earth panels and key components of the Water and Energy Cycle integrating theme.
Surface Biology and Geology	CATE Cap $650 million	Key to understanding active surface changes (eruptions, landslides, and evolving landscapes); snow and ice accumulation, melting, and albedo; hazard risks in rugged topography; effects of changing land use on surface energy, water, momentum, and carbon fluxes; physiology of primary producers; and functional traits and health of terrestrial vegetation and inland and near-coastal aquatic ecosystems. Further contributes to managing agriculture and natural habitats, water use and water quality, and urban development as well as understanding and predicting geological natural hazards and land-surface interactions with weather and climate. Depending on implementation specifics, the Targeted Observable may also contribute to hyperspectral open-ocean observation goals. Addresses many "Most Important" objectives of the Ecosystem, Hydrology, and Solid Earth panels, and addresses key components of the Water and Energy Cycle, Carbon Cycle, and Extreme Events integrating themes.
Surface Deformation and Change	Estimated Cap $500 million	Critical for assessing ice sheet stability and the potential for ice sheets to make large rapid contributions to sea-level rise. Key to mapping surface strain rates in order to understand earthquakes, volcanoes, landslides, and sea-level rise. Enables monitoring of tectonic plate deformation, changes in groundwater and subsidence, and thawing of permafrost. Directly addresses six "Most Important" and four "Very Important" objectives of the Earth Surface and Interior Panel, as well as one or more "Most Important" objectives of the Hydrology and Climate panels. Provides important insights into various components of the Water and Energy Cycle, the Carbon Cycle, and the Extreme Events integrating themes.

NOTE: These are listed in alphabetical order, with proposed development sequencing discussed in the text.

The CATE process is by its very nature conservative (NRC, 2015b). It does not, for example, incorporate innovative implementation approaches or account for partnership opportunities that have the ability to significantly lower the cost of implementation to NASA. For large (>$500 million) Targeted Observables listed in Table 3.5, the CATE process identified this cap as a cost category limit within which the observable could be implemented at acceptable risk. The actual estimated cost was always below the cost cap, suggesting the realistic expectation that each implementation can be completed for less than the cost cap values in Table 3.5 (potentially considerably less).

Implementation Sequence

Based on the relative costs and risks of the three higher-cost Targeted Observables, and the substantial synergy gained by obtaining overlap between the Aerosols and Convection and Precipitation Targeted Observables, the committee suggests that the order of implementation be (1) Surface Biology and Geology, (2) Aerosols, and (3) Clouds, Convection, and Precipitation. However, if opportunities present themselves that in NASA's judgment allow for a more effective implementation (through lower costs, better technologies, etc.), this implementation sequence should be flexible in order to be responsive to such opportunities. One reason for choosing the suggested sequencing is that cost-reducing opportunities, such as international partnerships, are particularly viable for Targeted Observables implemented late in the survey interval.

Cost Control

To further protect program balance, the committee expects that NASA will manage the Targeted Observables within the Designated program in such a way that the implemented missions adhere to their costs caps and do not adversely affect other elements of the flight program. To achieve this, the progress with developing and implementing these missions should be reviewed during the Midterm Assessment. The advantage of ensuring cost-effective investments, to NASA and its science/applications programs, is clear. When implementation can be achieved below the stated allocation (e.g., through innovative program implementation, partnerships, or other means), program breadth may be increased to address other identified priority observations consistent with the decision rules provided in Chapter 4.

Designated Targeted Observables

Each of the Targeted Observables in Table 3.5 recommended for the Designated program element is discussed in the following text, with Targeted Observables presented in alphabetic order. *The extent to which science and applications objectives of multiple panels are addressed within each Targeted Observable demonstrates the cross-disciplinary nature of the program.*

Aerosols

Earth Science/Applications Objectives for the Designated Targeted Observable: Aerosols

	Most Important	Very Important	Important
Hydrology	**1c**		**2b**
Weather	**1a, 2a, 5a**		**6a, 9a, 10a**
Ecosystems			
Climate	**2a, 2h**	**2g, 5a, 5c, 7a**	**3d, 4d, 5b, 5d, 7b, 8g, 9a**
Solid Earth	**1a**		

The Aerosols Targeted Observable corresponds to a combination of TO-1 and TO-2 in the Targeted Observables Table (see Appendix C). The IPCC 2013 Climate Change Assessment Report determined that uncertainties associated with aerosols and aerosol-cloud interactions are the largest radiative forcing uncertainty. Because of this, knowledge of their characteristics and processes is critical to reducing the uncertainty of future projections of climate change. As a result, aerosol observations are one of the higher priorities from the Climate Panel. In addition, the health effects from pollution are the largest environmental risk, and therefore aerosols are one of the most important boundary layer properties identified by the Weather Panel as essential both for air quality forecasting and for connecting health effects with pollution. Finally, aerosols, through their alteration of direct and diffuse radiation, change the amount of radiation available to ecosystems. The considered implementation of a backscatter lidar and multiangle, multispectral polarimeter would address important inputs for aerosol direct radiative forcing, and provide information that partially addresses indirect effects through aerosol effects on cloud hydrometeor size and cloud optical depth. These radiative forcings are a significant source of uncertainties in climate model projections. In combination with the Clouds, Convections, and Precipitation Targeted Observable, it would also address the additional aspects of the aerosol indirect effect (on clouds and precipitation formation), thus accomplishing key objectives of the ESAS 2007 recommended ACE mission.

- *Science Considerations.* Aerosol measurements are essential elements for understanding climate forcings and feedbacks. The types of systems that would contribute profiling (lidar) would also be capable of detecting height and optical properties of high thin clouds and cloud properties of lower thicker clouds, providing important information for cloud feedbacks in the climate system. In addition, such observations would provide information, critical for air quality forecasting, about aerosol profiles in the boundary layer. The information on clouds and aerosols would yield additional insights into cloud processes and processes that affect precipitation, particularly when Aerosols is flown simultaneously with a system for observing cloud, convection, and precipitation. As such, this observing system spans climate, weather, and air quality and directly maps to the water and energy cycles integrating themes.
- *Candidate Measurement Approaches.* The candidate measurement approach considered includes a lidar and a polarimeter. Expected lidar measurement implementations will provide aerosol extinction profiles and cloud top heights as well as vertical profiles of cloud occurrence in thinner clouds. The polarimeter provides aerosol/cloud properties information supporting science and applications objectives related aerosol/particulate matter optical depth, particle size, and some information on speciation. It also provides cloud optical depths and cloud droplet size (in the uppermost layer near cloud tops) and can distinguish between spherical cloud drops and nonspherical ice particles. The polarimeter also provides column-integrated information on aerosols that could be used to constrain lidar extinction profile estimates. Depending on implementation specifics, a lidar may also contribute to aquatic ecosystem structure, ocean mixed layer depth, ice-sheet topography, land topography, and PBL height. In particular, many of the scientific and technical opportunities and challenges for a joint aerosol-ocean measurement system have been mapped out in some detail as part of the planning for the ESAS 2007 Aerosol/Cloud/Ecosystems (ACE) mission (ACE Science Study Team, 2016). The recovery of upper-ocean plankton profiles from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) sensor indicates that, with appropriate consideration, the Aerosol Targeted Observable should also be able to address key aspects of the Ocean Ecosystem Targeted Observable TO-10 (Appendix B) and the associated high-priority science and applications objectives from the Ecosystem, Weather, and Climate panels (W-3a, E-1b, E-3a, C-2d, and C-8d).

The Aerosol Targeted Observable instrument and mission design, therefore, should seek to address these interdisciplinary objectives while recognizing that the primary mission focus is meeting the aerosol science objectives as described and remaining within the cost cap. Opportunities should be assessed to determine the extent to which these additional science goals can be achieved while also meeting the aerosol science objectives and maintaining overall costs at or below the recommended cost cap.

- *CATE Evaluation.* The CATE evaluation considered a reference concept consisting of a backscatter lidar and polarimeter. It found that the concept is based on mature technology and is consistent with a cost cap of $800 million or less (excluding operations). High Spectral Resolution Lidar (HSRL) was a desired capability as part of Aerosols, but cost and technical readiness considerations suggested it was incompatible with the recommended Aerosols cost cap.
- *Descope Options.* In the event development costs are expected to exceed the $800 million cost cap, the TO-1 and TO-2 Target Observables (Appendix C) could be instead included separately as candidates within the Earth System Explorer competition, using the available budget to fund two additional Earth System Explorer solicitations. This is preferred over descoping Aerosols to just one of the two (lidar and polarimeter) measurement techniques or to proceeding with a higher cost for the combined implementation.
- *POR Assumptions.* There are no dedicated atmospheric lidars in the POR after EarthCARE, which is expected to end in about 2022. The POR includes polarimetry from the European 3MI (Multi-viewing, Multi-channel, Multi-polarization Imager) instrument. Multiangle polarimetry will be provided by the Multi-Angle Imager for Aerosols (MAIA), but this measurement has limited coverage.
- *Partnerships.* NASA is encouraged to seek commercial or international partnership opportunities with the goal of reducing implementation costs and enabling overlap between the Aerosol and Clouds, Convection, and Precipitation efforts.
- *Budgetary Guidance.* In keeping with the guidelines of the Designated program element and this report's Recommendation 3.3, the Aerosols Targeted Observable has a maximum recommended development cost of $800 million (in $FY2018).

Clouds, Convection, and Precipitation

Earth Science/Applications Objectives for the Designated Targeted Observable: Clouds, Convection, and Precipitation

	Most Important	Very Important	Important
Hydrology	**1a, 1b, 1c**		**3b, 4b**
Weather	**1a, 2a, 4a**	**3a**	**9a, 10a**
Ecosystems	**3a**		
Climate	**2a**, **2h**	**2g**	**3f, 5d, 7e, 8h**
Solid Earth		**1c**	**4b**

The Clouds, Convection, and Precipitation Targeted Observable corresponds to TO-5 in the Targeted Observables table (Appendix C). Measurements associated with TO-5 are essential to advance understanding and prediction of cloud feedbacks, moist convection and its influence on weather and extremes, and the processes of precipitation, including important modes of precipitation not addressed within the POR. The Clouds, Convection, and Precipitation Targeted Observable also addresses priorities that emerged across multiple panel recommendations and from considerations of broader Earth science integration as, for example, described in the prior discussion of integrating themes.

Precipitation measurements and, notably, the combined information on cloud and precipitation processes to be addressed by the proposed measurements, are fundamental for addressing the high priorities of the Hydrology Panel, cloud feedbacks identified in the Climate Panel, and important topics on weather extremes. When combined with other measurements, such as those proposed to address the Aerosols Targeted Observable, other important objectives such as those associated with aerosol indirect effects can also be advanced.

TO-5 is motivated to address widely recognized critical challenges within Earth sciences. Clouds are a principal source of uncertainty in projections of climate change (IPCC, 2013, Assessment). These uncertainties are associated with low and high cloud feedbacks as described in the report from the Climate Panel (Chapter 9), and to the process of moist convection, which is a central theme of the cloud-climate sensitivity grand challenge of the World Climate Research Programme (WCRP,[13] Bony et al., 2015). Moist convection is also central to two high-importance weather priorities, being the essential building block of our major storm systems found throughout the tropics and midlatitudes. Convective storms are the sole source of precipitation in many regions of our planet and are major sources of severe weather and extreme precipitation. Measurements of the vertical distribution of cloud and precipitation properties, including measurements of water and ice contents, and other microphysical information, are essential for quantifying the processes that underpin the challenges of the Clouds, Convection, and Precipitation Targeted Observable and for better predicting the intensity of storms and extreme weather.

- *Science Considerations.* This observation will address science and applications goals related to cloud cover (with the assistance of the POR) and cloud property profiles (with the assistance of the POR and/or the Aerosols Targeted Observable), precipitation profiles, precipitation (including light rain and snowfall), diurnal cycle of precipitation (with the assistance of the POR), convective vertical motion or proxies of it, and cloud water and ice contents. When cloud and precipitation observations overlap with the aerosol measurements earlier, they can better address the aerosol indirect effect priority called out by the Climate Panel as high importance. This measurement is also a central component of the ACE mission identified in ESAS 2007. A short-pulse altimeter mode of operation of higher frequency radar could help measure snow depth on the ground, which is an important priority both of hydrology and to ice mass measurement objectives, though this capability should not be allowed to drive mission cost or complexity.
- *Candidate Measurement Approaches.* The expected radar measurements will provide joint cloud water and ice contents, rain and snow amounts, and Doppler motions within clouds and convection. The radar will also provide profiles of shallow and deep clouds and some information on microphysical properties through the combination of frequencies and Doppler. The radar is expected to be a dual frequency W-/Ka-band system. If the W-band radar includes an altimeter mode, it could also contribute to surface snow depth measurement needs; however, adding an altimeter mode to the W-band radar is not considered a priority and thus is not recommended if it drives cost. Cloud optical properties and diurnal cycle information will come from the POR observations of clouds from available advanced geostationary imaging radiometers. Time and spatial coverage of precipitation similarly relies on the microwave radiances data within the POR, and diurnal cycle coverage of precipitation could be anticipated if this POR is augmented in decade.
- *CATE Evaluation.* The CATE evaluation of a reference concept consisting of a dual-band radar building on CloudSat heritage found that the concept is based on mature technology and has the potential to be executed within a cost cap of $800 million or less (excluding operations). Recent

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[13] See the World Climate Research Program's Grand Challenges website at http://www.gewex.org/about/science/wcrps-grand-challenges/, accessed August 9, 2017.

technological advances have led to either miniaturized or greatly simplified microwave radiometers and radar systems, suggesting the possibility of leveraging technology innovation and miniaturization to achieve the selected goals at reduced cost. These innovations are seen in for example, Raincube (Radar in a CubeSat), the demonstration of Compact Ocean Wind Vector Radiometer (COWVR; Brown et al., 2016), and in the implementation of the Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats (TROPICS) and Temporal Experiment for Storms and Tropical Systems (TEMPEST) EV-I missions.

- *Descope Options.* In the event development costs exceed the maximum NASA development cost level recommended here, the radar can be descoped to a single band, retaining Doppler capability.
- *POR Assumptions.* Addressing this Targeted Observable requires fully leveraging missions in the POR and augmenting them with new measurements that offer a dimension of time and motion as a way of quantifying and understanding processes. New observations of the dynamical aspects of cloud, convection, and precipitation processes will place those processes within the context of global mapping of precipitation and its diurnal cycle. Cloud properties (such as cloud amount, optical depth, and particle size) are available from the spectral radiance measurements provided by MODIS and VIIRS on polar orbiting satellites that are assumed within the POR. The same information can now be extracted from the advanced imagers available from the current and planned constellation of operational geostationary satellites. Precipitation radar measurements from GPM are assumed within the POR, but higher latitude precipitation is not addressed within the POR after CloudSat and EarthCARE. Cloud profile data from CloudSat and CALIPSO will not be available in the decade, while EarthCARE will be available only in the early part of the decade. Precipitation information especially over ocean relies heavily on microwave imaging radiometer measurements, and the time/space coverage of this information will not be available in the coming decade (see Box 4.4, in Chapter 4).
- *Partnerships.* NASA is encouraged to seek commercial or international partnership opportunities with the goal of reducing implementation costs and enabling overlap between the Aerosol and Clouds, Convection, and Precipitation efforts. In particular, NASA is encouraged to assess the extent to which the three series of operational microwave radiometers that will be flying concurrently later in the coming decade—EUMETSAT/EPS-2G-B, USAF/WSF, and CMA FY-3—can contribute toward meeting the objectives of this mission.
- *Budgetary Guidance.* In keeping with the guidelines of the Designated program element and this report's Recommendation 3.3, the Clouds, Convection, and Precipitation Targeted Observable has a maximum recommended development cost of $800 million (in $FY2018).

Mass Change

Earth Science/Applications Objective for the Designated Targeted Observable: Mass Change

	Most Important	Very Important	Important
Hydrology	**1a, 2c**		**3b, 4c**
Weather			
Ecosystems			
Climate	**1a, 1b, 1c**	**1d**	**7d, 7e**
Solid Earth	**1b, 3a, 4a**	**5a**	**6b**

The Mass Change Targeted Observable corresponds to TO-9 in the Targeted Observables table (Appendix C). The movement of mass, whether it is moisture, groundwater, snow, ice, ocean water, and so on represents exchanges within and across elements of the Earth system. As such, the Mass Change Targeted Observable provides an integrated view of the entire physical Earth system, and allows the relating of changes in one system component to changes in another. By providing continuity of the GRACE measurement record, it addresses Most Important and Very Important objectives for three panels (Climate, Hydrology, and Solid Earth) and contributes to several integrating themes.

- *Science Considerations*. This Targeted Observable will ensure continuity of information on groundwater and water storage mass change, land-ice mass change, ocean mass change, glacial isostatic adjustment, and earthquake mass movement. When combined with altimetry, additional information on heat storage is obtained. Gravity-derived measurements of mass change, as have been shown by GRACE, address key objectives related to sea-level rise, ocean heat content (Box 3.7), terrestrial water storage, among others. Consequently, monitoring changes and movement of mass throughout the Earth integrates objectives of the Climate, Solid Earth, and Hydrology panels, as well as addressing key integrating themes such as water and energy cycle with linkages to assessing whether or not systems may be approaching thresholds or tipping points, and assessing trends in the parameters observed, especially given the continuity of mass change and gravity measurements since the launch of GRACE in 2002.
- *Candidate Measurement Approaches.* The GRACE gravity observation can be accomplished through either of two ranging techniques (microwave and optical) that are being evaluated as part of the GRACE-FO mission. Either approach provides bulk measurements of mass fluctuations that are primarily associated with water changes within the Earth system. A down-select to a single measurement technology is likely required to fit within the allocated investment level. These measurements provide a way to track bulk changes in terrestrial water, changes to ice mass, and ocean water mass. Although these measurements are coarse in scale, making their use in water resource management challenging, they provide valuable insights on how water in bulk form cycles through and the changes within the Earth system. When this information is augmented with the ocean altimeter observations of the POR and in situ data from ARGO floats, then additional but important information about ocean heat storage is obtained. Monitoring this energy change over time is fundamental for assessing the state of the Earth system and its future evolution.
- *CATE Evaluation*. Cost and technical evaluation of a notional mission concept similar to the original GRACE mission found the concept to be technically mature with costs that are well understood, supporting a low-risk implementation recommendation.
- *Descope Options.* No descope options have been identified.
- *POR Assumptions*. The POR includes mass change measurements from GRACE-FO and continued altimetry measurements from the JASON and Sentinel-6 missions.
- *Partnerships.* NASA is encouraged to seek international partnership opportunities to implement this mission, and to phase implementation to ensure flight readiness prior to the end of the GRACE-FO mission.
- *Budgetary Guidance.* In keeping with the guidelines of the Designated program element and this report's Recommendation 3.3, the Mass Change Targeted Observable has a maximum recommended development cost of $300 million (in $FY2018).

Surface Biology and Geology

Earth Science/Applications Objectives for the Designated Targeted Observable: Surface Biology and Geology

	Most Important	Very Important	Important
Hydrology	**1c**	**2a, 4a**	**2b, 3a, 3b, 3c, 4c, 4d**
Weather		**3a**	
Ecosystems	**1c, 2a, 3a**	**1a**	**1d, 5a, 5b, 5c**
Climate		**3a**	**3c, 3d, 6b, 7e, 8f**
Solid Earth	**1a**	**1c, 2b**	**4b, 4c, 7a**

The Surface Biology and Geology Targeted Observable, corresponding to TO-18 in the Targeted Observables table (Appendix C), enables improved measurements of Earth's surface characteristics that provide valuable information on a wide range of Earth System processes associated with geological dynamics and terrestial and marine ecosystem changes. Society is closely tied to the land surface for habitation, food, fiber, and many other natural resources. The land surface, inland, and near-coastal waters are changing rapidly due to direct human activities as well as natural climate variability and climate change. New opportunities arising from enhanced satellite remote sensing of Earth's surface provide multiple benefits for managing agriculture and natural habitats, water use and water quality, and urban development, as well as understanding and predicting geological natural hazards. The Surface Biology and Geology observable is linked to one or more Most Important or Very Important science objectives from each panel and feeds into the three ESAS 2017 integrating themes: water and energy cycle, carbon cycle, and extreme events.

- *Science Considerations.* This Targeted Observable will likely be addressed through hyperspectral measurements that support a multidisciplinary set of science and applications objectives. Visible and shortwave infrared imagery addresses multiple objectives: active surface geology (e.g., surface deformation, eruptions, landslides, and evolving landscapes); snow and ice accumulation, melting, and albedo; hazard risks in rugged topography; effects of changing land use on surface energy, water, momentum and carbon fluxes; physiology of primary producers; and functional traits of terrestrial vegetation and inland and near-coastal aquatic ecosystems. Thermal infrared imagery provides complementary information on ground, vegetation canopy, and water surface temperatures as well as ecosystem function and health. Depending on implementation specifics, the Targeted Observable may also contribute to hyperspectral open-ocean observation goals. However, such goals are met to a large degree by POR elements, in particular the hyperspectral PACE mission, and are not considered a priority for additional implementation (and thus are not recommended if they drive cost). Observations of the Earth's surface biology and geology, with the ability to detect detailed spectral signatures, provide a wide range of opportunities for Earth system science parameters across most of the panels and integrating themes. As such, this Targeted Observable maps to some of the highest panel priorities as well as the Integrating Themes.
- *Candidate Measurement Approaches.* High spectral resolution (or hyperspectral) imagery provides the desired capabilities to address important geological, hydrological, and ecological questions, building on a successful history of past and ongoing multispectral remote sensing (e.g., MODIS). Consequently, hyperspectral imagery with moderate spatial resolution (30-60 m) is identified as a priority for implementation.
- *CATE Evaluation.* The CATE evaluation considered the Hyperspectral Infrared Imager (HyspIRI) concept, which was developed by NASA Science Mission Directorate following a recommendation

from the 2007 ESAS decadal survey, and found that the concept is technically mature and costs are well-understood, supporting a recommendation for early implementation.

- *Descope Options.* In the event costs exceed the maximum recommended here, relaxing instrument requirements or eliminating the Thermal Infrared Radiometer (TIR) instrument is advised.
- *POR Assumptions.* It is assumed that the Sustainable Land Imaging program continues to provide Landsat-class land imagery to complement the measurements described here.
- *Budgetary Guidance.* In keeping with the guidelines of the Designated program element and this report's Recommendation 3.3, the Surface Biology and Geology Targeted Observable has a maximum recommended development cost of $650 million (in $FY2018).

Surface Deformation and Change

Earth Science/Applications Objectives for the Designated Targeted Observable: Surface Deformation and Change

	Most Important	Very Important	Important
Hydrology	**1c, 2c**	**4a**	**4b**
Weather			
Ecosystems			
Climate	**1c**		**7b, 8f**
Solid Earth	**1a, 1b, 2a, 3a, 3b, 4a**	**1c, 2b, 2c, 5a, 6a**	**4b, 6b, 6c, 6d, 7a**

The Surface Deformation and Change Targeted Observable corresponds to TO-19 in the Targeted Observables table (Appendix C). By monitoring the physical dynamics of Earth's surface, we increase our ability to anticipate devastating geologic hazards, and monitoring progressive surface deformation can reveal how Earth's systems are changing either naturally or through human activity. Such monitoring is key to avoiding surprises and improving our ability to anticipate future Earth states. This Targeted Observable is cited by nearly all of the Earth Surface and Interior objectives; it also matches needs expressed by the Hydrology Panel and the Climate Panel.

- *Science Considerations*. The Targeted Observable will provide surface deformation measurements including surface change monitoring, ice-sheet dynamics, the Antarctic grounding line migration, and permafrost thaw derived from subsidence. The measurements support science and applications objectives related to earthquakes, volcanoes, landslides, sea level, plate tectonics, the cryosphere, and groundwater. InSAR also is applicable to examining terrestrial ecosystem structure (Treuhaft et al., 2004). Measurements of displacement and surface deformation capture many of the Most Important and Very Important objectives of the Solid Earth, Hydrology, and Climate panels. Moreover, the more than 25-year history of InSAR observations of deformation and displacement establishes a long history of displacement observations, enabling detections of trends in behavior of land and ice processes.
- *Candidate Measurement Approaches.* The presumed measurement implementation involves Synthetic Aperture Radar (SAR) and Interferometric SAR (InSAR). SAR and InSAR have wide application across Earth science, including detection and monitoring of ice-sheet motion and grounding line locations, which are critical for assessing stability of ice sheets and their potential to cause rapid sea-level rise; detection of ground motion from earthquakes; detection of surface deformation and eruptive products of the active volcanoes; and mapping of landslides. Consequently, providing

surface deformation measurements with improved space-time coverage post-NISAR was identified as a priority for implementation.

- *CATE Evaluation*. The recommended cost level does not support InSAR continuity through a reflight of a NISAR-like mission. Instead, continuity is to be pursued through consideration of international partnerships or a constellation of small satellites with relaxed performance characteristics to provide for the desired continuity within the specified NASA cost level. The decade's priority science and applications objectives suggest that implementation should consider reduced spatial resolution in favor of improved temporal resolution, which further enables innovative implementation approaches (i.e., smaller aperture requirements imply the possibility of smaller satellites and lower cost).
- *Descope Options.* Should the maximum NASA development cost recommended here prove insufficient, the committee does not recommend a higher-cost implementation. Instead, the funding should be used to allow one additional Earth System Explorer competition and the Surface Deformation and Change Targeted Observable made eligible for competition in that flight program element.
- *POR Assumptions*. The POR includes NISAR, which is currently planned to launch in late 2021 and is designed to operate for 3-5 years, with no planned follow-on. NISAR's primary science requirements are crustal deformation, glacier and ice-sheet motion, biomass structure, and sea-ice dynamics. NISAR operates at L-band, and can also look left to view Antarctica, for ice-sheet monitoring. It will have a dual-frequency ionospheric correction to enable improved detection of slow solid Earth signals.
- *Partnerships.* NASA is encouraged to seek international partnership opportunities to implement this mission, and to phase implementation to follow the NISAR mission. If the NISAR mission launch date slips, implementation of this mission may also move to the right.
- *Budgetary Guidance.* In keeping with the guidelines of the Designated program element and this report's Recommendation 3.3, the Surface Deformation and Change Targeted Observable has a maximum recommended development cost of $500 million (in $FY2018).

Program Element: Earth System Explorer

To improve programmatic responsiveness while also maximizing the role of competition in implementing flight recommendations, a new medium-class (<$350 million FY 2018) cost-capped solicitation is recommended. The Earth System Explorer would be aimed at addressing the specific list of observing system priorities identified in Table 3.3 and summarized in Table 3.6 (no relative priorities are assigned to the candidates in the list).

The new Earth System Explorer line consists of a set of competitively selected principle investigator (PI)-led missions intended to mirror the proven success of the Astrophysics and Heliophysics Medium Class Explorer (MIDEX)[14] lines. This program is designed to accomplish high-quality Earth system science investigations addressing one or more priority Targeted Observables in Table 3.6, utilizing innovative, streamlined, and efficient management approaches that seek to contain mission cost through commitment to, and control of, design, development, and operations costs. Analogous to MIDEX, specific mission objectives are defined by the PIs in their proposals and approved by NASA through confirmation review.[15]

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[14] Medium Class Explorer (MIDEX) spacecraft generally include selective redundancy with a cost in the range of $60 million to $85 million, depending on attitude control performance, communication requirements, and the need for propulsion. Launch costs are generally in the range of $55 million. MIDEX missions typically consist of a 250 kg payload (approximately 100 kg for instruments and 150 kg for the spacecraft) launched on a Pegasus-class vehicle to orbit.

[15] While Table 3.3 lists the observing system priorities to be addressed in proposals to Earth System Explorer solicitations, the scope and technical requirements, and thereby the extent to which any particular objective associated with a Targeted Observable is met, depend on the proposed implementation approach, which will be assessed as part of the competitive selection process.

TABLE 3.6 Targeted Observables to Be Addressed Through the Competitive Earth System Explorer Program Element

Targeted Observable	Implementation Considerations
Atmospheric Winds[a]	*Addresses all or part of TO-4.* Active sensing (lidar, radar, scatterometer); passive imagery or radiometry-based atmospheric motion vectors (AMVs) tracking; or lidar.[b]
Greenhouse Gases	*Addresses all or part of TO-6.* Can be active or passive, global or regional; or lidar.[b]
Ice Elevation	*Addresses all or part of TO-7.* Lidar;[b] if CryoSat-3 not approved, then highest-priority function for multifunction lidar.
Ocean Surface Winds and Currents	*Addresses all or part of TO-11.* Doppler scatterometer.
Ozone and Trace Gases	*Addresses all or part of TO-12.* UV/VIS/IR microwave limb/nadir sounding and/or UV/VIS/IR solar/stellar occultation.
Snow Depth and Snow Water Equivalent	*Addresses all or part of TO-16.* Radar (Ka-/Ku-band) altimeter or lidar.
Terrestrial Ecosystem Structure	*Addresses all or part of TO-22.* Lidar.[b]

[a] Indicates Incubation program investment is also recommended to ensure competitiveness prior to the end of the decade (see description of Incubation program in the following section).
[b] Could potentially be addressed by a multifunction lidar designed to address two or more of the Targeted Observables.

NOTE: All rows are of equal ESAS 2017 priority and are shown here in alphabetical order.

These missions seek to conduct scientific investigations of modest and focused programmatic scope, and can be developed relatively quickly (generally in 40 months or less) and executed on-orbit in 3 years or less. The program does not maintain a budget reserve to which investigations exceeding their cost commitments may have access for cost overruns. If, at any time, the cost, schedule, or scientific performance commitments of a selected mission appear to be in peril, and descope options are not available, the mission can be subject to a cancellation review by NASA.

Each Earth System Explorer mission is cost-capped at $350 million, including the launch vehicle and 3 years of operations. Cost-capping the missions at $350 million leaves ample room for instrument costs, operations costs, reserves, and a range of mission-unique trades (from use of larger launch vehicles to more sophisticated payloads to multiple-spacecraft constellations, or integration/coordination with existing or new ground/suborbital assets). The program element line opens Earth system science to the benefits of innovation and to new, but flight-ready, technology alternatives including novel spacecraft bus concepts, miniaturized instrumentation, small satellites, constellations, and distributed launch options.

Competition is an excellent motivator, and competing for these medium-class missions will likely stimulate an already creative and motivated community to be even more so. Moreover, the health of the diverse scientific communities is strengthened when they see opportunities to compete for their priorities. As such, the Earth System Explorer program element is expected, as Earth Venture has done, to drive engagement across the scientific community and to attract and retain talented scientists and engineers who are motivated by opportunity. The Earth System Explorer program element is recommended in part because the science priorities identified are of sufficiently similar importance that the key discriminators on what should go forward are those that will emerge through competition addressing cost, scope, technical performance, technical readiness, and programmatic capabilities.

By identifying seven science areas for three competitions, community members associated with different science areas and different measurement approaches will be more inclined to seek innovative and creative approaches, partnerships, and technologies so they can compete successfully.[16] The selection among them should be made on the basis of competitive peer review, and in the context of the international POR as it stands at the time of competition. The recommended program includes funding to support three solicitations in the decadal period, with a goal of supporting additional solicitations if additional funding is made available per the decision rules outlined in Chapter 4.

The Earth System Explorer program element differs significantly from Earth Venture, in terms of both underlying philosophy and scope, which is why it is introduced as a new class of missions distinct from Earth Venture. The Earth System Explorer program element is confined to addressing any of seven priorities in Table 3.6. In recognition of the types of missions required to address these objectives, it carries a $350 million cost cap, which is significantly greater than that of Earth Venture. In contrast, the intent of Earth Venture is to present an opportunity for relevant observing systems without any prescribed focus or science and applications objectives and smaller in scope than the observing systems in Earth System Explorer.

Each of the Targeted Observables in Table 3.6 recommended for Earth System Explorer competition is discussed in the following text, listed without priority in alphabetical order.

Atmospheric Winds

Earth Science/Applications Objectives for the Earth System Explorer Targeted Observable: Atmospheric Winds

	Most Important	Very Important	Important
Hydrology		**2a, 4a**	**4b**
Weather	**1a, 2a, 4a**		**9a, 10a**
Ecosystems			
Climate		**4a, 5a, 7a, 7c**	**3f, 4b, 5b, 7b, 7d, 7e, 8i**
Solid Earth			

The Atmospheric Winds Targeted Observable corresponds to TO-4 in Appendix C. It is included in ESAS 2017 recommendations for both the Earth System Explorer and the Incubation program element. The committee believes Atmospheric Winds is not yet ready for immediate implementation with acceptable risk, but could be during the decade with proper technology advances. The expectation is that Incubation investment could reduce risk sufficiently to accomplish that. A detailed description is included in the Incubation section.

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[16] NASA's Earth System Science Pathfinder (ESSP) program, which was a cost-capped program in the late 1990s and early 2000s, produced such successful missions as GRACE, Cloudsat, CALIPSO, and Aquarius. Currently, the ESSP program is limited to Earth Venture (EV) concepts, which include open solicitations for suborbital strand (EV-S; $30 million each) competitions with five selections every 4 years, an instrument strand (EV-I) with one selection every 18 months, and missions (EV-M; up to $150 million each) with one selection every 4 years. Providing opportunities with higher cost caps that are similar to those of the previous ESSP program (in today's dollars), will likely produce similarly successful concepts that can substantially advance important science and applications objectives. Unlike ESSP, however, the recommended Earth System Explorer solicitation is designed to solicit proposals responsive to a specific set of identified science and applications priorities.

Greenhouse Gases

Earth Science/Applications Objectives for the Earth System Explorer Targeted Observable: Greenhouse Gases

	Most Important	**Very Important**	**Important**
Hydrology			
Weather			**8a**
Ecosystems	**2a, 3a**		**4a, 5a, 5b, 5c**
Climate	**2d**	**3a, 4a**	**3b, 3c, 3e, 3g, 4d, 7b**
Solid Earth			

The Greenhouse Gases Targeted Observable corresponds to all or part of TO-6 in Appendix C. Carbon dioxide (CO_2) and methane are the two most important anthropogenic greenhouse gases (Hofmann et al., 2006; Montzka et al., 2011; IPCC, 2014), but their atmospheric budgets are still poorly understood, limiting our ability to predict future concentrations. A central question for CO_2 is the role of the terrestrial biosphere as a sink to moderate the rise in atmospheric concentrations. This terrestrial sink is poorly quantified, the contributions from different regions are highly uncertain, and the environmental controls are largely unknown. For methane, there are very large uncertainties in the factors controlling wetland emissions and the magnitudes of different anthropogenic source sectors and regions.

- *Observational Approach.* Observations of CO_2 and methane from space can provide unique information to constrain surface fluxes of these gases at the continental/regional level and down to the scale of point sources, considerably enhancing coverage relative to the sparse network available from surface sites. Inverse analyses exploiting the satellite observations can guide improvements in process-based biogeochemical models and emission inventories that provide the basis for enabling projections of future concentrations. Space-based measurement approaches include the following:
    - —Global observations of CO_2 and methane at horizontal resolution of a few km and daily revisit with sufficiently high precision to constrain regional budgets of surface fluxes on a weekly time scale. This might be achieved with shortwave infrared (SWIR) spectrometers that observe the atmospheric column with sensitivity down to the surface, complemented by TIR spectrometers that provide information on vertical distribution as well as data over the oceans and at night. Lidars may provide complementary information with sensitivity down to the surface over the oceans and at night.
    - —Geostationary continental-scale observations with sub-km horizontal resolution and revisit of at most a few hours. This could involve SWIR spectrometers with high precision, possibly complemented by TIR spectrometers. The capability to stare over selected regions with large surface fluxes may provide unique insights into daily variations of these fluxes and sporadic high emissions.
    - —Low Earth orbit (LEO) observation of plumes from point sources using SWIR spectrometers with very high spatial resolution (less than 50 m) over limited viewing domains. Precision should be sufficient to quantify source magnitudes on the basis of a single pass of the satellite.
- *Science and Applications Value.* Atmospheric levels of CO_2 and methane play a critical role in driving climate change. They are controlled by biogeochemical cycling and anthropogenic emissions in ways that are presently not well understood. As a result, we lack a sound basis to interpret current atmospheric trends and to project future trends. Coupling of atmospheric changes with biogeochemical cycles could lead to important climate feedbacks. Air quality is also expected to respond

significantly to changes in greenhouse gases, both indirectly through meteorological variables and directly through the role of methane as a precursor of ozone pollution. Improved measurements of atmospheric CO_2 and methane from space, combined with mapping of surface properties, would allow us to better understand and quantify the sources and sinks of CO_2 and methane. This spans the interests of multiple panels and is central to the carbon cycle integrating theme.

Ice Elevation

Earth Science/Applications Objectives for the Earth System Explorer Targeted Observable: Ice Elevation

	Most Important	Very Important	Important
Hydrology			**4b**
Weather		**3a**	
Ecosystems			
Climate	**1c**	**8a, 8b, 8c**	**8h**
Solid Earth	**3a**		

The Ice Elevation Targeted Observable corresponds to all or part of TO-7 in Appendix C. Land ice and sea ice are both important components of the cryosphere that play different roles in Earth's climate system; a fundamental parameter that should be monitored for both of them is surface elevation.

- *Observational Approach.* For land ice, the surface elevation measurement is used to determine glacier and ice sheet mass balance. The largest uncertainty in future sea-level rise is the contribution from melting land ice (glaciers and ice sheets), which is increasing. The ice-sheet contribution (Greenland and Antarctica) likely will soon surpass thermal expansion as the dominant component, and they have the potential to cause rapid and large amounts of sea-level rise (tens of cm per decade). Observations of dramatic changes in the ice sheets have made us realize the complexity of ice-sheet response to atmospheric and oceanic forcing on various time scales, challenging our traditional view of ice sheets that evolve slowly. Improved understanding of processes driving ice-sheet changes is vital for predictions of future ice-sheet mass loss and sea-level rise. Only continual monitoring of land ice provides a multidecadal record of change, and the continuous nature of these observations is critical, if we are to learn which processes are contributing to the observed changes. Continual monitoring allows assessment of the contributions of seasonal, interannual, and interdecadal variability in snow accumulation, surface-melt, and ice flow dynamics and their impact on ice-sheet mass balance.

  For sea ice, the freeboard (height of the ice surface above the sea surface) enables estimates of sea-ice thickness. The shrinking sea-ice area in the Arctic is one of the most striking manifestations of climate change since the satellite record began and the resulting albedo reduction is an important climate feedback. The ice thickness is an indication of the ice age, as older ice is thicker. Estimation of sea-ice thickness enables us to examine exchanges of energy, mass, and moisture between the ice, ocean, and atmosphere. In the Antarctic, estimation of sea-ice thickness is more challenging, as there is significant snow on the sea ice and often the freeboard is negative.

  Measuring land-ice surface elevation and sea-ice freeboard height by satellite or radar laser altimeter along repeated ground tracks provides an estimate of the volume change of land ice and sea ice over time. ICESat-2 is planned for launch in September 2018. The planned lifetime of the mission is 5 years. After that, there will be a gap on our observing capabilities for ice-surface elevation and freeboard, and it is critical that this gap be filled by a satellite system. Operation IceBridge has been successful in filling the gap between ICESat and ICESat-2, but provides only one measurement per year for a very limited portion of the ice sheet. Space-based measurements of ice surface elevation would include a polar-orbiting satellite (to 88 degrees) carrying a scanning laser or radar altimeter, as a follow-on to ICESat-2 and CryoSat-2. Over land ice, the spatial sampling should be at least 1 km over the central parts of the ice sheets, with 0.1 km sampling around the ice-sheet margins and should be accurate to 10-20 cm over areas with slopes greater than 1 degree. The repeat period should be weekly or better. Over sea ice, the spatial sampling should be at least 1 km with a precision of at least 3 cm. The repeat period should be weekly.

- *Science and Applications Value.* Land and sea ice play critical roles in the areas of climate, weather, energy balance and the water cycle. Sea ice insulates ocean water from overlying polar air, with direct impacts on atmospheric and ocean circulation. As sea ice forms and ages, it loses some of the salt in the seawater to the surface, altering the density structure of the underlying water, which in turn impacts ocean circulation. These processes directly affect weather, climate, and the energy cycle. The Greenland and Antarctic ice sheets are vast stores of highly reflective frozen water containing the equivalent of 7 m and 58 m of sea level, respectively.[17] The topography of these ice sheets, which rise to several km in elevation, and the energy, mass, and momentum exchanges with the atmosphere affect regional and global weather patterns, climate, sea level, and the cycling of water. Moreover, the hydrology of mountain glaciers directly contributes to timing and amount of water availability for rivers, reservoirs, and consumption throughout the world.
- *Implementation Contingency.* In the event that ESA implements the CryoSat-3 radar altimetry mission, which has a different implementation but similar goals to the ice altimetry mission described here, this priority can be changed to a multipurpose altimeter. The altimeter need not be optimized for ice-sheet observations (although it can be), but rather can be designed for any relevant geophysical parameter addressed through altimetric measurements. However, absent a commitment to CryoSat-3, ice altimetry should be the mission driver.

Ocean Surface Winds and Currents

Earth Science/Applications Objectives for the Earth System Explorer Targeted Observable: Ocean Surface Winds and Currents

	Most Important	Very Important	Important
Hydrology			**4b**
Weather	**1a, 2a**	**3a**	
Ecosystems			
Climate		**4a, 5a, 6a, 7a, 8d**	**3d, 4b, 7b, 7d, 7e, 8i**
Solid Earth			

The Ocean Surface Winds and Currents Targeted Observable corresponds to all or part of TO-11 in Appendix C. Ocean surface winds are important to the Earth system for a number of reasons. These winds are critical elements in the coupling between ocean and atmosphere, strongly influencing the fluxes of heat and momentum transferred at the interface (e.g., questions/objectives W-3, C-9). Ocean surface winds are also a central driver of upper ocean currents, and thus the interaction between winds and currents

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[17] See Fretwell et al. (2013). Using data largely collected during the 1970s, Drewry et al. (1992), estimated the potential sea-level contribution of the Antarctic ice sheets to be in the range of 60-72 m; for Bedmap1 this value was 57 m (Lythe et al., 2001), and for Bedmap2 it is 58 m.

provides a measure of momentum exchange between the atmosphere and ocean. Small-scale variations in sea-surface temperature modulate heat and momentum exchanges, which can vary on time scales of hours to days.

- *Observational Approach.* Advancing our understanding of the coupling between the atmosphere and ocean will require coincident swath measurements of surface winds, near-surface atmospheric properties, and surface currents. Space-based measurement approaches include the following:
  - —Vector surface winds from scatterometers. Scatterometers provide accurate ocean wind speed and direction over a wide range of conditions.[18]
  - —Surface currents from Doppler anomalies measured by scatterometer, using a larger antenna and higher pulse repetition frequency in order to measure interferometric phase. A system that can measure surface winds and currents can also be used to infer sea-ice drift to show pathways by which freshwater can propagate through Arctic and Antarctic regions. Doppler scatterometer measurements are a new technology tested in aircraft measurements conducted in 2017.
  - —International partners operate single-band scatterometers, as noted in the POR, but no systems in operation are capable of observing wind and currents.
- *Science and Applications Value.* Ocean surface winds are critical elements that couple the ocean to the atmosphere, driving oceanic circulation and exerting a momentum drag on the atmosphere. They strongly influence the fluxes of heat, gas, and momentum across the air-sea interface. Jointly measuring winds and currents will provide a direct assessment of the momentum transfer between the ocean and atmosphere. In the short term, these processes have significant impact on weather, and, in the long term, they affect regional and global climates. Observing and understanding ocean-surface winds and currents together will provide key insights into Earth's weather, climate, and energy cycles.

Ozone and Trace Gases

Earth Science/Applications Objectives for the Earth System Explorer Targeted Observable: Ozone and Trace Gases

	Most Important	Very Important	Important
Hydrology			
Weather	**2a, 4a, 5a**		**6a, 7a, 8a**
Ecosystems			
Climate		**2g**	**3f, 3g, 6c, 9a**
Solid Earth			

The Ozone and Trace Gases Targeted Observable corresponds to all or part of TO-12 in Appendix C.

- *Observational Approach.* The UV shield from stratospheric ozone is critical to life on Earth. NASA satellites have played a central role in mapping ozone depletion over the past decades, and are now poised to observe the ozone recovery expected in response to the Montreal Protocol. Satellite observations are needed to monitor the ozone recovery at different latitudes and altitudes, and to examine whether it is consistent with our understanding of the underlying chemical processes. An improved understanding of how meteorological variability and other natural factors such as volcanic eruptions affect the ozone layer is also essential. Tropospheric ozone is of separate interest as

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[18] Active remote sensing from scatterometers provides accurate ocean surface wind speed and direction over a wide range of wind speeds, including in the presence of clouds. Polarimetric radiometers can provide wind direction for high wind speeds (>3 mph) but with greater uncertainty than scatterometers. SAR can provide wind vectors but with lower directional accuracy.

a greenhouse gas, a surface air pollutant, and a precursor of the hydroxyl (OH) radical, the main atmospheric oxidant. The factors controlling tropospheric ozone are poorly understood, including the effect of human activity on a global scale, and multidecadal trends have been challenging to explain. Anthropogenic emissions affecting tropospheric ozone are rapidly changing and satellites offer a unique perspective for observing these trends. Observations of tropospheric ozone precursors can also advance understanding of the sources, chemistry, and transport controlling ozone concentrations. Space-based measurement approaches include the following:

  - —Solar/stellar occultation and TIR/microwave limb observations of the stratosphere and upper troposphere with ~1 km vertical resolution for ozone and related chemical species including H_2O, CH_4, N_2O, NO_2, CO, halogens, and aerosols. Characterizing the relationships between these different species and ozone in different regions of the stratosphere will provide important information for understanding the factors controlling ozone.
  - —Combined nadir/limb observations of the global troposphere in the UV/VIS/IR to integrate vertical profiling capability of the limb measurement approach with the spatial resolution of nadir measurements. The combined observations should provide approximately 1-day temporal resolution, and the nadir observations should provide pixel resolution of a few kilometers and sensitivity to the boundary layer for ozone and related atmospheric species (including CO, NO_2, and HCHO). This combined measurement approach will allow improved quantification of the factors controlling ozone on scales ranging from global to urban, and enable understanding of the connections between those scales.

- *Science and Applications Value.* NASA's history of mapping stratospheric ozone depletion and its role in mapping the expected recovery resulting from the implementation of the Montreal Protocol, provide an excellent example of direct connections between scientific observations and life-saving policies. In addition to its response to destructive anthropogenic chemicals, the behavior of stratospheric ozone is also linked to meteorological variability and other natural factors such as volcanic eruptions in ways that are not yet well understood. In the troposphere, ozone is a greenhouse gas and a pollutant, and as such has direct linkages to climate, weather, and air quality. It and other trace gases, even though they exist in relatively small quantities in the atmosphere, have direct implications for Earth's energy cycle from the UV to the thermal infrared by influencing the radiative exchanges among the Sun, atmosphere, and Earth's surface.

Snow Depth and Snow Water Equivalent

Earth Science/Applications Objectives for the Earth System Explorer Targeted Observable: Snow Depth and Snow Water Equivalent

	Most Important	Very Important	Important
Hydrology	**1a, 1c**	**4a**	**2b**
Weather		**3a**	
Ecosystems			
Climate		**8c**	**8f**
Solid Earth	**4a**		**4b, 4c**

The Snow Depth and Snow Water Equivalent Targeted Observable corresponds to all or part of TO-16 in Appendix C. Snow cover is the second largest area component of Earth's cryosphere, covering 1.9 to 45 million km^2. Half of the Northern Hemisphere is covered by snow in winter. Most snow falls outside the high Arctic and Antarctica because extreme cold does not allow much moisture in the air. Two properties of snow contribute to snow cover being a key climate variable: It has a high albedo (fresh snow can reflect up to 90 percent of incoming solar radiation), and it is a very good insulator. Snow's high albedo means that decreases in snow-cover extent act as a positive feedback to climate change by changing the global albedo. Its insulating properties mean that a snow layer over Earth's surface has a major effect on the energy exchange between surface and atmosphere, which prevents soil freezing and slows down ablation of glaciers, ice sheets, and sea ice. Only a few decimeters of snow cover can insulate underlying ground or ice from atmospheric temperatures. Insulation increases with snow layer thickness, thus it is important to know its depth and how it changes over time. As snow ages, its density increases, and its albedo decreases.

- *Observational Approach.* Snowmelt plays a major role in water resources, affecting soil moisture, evapotranspiration, and runoff. Snow in mountain regions contributes to water supplies for almost one-sixth of the world's population (e.g., snowmelt supplies 85 percent of Colorado River water). Changes in snow cover are having a dramatic impact on water resources. The important parameter for hydrology and water supply forecasting is snow water equivalent (SWE; how much water is contained in snow, equal to snow depth multiplied snow density). SWE is important for hydrological modeling and runoff prediction; snowfall as a fraction of total precipitation is important in hydrology models and in monitoring climate change. Snow area is mainly monitored by satellites (Dietz et al., 2012). Snow depth is monitored with passive microwave AMSR-E and SSM/I (passive microwave since 1978), as the ground emissivity changes with snow cover and also is affected by melt. Ground measurements are used to calibrate satellite data and constrain snow models and are also assimilated in NWP and reanalysis systems.

  In the western United States, the Jet Propulsion Laboratory (JPL) Airborne Snow Observatory has been flying since 2013 and carries an imaging spectrometer to measure albedo and laser altimeter to measure snow depth before and after a snowfall event. Combination of albedo (to estimate age, and therefore density) and snow depth yields an estimate of SWE. An alternative to lidar for measuring snow depth is a high-frequency (W- or Ka-band) radar altimeter or interferometer. A Ka-band interferometer has been flown as an airborne sensor as GLISTIN, the Glacier and Land Ice Surface Topography Interferometer.
- *Science and Applications Value.* Snow cover, which spans half of the land area of the Northern Hemisphere in winter, directly affects climate through its high albedo (reflecting as much as 90 percent of incident sunlight) and its strongly insulative properties. The albedo in particular plays an outsized role in the surface energy balance, because of the strong difference in reflectivity between fresh new snow and old wet snow as well as the difference between snow-covered land and land that is not snow-covered. These albedo differences also directly impact weather, as the radiative and thermodynamic properties of snow-covered and non-snow-covered surfaces are dramatically different and have a substantial impact on near surface energy, mass, and momentum exchanges. Finally, snow plays a critical role in hydrology and the water cycle by modulating the delivery of freshwater to streams and reservoirs. This is because snow serves as a storage for water in winter and releases that water relatively slowly over time through the spring and summer.

Terrestrial Ecosystem Structure

Earth Science/Applications Objectives for the Earth System Explorer Targeted Observable: Terrestrial Ecosystem Structure

	Most Important	Very Important	Important
Hydrology			**3c**
Weather			
Ecosystems	**1b, 3a**		**1e, 4a, 5a, 5b, 5c**
Climate	**2d**		**3c, 8f**
Solid Earth			**4c**

The Terrestrial Ecosystem Structure Targeted Observable corresponds to all or part of TO-22 in Appendix C. Characterization of the 3D structure of land-based vegetation, particularly for forested ecosystems, provides utility for multiple research, resource management, and conservation perspectives. Canopy and understory structure reflects the species and functional composition of the ecosystem as well as competition for light, water, and nutrients across the landscape. Measurements of ecosystem structure inform on rates of primary production, ecological functioning, carbon storage, and changing land use.

- *Observational Approach.* A measurement approach using satellite-based lidar would build on successful airborne experimentation and the 2-year pilot Global Ecosystem Dynamics Investigation (GEDI) instrument in the POR to be flown on the International Space Station beginning in 2018. Vertical structure of plankton biomass and mixed layer depth across the upper ocean is also of considerable scientific interest and accessible via lidar approaches, although requiring different technical constraints from land vegetation structure (see TO-10 in Appendix C). Recovery of useful oceanographic data from the CALIOP sensors motivate the inclusion of marine ecosystem structure as an opportunistic measurement within the Aerosol Targeted Observable.
- *Science and Applications Value.* Observations and characterization of the 3D structure of land-based vegetation provide critical information on ecosystem structure primary production, ecological functioning, carbon storage, and changing land use. In addition to the obvious linkages between vegetation structure and ecosystems and the carbon cycle, the changes over time of these characteristics have direct connections to climate and hydrological processes that influence vegetation growth and health, as well as the water and energy cycle, through evapotranspiration. Trees, shrubs, and other land plants compete for space, light, and other resources, resulting in the complex landscapes in forests and other land ecosystems. The 3D structure of vegetation strongly influences ecosystem dynamics and carbon cycling but is difficult to decipher from standard satellite imagery alone. For example, primary production, plant functional types, and carbon storage vary substantially from the canopy top through the canopy and understory to the ground surface. Therefore, new observational approaches to characterize 3D vegetation structure will provide critical information on ecosystem fluxes, carbon cycling, and changing land use. In addition, geographic and temporal variations in vegetation structure have direct connections to climate and hydrological processes that influence vegetation growth and health, as well as the water and energy cycle, through evapotranspiration.

ESAS 2017 established priorities based on an Earth system science perspective, but also recognized the importance of achieving disciplinary priorities. In doing so, the committee examined the combination of observations already available through the POR and any new observations proposed in this report. It is instructive to examine how this approach informed the prioritization of Targeted Observables; an example is detailed in Box 3.9.

BOX 3.9 ACHIEVING DISCIPLINARY PRIORITIES: A CASE STUDY FOR THE OCEANOGRAPHIC COMMUNITY

In April 2006, while the inaugural decadal survey was ongoing, the oceanographic community wrote a community letter[1] to highlight key ocean variables that the community valued and that had been identified as priorities by the U.S. Commission on Ocean Policy report *An Ocean Blueprint for the 21st Century* (2004) and the NOAA report *U.S. Detailed National Report on Systematic Observations for Climate: U.S. Global Climate Observing System (U.S-GCOS Program)* (2001) as candidates for space-based observation. This baseline of six needed observations, and their disposition in ESAS 2017, are listed here:

1. *Ocean surface vector winds.* Ocean surface vector winds, which provide key information about the transfer of momentum between the atmosphere and ocean, are in the Program of Record of international partners, as part of the Meteorological Operational Satellites (METOP-A and METOP-B), CFOSAT, and Scatterometer Satellite (Scatsat). The community has noted that a multisatellite approach with appropriately timed equator crossings would facilitate better investigation of high-frequency winds and diurnal variations. The community letter emphasized the importance of achieving the coverage and accuracy of Quick Scatterometer (QuikSCAT) with good measurements in the presence of rain. With this in mind, ESAS 2017 recommended the Ocean Surface Winds and Currents Targeted Observable, which will provide critical insights into the coupling and exchanges between ocean and atmosphere.
2. *All-weather sea-surface temperature (SST).* Sea-surface temperature has been assumed to be in the Program of Record, as part of ongoing collaborations with international partners. However, with the potential loss or interruption of the passive microwave time series (see Box 4.4, in Chapter 4), this capability is currently at risk. The opportunity for avoiding losses lies in the successful competition in the Earth Venture-Continuity strand. Alternatively, international partners could fulfill the need, but there is currently no partner with a demonstrated capability to do so.
3. *Sea-surface height (SSH).* Sea level has been identified as a priority measurement that is contained within the Program of Record through the international partnership provided by the JASON-CS/Sentinel-6 mission and the ongoing Sentinel-3 series. In addition, ESAS 2017 supports continuation of the GRACE satellite series through the Mass Change Targeted Observable, which will enable appropriate attribution of observed sea-level rise to its thermal expansion and mass gain components.
4. *Wide-swath altimeter.* This objective will be addressed by the U.S.-French Surface Water and Ocean Topography (SWOT) mission within the Program of Record, which was recommended in ESAS 2007 and is scheduled to launch in 2021. In addition, the steering committee has recognized the importance of wide-swath ocean altimetry (as Targeted Observable TO-21 in Appendix C), identifying it as a candidate for Earth Venture opportunities.
5. *Ocean color.* For the open ocean, the Program of Record includes a number of sensors (Moderate-Resolution Imaging Spectroradiometer [MODIS], Operational Land Imager [OLI], Visible Infrared Imaging Radiometer Suite [VIIRS], and the hyper-spectral radiometer on Pre-Aerosol, Clouds, and Ocean Ecosystem [PACE]) that will help to meet ocean color objectives. In the coming decade, the hyperspectral radiometer on PACE is likely to provide more advanced ocean color capabilities for addressing key science priorities addressed in this survey's SATM, including marine ecosystem fluxes and structure, function, and biodiversity. The global ocean ecosystem data from PACE complements the near-shore coastal, aquatic inland, and terrestrial ecosystem information that would be derived from the Surface Biology and Geology Targeted Observable. High spatial/temporal resolution coastal and inland aquatic

continued

BOX 3.9 Continued

ocean color also has been identified as a variable of interest (see Aquatic-Coastal Biogeochemistry Targeted Observable, Ecosystem Panel, Appendix C), the Moore Foundation Proof of Concept mission (the HawkEye Ocean Color Sensor on a CubeSat) will help to address some questions regarding high spatial resolution.

6. *Sea-surface salinity (SSS)*. Salinity is a desirable variable that helps to identify the impact of the water cycle and together with temperature determines density of surface waters, which in turn impact circulation. In addition to the now-completed Aquarius mission, salinity is measured as part of the ongoing SMOS and SMAP missions in the Program of Record. ESAS 2017 recommended Salinity as a Targeted Observable candidate for an Earth Venture mission opportunity, as well as for continued technology development to reduce costs and better address the accuracy and cold-temperature limitations inherent in microwave salinity sensing. The RFI submissions concerning salinity identify a number of promising options worthy of research and competition for further technology development.

Thus, each of the six priorities identified by the oceangraphic community in its 2006 community letter is addressed in some way over the next decade by the Program of Record, and potentially with an Earth System Explorer or Venture mission. ESAS 2017 also offers additional opportunities to expand beyond these capabilities. Among these opportunities are:

- The Atmospheric Winds and Planetary Boundary Layer Targeted Observables to measure atmospheric winds and profiles in the atmospheric boundary layer, which will enable examination of air-sea exchanges.
- Lidar systems with the potential to measure mixed-layer depth, upper ocean turbulence, or biological productivity in the upper ocean (as called for to address the Ocean Ecosystem Structure Targeted Observable) offer a possibility for improved understanding of marine ecosystems and the ocean side of air-sea exchange. These measurement needs may be addressed opportunistically through implementation of the Aerosols Targeted Observable or as part of a multifunction lidar proposed in response to an Earth System Explorer opportunity.
- The ESAS 2017 unallocated Aquatic-Coastal Biogeochemistry addresses distribution, composition, and functioning of rapidly changing coastal and inland water ecosystems and associated biogeochemical impacts. It fills a geographic and high-temporal resolution gap in open-ocean ocean color from the Program of Record (e.g., PACE) and a gap in inland and shallow, near-coastal measurements from the Surface Biology and Geology Targeted Observable. It may be implemented via geostationary orbits or a constellation of small satellites with orbits optimized to cover priority coastal waters (e.g., U.S. coastal waters), and thus could be a strong candidate for international collaborations and/or Earth Venture funding.
- The ESAS 2017 unallocated Ocean Ecosystem Structure Targeted Observable addresses 3D distributions of ocean stocks of planktonic biomass, primary productivity, particle characteristics, and mixed layer depth, possibly from multi-frequency imaging lidar. It has the potential to be addressed opportunistically through implementation of the Aerosols Targeted Observable or as part of a multifunction lidar proposed in response an Earth System Explorer opportunity.

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[1] The letter is available at http://cioss.coas.oregonstate.edu/CIOSS/final_letter.html.

Program Element: Incubation

The Incubation program element provides investment funds to support maturation of mission, instrument, technology, or measurement concepts to address specific high-priority science and applications Targeted Observables as needed to enable cost-effective implementation.

Three observing system priorities are recommended for maturation via Incubation program funding (see Table 3.7). These are observations that, despite their high priority, lack sufficient technical maturity to be considered ready for low-risk implementation. Each of the identified Targeted Observables would benefit from focused and sustained attention to establish and mature its associated prospective user communities to make material progress toward maturing both measurement requirements and implementation concepts within this decade.

To foster program-level innovation, the committee also recommends that NASA establish an Innovation Fund within the Incubation program to enable responses to unexpected opportunities that occur on subdecadal scales. Such responses could include leveraging new technologies; responding to international, commercial, or private partnership opportunities; or providing seed investments to evaluate or demonstrate new approaches (e.g., alternative procurement models, novel launch services concepts, data buys,

TABLE 3.7 Targeted Observables Selected by the Committee to Be Addressed Through the Incubation Program Element

Targeted Observable	Candidate Incubation Program Goals
Atmospheric Winds	• Improve understanding of measurement needs through advanced Earth system modeling representative of winds in coupled atmosphere-ocean-land-ice models with realistic planetary boundary layer (PBL). • Explore the best combination of active (lidar, radar) and passive (radiometry) technologies that can leverage ESTO investment in active technologies and POR AMVs from GOES-R and international GEO and LEO satellites. • Develop mission concept studies to define which measurement needs can be addressed with state-of-the-art technology via Venture and/or Earth System Explorer opportunities and which require further development. • Strategic technology development investments to ensure flight maturity of needed measurement technologies by end of decade.
Planetary Boundary Layer	• Improve understanding of measurement needs, through modeling and mission concept studies, to define which can be addressed with state-of-the-art technology and which require further development. • Identify needs that can be addressed through ground-based or airborne mechanisms rather than requiring a space-based component. Identify any needed technology developments. • Identify any elements that are mature and suited to Venture-class opportunities. Identify any proposed components that could be ready for Earth System Explorer opportunity, for consideration by Midterm Assessment. Identify elements that may be appropriate for NOAA consideration as "on-ramps" (described in Chapter 4). • Consider suborbital observations of temperature/humidity and modeling needs to complement atmospheric winds and PBL height measurements.
Surface Topography and Vegetation	• Improve understanding of measurement needs, through modeling and mission concept studies, to define which can be addressed with state-of-the-art technology and which require further development. • Identify which measurement needs can be obtained through suborbital means and which require a space-based component. Identify those ready to compete in Venture-class opportunities. • Identify any proposed components that could be ready for Earth System Explorer opportunity, for consideration by Midterm Assessment. • Consider appropriate split between global observations from space and potentially less expensive and higher resolution airborne measurements. • Look into obtaining commercial data to meet needs; define a pathway to ensure any identified spaceborne component matures toward flight in the following decade.

leveraging unconventional data sources, block buys, exploiting available multi-instrument platforms) to implementing priority Targeted Observables.

The committee has included an additional $20 million/year from the budget wedge (see Figure 3.4) to support these activities, some portion of which is allocated to programs such as the Earth Science Technology Office (ESTO), and notes that the maturation of mission, instrument, technology, or measurement concepts (described later) further requires the coordinated use of existing resources.

For each Targeted Observable in the Incubation program element, a coordinated program of strategic investments in technology, research, modeling, or data system development would be developed by NASA toward maturing the overall measurement concepts. This would entail strategic coordination of resources and support from the Technology, R&A, and Flight program elements to support concept maturation. Several existing programs already provide funding to mature individual technologies and instrument concepts. However, those programs tend to be implemented as individual open calls and do not provide a mechanism to make coordinated long-term progress toward a defined objective as is called for here. A team of scientists and engineers will be expected to develop an understanding of measurement needs through modeling and mission concept studies to address the specific goals outlined in Table 3.7. Activities might include:

- *Trade Space Examination.* Formally define and explore the trade space of implementation options.
- *Solutions Brainstorming.* Explore means to achieve breakthroughs and alternative sources to obtaining the needed measurements. Consider commercial, ground, airborne, and partnership opportunities
- *Impact Evaluation and Sensitivity Assessment.* Establish a quantitative understanding of the impact of the observations on science and applications, including sensitivity analysis showing which aspects are most important, using techniques such as OSSEs when appropriate.
- *Requirements Refinement.* Evaluate the observations' impact parametrically, through mechanisms such as OSSEs when appropriate, to assess the most important observational requirements with the objective of relaxing less important requirements.
- *State-of-the-Art Evaluation.* Evaluate the current capability of technologies, models, and data systems to achieve and utilize the considered observations.
- *Evaluation of Opportunities.* Evaluate the identified needs to determine which are candidates to be addressed via open-solicitations such as Earth Venture (all strands) and Research Opportunities in Space and Earth Sciences (ROSES), and which (if any) might be candidates for future Earth System Explorer solicitations to be considered by the Midterm Assessment. The committee has identified only Atmospheric Winds as a potential candidate for this decade's Earth System Explorer opportunities based on its current level of technical maturity. Should substantial development advances be made in Surface Topography and Vegetation or Planetary Boundary Layer by the Midterm Assessment, their suitability for the Earth System Explorer competition can be reassessed.
- *Identification of Gaps and Investment Needs.* Identify specific shortfalls in the state-of-the-art of technologies, models, and/or data systems that are barriers to achieving or utilizing the observation. Identify and invest in needed ground, aircraft, or suborbital instrument, subsystem, or mission technologies to increase the flight readiness of these mission concepts.

Each of the Targeted Observables in Table 3.7 recommended for the Incubation program element is discussed in the following text, listed without priority in alphabetical order.

Atmospheric Winds

Earth Science/Applications Objectives for the Incubation Targeted Observable: Atmospheric Winds

	Most Important	Very Important	Important
Hydrology		**2a, 4a**	**4b**
Weather	**1a, 2a, 4a**		**9a, 10a**
Ecosystems			
Climate		**4a, 5a, 7a, 7c**	**3f, 4b, 5b, 7b, 7d, 7e, 8i**
Solid Earth			

The Atmospheric Winds Targeted Observable corresponds to all or part of TO-4 in Appendix C. Measurement of atmospheric winds was identified as a recommendation in ESAS 2007 (Table 2.1, in Chapter 2), and this observation again appears as a high priority within ESAS 2017. The technology readiness of this measurement and apparent high cost of considered approaches, however, presents challenges for near-term implementation. For this reason the TO is included within the Earth System Explorer candidates and also within the Incubation candidates. The expectation is that Incubation investment could achieve sufficient risk reduction to achieve readiness for competition within the Earth System Explorer program element during the decade.

- *Science and Applications Value.* One of the most pressing science and application priorities in the coming decade is to better observe the properties in the PBL and lower troposphere and improve prediction of high-impact natural hazards such as severe air pollution outbreaks and tropical and winter storms, renewable wind energy applications, transport and distribution of global water, and carbon in hydrological and energy cycles of the Earth system. Observing 3D winds[19] is key to addressing these priorities to meet societal needs.

  Measurement of atmospheric winds is not only important to weather and air quality forecasts but also fundamental to other components of the Earth system. Wind is a central driver for ocean currents and essential for determining air-sea-land-ice surface fluxes. Atmospheric 3D winds are an essential expression of the circulation of the atmosphere, and the coupling between clouds and the general circulation is central to address cloud and climate grand challenges (Bony et al., 2015). Large-scale winds also transport energy and water through the atmosphere and, together with vertical motions of convection, are a principal input in quantifying transports of trace gases and other constituents around the globe. Transports by winds are critical inputs to methodologies that invert concentration of trace gases to eco-system fluxes. Winds are also fundamental to understanding the hydrological cycle and related water resource applications. For example, the narrow ribbons of water-laden tropospheric winds of the subtropics act like rivers of moisture bringing heavy rains and snows to the southwestern United States. Observations of winds in the PBL are critical for better understanding and forecasting of extreme high winds in winter storms, tornadoes, hurricanes, and wind-induced storm surge.
- *Observational Approach, Technology Readiness, and Risk.* The importance of global measurements of the evolution of atmospheric wind vectors is highlighted as an urgent need in the NASA Weather Research Community Workshop Report (Zeng et al., 2016). Measurement of the atmospheric winds was identified as a priority in ESAS 2007, and this observation again is a priority in ESAS 2017. Yet,

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[19] 3D winds here refer to vertical profiles of horizontal wind vectors and vertical velocity in convective precipitation, which can be observed from space.

progress in advancing observation of 3D winds has been relatively slow. The technology readiness of this measurement and apparent high cost of current approaches presents challenges for near-term implementation.

A detailed assessment is required to determine where wind information will most impact forecasts[20] as well as the temporal and spatial resolution required for the upper tropospheric and lower troposphere/PBL winds for various applications such as extending weather and air quality forecasting from hours to 2 weeks and Earth system modeling and prediction on subseasonal-to-seasonal and longer scales.

Multiple active and passive technologies currently receive ESTO investment.[21] A number of OSSE studies have been performed to evaluate potential impact of specific Doppler wind lidar (DWL) approaches (Baker et al., 2014). Some OSE studies have evaluated the impacts of atmospheric motion vector (AMV) measurements on numerical weather predictions (NWPs; Warrick, 2016). The long-anticipated launch of the ESA Atmospheric Dynamics Mission (ADM) Aeolus (planned for January 2018), designed to produce line-of-sight winds, may offer some partial assessment when it becomes available. Trade studies may still be needed to design the most cost-effective strategy for wind measurements (based on lidar, radar, and AMVs) from satellites and airborne flights and the benefits of combinations of approaches. As Zeng et al. (2016) states, “it is important to avoid all-or-nothing strategies for three-dimensional (3D) wind vector measurements, as important progress is possible with less than comprehensive observing strategies.”

For these reasons, the TO-4 is included within the Earth System Explorer candidates and also within the Incubation Program. The expectation is that Incubation investment could achieve sufficient risk reduction to achieve readiness for competition within the Earth System Explorer program element during the coming decade.

- *Incubation Goals.* Particular incubation goals are described in Table 3.7.

Planetary Boundary Layer

Earth Science/Applications Objectives for the Incubation Targeted Observable: Planetary Boundary Layer

	Most Important	Very Important	Important
Hydrology		**2a**	
Weather	**1a, 2a**	**3a**	**10a**
Ecosystems			
Climate		**2b, 4a, 7a, 7c**	**7b, 7d, 7e**
Solid Earth			

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[20] For example, it is expected that wind information more directly impacts tropical regions than the extra-tropics, where available strong atmospheric mass constraints serve to constrain large-scale winds.

[21] Each measurement approach has advantages and disadvantages, and the optimal approach varies depending on application. Passive sensing atmospheric motion vectors (AMVs) use indirect measurements of atmospheric water vapor and clouds to derive winds, which have large errors in assigning a height of retrieved wind in the atmosphere and wind speed (Forsythe, 2007; Maschhoff et al., 2015). Good temporal coverage is provided by geostationary satellites; however, the low vertical resolution of AMVs is a limiting factor for observing winds in the Planetary Boundary Layer (PBL). Active sensing using a 2 μm aerosol backscatter Doppler wind lidar (DWL; Kavaya et al., 2014) may be best suited for observing winds in the PBL/lower troposphere where aerosol is abundant, though a 355 nm or 532 nm molecular backscatter DWL (Tucker et al., 2015) may have advantages in observing upper tropospheric winds. The combination of lidar winds and AMV winds might also provide some advantages where one is used to calibrate the other.

The Planetary Boundary Layer Targeted Observable corresponds to all or part of TO-13 in Appendix C.

- *Science and Applications Value.* The PBL literally couples the surface of the Earth to the atmosphere above. The importance of the PBL to the Next-Generation Global Prediction System (NGGPS), which requires better understanding and modeling of the coupling among the atmosphere, ocean surface, sea ice, and land in the integrated Earth system, is now recognized (NRC, 2016a). Boundary layer wind and thermodynamic information together with air quality measurements are needed to improve understanding and prediction of severe air pollution outbreaks that affect human health (NRC, 2016b). The boundary layer is also a critical element in understanding the role of biospheric feedbacks in the Earth system as well as air-sea exchanges. Processes within the PBL and how the PBL mixes with the air have been proposed as new emergent constraints on understanding climate sensitivity (Sherwood et al., 2015). This relation to climate sensitivity arises from the influence of these mixing processes on boundary layer clouds, thus making PBL processes central to low cloud feedbacks.
- *Observational Approach, Technology Readiness, and Risk.* The PBL is the lowest layer of the atmosphere and is directly influenced by its contact with the Earth surface. The PBL includes the air we breathe and the weather we experience. Yet, this near-surface layer of the atmosphere is relatively poorly observed and modeled, as is the exchange of energy, moisture, and pollutants between this layer, the surface, and the free atmosphere. These exchanges are critical to weather and climate because the bulk of the interactions with solar heating and surface evaporation that drive the atmosphere and ocean take place within the PBL rather than the free atmosphere. For forecasts longer than a few days, errors in these exchanges lead to substantial and growing errors in weather forecast models. In order to adequately represent the key boundary layer processes, high-resolution, diurnally resolved, 3D/2D measurements of the PBL are required. While the POR and other elements of the Designated program provide measurements in the PBL, the global temporal (3 hourly) and vertical resolution required by the SATM for thermodynamic profiles is not achieved. Further study is needed to quantify the limitations of POR and determine appropriate investments through technology development and strategic combination of the elements of the POR (and other parts of the Designated program) to fill the gap.

  PBL profiles include measurements of 3D temperature, water vapor, aerosol and trace gas (e.g., ozone) concentrations. They also include two-dimensional (2D; in the horizontal direction) PBL height, cloud liquid water path, cloud base, precipitation, and surface fluxes of water and energy. Three-dimensional horizontal wind vector measurements, which are part of the Atmospheric Wind Targeted Observable, are also essential to understanding PBL processes and thus consideration of the Atmospheric Wind and Planetary Boundary Layer Targeted Observables together is warranted.

  A number of the 2D variables can be measured by existing ground-based networks (mostly over land) and by a variety of instruments on board polar-orbiting and geostationary satellites within the POR. The recommended Aerosol TO investment (part of the Designated program element) will provide measurements of aerosols in the boundary layer and the height of the PBL. GNSS measurements in the POR will also contribute PBL height measurements. The recommended Clouds, Convection, and Precipitation Targeted Observable (part of the Designated program element) will contribute to PBL cloud and precipitation properties. Microwave radiance measurements within the POR provide cloud liquid water path and precipitation. Although thermodynamic properties of water vapor and temperature are also contained within the POR, much higher vertical resolution and diurnally resolved information is needed to advance understanding of the role of the PBL on Earth system processes.

The PBL processes that are important to weather prediction and to the Earth system more broadly exhibit a strong diurnal cycle. For instance, the PBL height can increase by an order of magnitude from near sunrise to midafternoon over land. While current observations from geostationary satellites can fully resolve the diurnal cycle and provide useful information on cloud properties (refer to the Cloud, Convection, and Precipitation Targeted Observable), temperature and humidity soundings with sufficient capability to resolve the PBL does not yet exist, let alone from GEO platforms. A combination of geostationary, polar, and suborbital profiles is needed to obtain diurnally resolved PBL observations. Active or advanced hyperspectral sensors on the orbital platforms are capable of providing high vertical resolution, but investment in each technology is needed to achieve the required vertical resolution. For example, previous study has demonstrated the readiness of prototypes such as the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS), which was developed through the NASA New Millennium Program. Further, there are international efforts to develop sensors that nearly match the capabilities of GIFTS; these include China's Geostationary Interferometer Infrared Sounder (GIIRS), and a European advanced IR sounder (IRS) similar to GIFTS, which will be a key part of Meteosat Third Generation (KTG).

- *Goals of the Incubation Program Element* (some of which will benefit from cross-coordination with the Atmospheric Wind incubation effort described earlier):
  - — Determine optimal augmentations to the POR—both space- and ground-based—that would address the requested requirements for the PBL targeted observables listed in the SATM (e.g., 0.2 km vertical resolution for 3D variables, and 2-3 hourly temporal resolution and 5-20 km horizontal resolution for all observables), to resolve the structure and diurnal variability of the PBL.
    - o Develop capabilities to provide advanced thermodynamic profiling of the PBL by:
    - o Assessing the state-of-the-art of passive and active technologies (such as DIAL), including their capability to provide water vapor profiling and thermodynamic profiles in the clear and cloudy PBL; and
    - o Identifying where additional technology investment—in existing or emerging technologies—may be required.
  - — Resolve the diurnal cycle of important PBL properties. This may require a combination of the following:
    - o Exploitation of existing geostationary and GNSS assets in the POR;
    - o The use of suborbital (ground or airborne) observations;
    - o The capabilities of hyperspectral instrument prototypes for geostationary application (e.g., GIFTS or the Hyperspectral Environmental Suite [HES]);
    - o Technology development investments to mature measurement needs not met with existing technologies; and
    - o Novel concepts involving PBL-capable sensors alone or in constellations to meet identified needs.

Surface Topography and Vegetation

Earth Science/Applications Objectives for the Incubation Targeted Observable: Surface Topography and Vegetation

	Most Important	**Very Important**	**Important**
Hydrology	**2c**		**2b, 3c, 4b, 4d**
Weather		**3a**	
Ecosystems	**1b**		**1e**
Climate	**1c**		**8f**
Solid Earth	**1a, 1b, 3a, 3b, 4a**	**1c, 2b, 2c**	**1d, 4b, 4c, 6b, 7a**

The Surface Topography and Vegetation Targeted Observable corresponds to all or part of TO-20 in Appendix C.

- *Science and Applications Value.* Characterizing surface topography with contiguous measurements at 5 m spatial resolution and 0.1 m vertical resolution will allow for detailed understanding of geologic structure and geomorphological processes, which in turn can provide new insights into surface water flow, the implications of sea-level rise and storm surge in coastal areas, the depth of off-shore water in near coastal areas, and more. In addition, assuming a lidar-based system, the implications for understanding ecosystem structure, and the associated cycling of carbon will be significant, as described earlier under the Terrestrial Ecosystem Structure Targeted Observable.
- *Observational Approach, Technology Readiness, and Risk.* Space-based lidar offers the possibility of simultaneously mapping at high spatial resolution the vegetation structure and underlying "bare earth" topography across the globe. Such data would revolutionize our capability to understand how Earth's surface works, and greatly enhance our ability to predict hazards and anticipate the effects of surface change. Although increased topographic resolution from 30 m (SRTM) to 12 m (TanDEM-X) using synthetic aperture radar has been accomplished, much higher resolution is needed. Deriving vegetation height from radar involves much analysis. Optical methods, such as that provided by DigitalGlobe, have increased the resolution to 2-5 m, but such methods track canopy heights, not the ground surface in vegetated environments.

  In the 2007 decadal survey, the Lidar Surface Topography (LIST) mission was proposed to obtain a 5 m global topographic survey with decimeter precision. Although the mission did not go forward, a NASA-commissioned LIST study identified major challenges in detection efficiency, imaging technology, data rate and throughput, and high average power and long lifetime lasers. Advances have been made in all of these areas. Substantial progress in lidar technology has been made since 2007 through significant funding from NASA, other U.S. agencies, and the commercial sector. NASA has supported technology advancement for the LIST program through airborne programs (LVIS, SIMPL, MABEL, ALISTS) and space-based missions (ICESat-2 and GEDI). A lidar would have significant synergy with the recommended Terrestrial Ecosystem Structure Targeted Observable, depending on choices and trade-offs among vertical resolution, spatial footprint, and repeat time. Higher temporal resolution may be needed for some ecological science objectives.

  Although perhaps now practicable, a program to make the entire Earth to 5 m resolution using a space-based lidar would likely have a cost in the flagship mission range. International collaborations could reduce the cost, and some combination of high-altitude airborne (where flights are permitted) and optical systems (e.g., DigitalGlobe) where vegetation density is low may reduce the area needed to be surveyed by a space-based system. For example, NASA's LVIS system provides 10 m footprints, but can do 5 m in a swath several kilometers wide.

The solid Earth community expressed the goal of reaching 1 m spacing at 0.1 m vertical precision (the common standard in airborne lidar surveys) from space. Whether the spacing is 5 m or finer, the data collect needs to be spatially continuous, not a series of swaths separated by large distances. This Incubation program should encourage active collaboration between those who advance the technology and those who seek applications such that compromises may be found to move forward in reaching the long-held goal of high-resolution topographic mapping (and vegetation structure) from space.

- *Incubation Goals.* Particular incubation goals are described in Table 3.7.

Program Element: Venture-Continuity

The Venture program is considered a critical element of the ESAS 2017 observing system program, although the open competitive selection process involved meant the committee did not specify candidates for the Venture program.

In its statement of task, the committee was charged with evaluating whether the present three-strand Venture-Class competed program should be expanded or modified, including whether ESD should initiate additional or different Venture Class strands, possibly with different cost caps. As the committee describes in Chapter 4, the Venture program appears to be working well overall, serving its intended purpose of restoring more frequent launch opportunities and facilitating the demonstration of innovative ideas and higher-risk technologies. The current three-strand Venture-class program responds directly to the ESAS 2007 recommendation, which suggested that the program include "stand-alone missions . . . more complex instrument of opportunity . . . or complex sets of instruments flown on suitable suborbital platforms to address focused sets of science questions."

Similar innovation is warranted *specifically in the context of providing for long-term, sustained observations*, and therefore the committee proposes that a new Venture strand be established to incentivize innovation to enable sustained observations in a more cost-effective way. Sustained observations are identified in Chapter 4 as a priority area for achieving programmatic balance.

The Venture-Continuity strand would specifically seek to lower the long-term carrying cost of providing for continuity observations, rewarding innovation in mission-to-mission cost reduction through technology infusion, or programmatic efficiency, or other means. Box 4.5, in Chapter 4, provides a recognized example for the significance of this need. Note that funding for the proposed expansion of Venture opportunities is included in the survey's allocation of available funds from the expected budget wedge.

Both the international and national communities continue to call for the creation of a sustained global satellite-based Earth monitoring system (NRC, 1999, 2008). The need for such monitoring for the purpose of understanding the Earth system is self-evident to scientists. However, such endeavors are costly undertakings, and justification for them requires clear, important, societal objectives with well-articulated, achievable goals in addition to the need to understand the behavior of the Earth system and predict its change over time.

Limited resources force an inherent tension between continuity of measurements and the introduction of new observation capabilities.[22] As a result, it is imperative that as technologies that were once ground-breaking in enabling observations of new variables become more routine, a shift in emphasis toward reduced cost through programmatic or technical innovation is needed. Otherwise, either the sustained monitoring of critical variables will be put at risk or innovation and new observations will stagnate as the need to fund long-term measurement records further strains an already resource-limited budget.

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[22] The evaluation of space-based continuity measurements in the context of quantified Earth science objectives was an important recommendation of the 2015 NRC report *Continuity of NASA Earth Observations from Space: A Value Framework* (NRC, 2015a).

The Venture-Continuity strand provides a much-needed opportunity to incentivize development of cost-efficient means to provide for sustained observations of those critical parameters for which development and implementation costs can be brought down significantly by leveraging innovation to reduce costs rather than improve performance. It is envisioned to be similar to the Venture-Mission strand, including full mission implementation costs whether for instruments, spacecraft, and launch vehicles or hosted payloads with hosting services included. Implementation of the Venture-Continuity strand will challenge the science and engineering communities to make full use of technical advances and programmatic opportunities in order to develop the low-cost capabilities that will be necessary to enable sustained monitoring.

Opportunities for Targeted Observables Not Allocated to a Flight Program Element

A number of Targeted Observables identified by the committee and shown in Table 3.3 were not specifically allocated to a flight program element:

- Aquatic-Coastal Biogeochemistry (details in Ecosystem Panel chapter)
- Salinity (details in Climate Panel chapter)
- Ocean Ecosystem Structure (details in Ecosystems Panel chapter)
- Radiance Inter-calibration (details in Climate Panel chapter)
- Magnetic Field Changes (details in Solid Earth Panel chapter)
- Soil Moisture (details in Hydrology and Ecosystems Panel chapters)
- Surface Water Height[23]

As discussed earlier in this chapter (e.g., Box 3.9) and summarized in Table 3.8, there are opportunities within the recommended program to potentially address each of the unallocated Targeted Observables. Opportunities include consideration via the open Earth Venture solicitations,[24] collaborations with international partners, or opportunistic inclusion in Earth System Explorer or Designated missions (when associated measurement needs can be accommodated within cost caps).

ACCOMPLISHING INTEGRATED SCIENCE WITH THE OBSERVING SYSTEM

The four elements of the ESAS 2017 observing program—Designated, Earth System Explorer, Incubation, and Venture—will augment the Program of Record to address a broad range of topics within Earth system science and applications, spanning both the panel priorities and ESAS 2017 Integrating Themes. Taken collectively, these ongoing and new observations will advance our understanding of Earth as a system and the interaction of its various components in ways that directly affect the way we live.

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[23] The Surface Water Height Targeted Observable is focused on observing several topographic-oriented aspects of both ocean and inland water (see Table 3.5 for details). A candidate implementation could be based on broad-swath altimetry, which is distinct from the along-track altimetry being addressed by the ESA/EUMETSAT/NASA/NOAA collaborative Sentinel-6A and -6B. Those missions will continue the climate record of sea level beyond Jason-3 through 2030, as reflected in the Program of Record. The US-French Surface Water and Ocean Topography (SWOT) mission (within the Program of Record) was recommended in ESAS 2007 as the first spaceborne demonstration of broad-swath altimetry and is scheduled to launch in 2021. The Program of Record does not include a follow-on to SWOT.

[24] For example, the unallocated Radiance Inter-calibration Targeted Observable has heritage to the CLARREO recommendation from ESAS 2007 and CLARREO Pathfinder in the POR; in not allocating this Targeted Observable to a flight element the committee noted the long-term value of this calibration facility was best achieved by seeking lower-cost options, such as Venture-Continuity, to enable multi-decade continuity of this important measurement.

TABLE 3.8 Implementation Opportunities for Non-Allocated Targeted Observables

Targeted Observable	Description	Related Science and Applications Objectives				Implementation Possibilities
			MI	VI	I	
Aquatic-Coastal Biogeochemistry	• Distribution, composition, and functioning of aquatic ecosystems and their biogeochemical impacts • Chlorophyll, particulate organic carbon and primary production • Phytoplankton biomass and composition	H			3a, 3b	Consider any related submissions to Venture solicitations, R&A efforts
		W				
		E	1c, 3a	1a	2b, 3b, 4a, 4b, 5a, 5b	
		C	2d		3c, 4d, 5b, 7b	
		S			4c	
Magnetic Field Changes	• Magnetic field changes	H				Consider any related submissions to Venture solicitations, R&A efforts
		W				
		E				
		C				
		S	5a		5b	
Ocean Ecosystem Structure	• Stocks of planktonic biomass • Primary productivity estimates • Mixed layer depth • Changes in particle biomass, particle size, spectral light attenuation differences	H				Consider opportunistic use of data from recommended Aerosols TO-2 to address TO-10; Consider any related submissions to Venture solicitations, R&A efforts
		W	3a			
		E		1b, 3a	3b, 4b, 5a, 5b	
		C	8d	2d	3d	
		S				
Radiance Inter-calibration	• Climate sensitivity • Inter-calibration of in-flight radiometers	H				Consider any related submissions to Venture solicitations
		W				
		E				
		C	2b, 2c, 5c, 7c	2a, 2h	2e, 5d, 7b	
		S				
Salinity	• Sea surface salinity	H			3a	Consider any related submissions to Venture solicitations, R&A efforts, technology development initiatives to reduce cost and improve performance
		W	3a			
		E			2b	
		C	6a, 7a		3d, 7d, 7e	
		S		3a		
Soil Moisture	• Soil, root zone moisture • Freeze/thaw, active layer monitoring • Evapotranspiration • GPP	H	2a, 2c	1a	4b, 4c, 4d	Consider any related submissions to Venture solicitations, R&A efforts, technology development initiatives to reduce cost and improve performance
		W	3a	2a		
		E			1d, 2c	
		C	3a, 5a, 6a, 7a		3c, 5b, 7b, 7e, 8	
		S	1c		4b, 6b	

TABLE 3.8 Continued

Targeted Observable	Description	Related Science and Applications Objectives				Implementation Possibilities
			MI	VI	I	
Surface Water Height	• Horizontal structure of ocean surface height • Two-dimensional geostrophic velocities • Bathymetry/gravity • Significant wave height • Tsunami height • Inland waters/ ecosystems • Tides and dissipation of tidal energy • Sea ice thickness • River flow and terrestrial water storage • River height variations for transport of material from land to ocean	H	1c			Consider any related submissions to Venture solicitations, R&A efforts
		W		3a		
		E				
		C	1a, 1b	1d, 4a, 6a, 7a, 8a, 8b, 8c	4b, 8g, 8i	
		S	3a		1d	

To illustrate the ability of the program to address integrated science, it is useful to consider the contributions of the Targeted Observables in the context of the three Integrating Themes examples discussed previously: Water and Energy Cycle, Carbon Cycle, and Extreme Events. Table 3.9 shows how the various Targeted Observables map to these Earth system themes. In most cases, each observable addresses elements of multiple integrating themes. It is clear from this mapping that each Targeted Observable will contribute substantially to integrated science, and that collectively they can advance progress in high-priority Earth system science challenges.

In addition to the contributions, listed earlier, of individual observations to advance Earth system science, simultaneous combined observations offer an opportunity for more comprehensive insight into critical Earth system processes. One example is the combination of the Aerosols observable, which targets direct aerosol radiative forcing and feedbacks by observing aerosol optical properties, with the Clouds, Convection, and Precipitation observable, which targets the effects of aerosol forcings and feedbacks by observing cloud thermodynamics and optical properties. The combination of the two produces a far more complete understanding of components of the energy cycle that have the strongest forcings and feedbacks.

Similarly, combining the Greenhouse Gases observable with the Terrestrial Ecosystem Structure and Surface Biology and Geology observables enables a more comprehensive tracking of sources of CO_2 as inferred from the quantity and locations of observed CO_2 and the sinks as inferred from biomass and ocean primary productivity. Observing the sources, sinks, and transport between them provides much more insight into the dynamics of CO_2 than any of the individual observations could.

These examples illustrate the value of a coordinated program with concurrent observations in advancing an integrated approach to Earth system science in which the whole of the observations is much greater than the sum of its parts.

TABLE 3.9 Potential Roles of Targeted Observables in Addressing ESAS 2017 Integrating Themes

Integrating Theme	Targeted Observable Contribution
Water and Energy Cycle	• *Aerosols:* Radiative forcing and feedbacks, aerosol cloud interaction • *Atmospheric Winds:* Role of winds in energy transport and evapotranspiration • *Clouds, Convection, and Precipitation:* Forcings and feedbacks, thermodynamic processes • *Greenhouse Gases:* Contributions of various greenhouse gases in Earth's energy balance • *Ice Elevation:* Ice-sheet contributions to the water cycle, modulation of ocean/atmosphere energy exchanges by sea ice • *Mass Change:* Movement of water throughout the Earth, ocean heat content • *Ocean Surface Winds and Currents:* Ocean/atmosphere energy and moisture exchanges, ocean energy transport • *Planetary Boundary Layer:* Energy and moisture exchanges in the boundary layer, cycling of water through evaporation and precipitation • *Snow Depth and Snow Water Equivalent:* Storage and distribution of water, latent energy associated with snowmelt, insulation modulating land/atmosphere energy exchanges, surface radiative balance associated with snow cover • *Surface Topography and Vegetation:* Cycling of water and energy through evapotranspiration, carbon uptake, soil moisture • *Terrestrial Ecosystem Structure:* Cycling of water and energy through evapotranspiration, carbon uptake, soil moisture
Carbon Cycle	• *Atmospheric Winds:* Surface fluxes, vertical and horizontal transport of CO_2 and CH_4 • *Greenhouse Gases:* Emissions and uptake of CO_2 and CH_4 and contributions to greenhouse warming • *Planetary Boundary Layer:* Inhibition of vertical transport of greenhouse gases • *Surface Biology and Geology:* Carbon uptake by terrestrial and marine ecosystems • *Surface Deformation:* Methane release from thawing permafrost • *Surface Topography and Vegetation:* Carbon uptake from terrestrial vegetation • *Terrestrial Ecosystem Structure:* Carbon uptake from terrestrial vegetation
Extreme Events	• *Aerosols:* Severe outbreak of air pollution in the boundary layer • *Atmospheric Winds:* Dynamic forcing of severe convective storms, transport of water vapor for heavy rain events and flash floods, extreme winds in severe storms, hurricanes and winter storms • *Clouds, Convection, and Precipitation:* Intense convective storms, floods, precipitation-induced landslides • *Ice Elevation:* Increased risks of storm surge associated with sea-level rise, episodic events associated with coastal erosion • *Ocean Surface Winds and Current:* Storm surge, hurricanes, and severe storm-induced maritime wind/wave hazards • *Ozone and Trace Gases:* Fire plumes, volcanic plumes, industrial disasters, surface ozone smog events, stratospheric ozone depletion events • *Planetary Boundary Layer:* Processes that affect severe weather • *Snow Depth and Snow Water Equivalent:* Flooding associated with rapid melt • *Surface Deformation:* Hazards related to landslides, earthquakes, volcanic eruptions, and both coastal and river erosion and flooding

DISPOSITION OF ESAS 2007 MISSIONS IN THE ESAS 2007 OBSERVING SYSTEM

The missions recommended by ESAS 2007 reflected the highest-priority science and application needs at the time. It is instructive to assess how the ESAS 2007 priorities are reflected within the ESAS 2017 recommended observing system, including the POR. Table 3.10 summarizes how the ESAS 2007 missions map to this committee's proposed observing system.

TABLE 3.10 Disposition of ESAS 2007 Priorities Within the Observing System Proposed by ESAS 2017

ESAS 2007 Mission	ESAS 2017 Disposition
NASA-DIRECTED	
SMAP	Implemented by NASA, in POR
ICESat-2	Implemented by NASA, in POR
DESDynI	Key objectives addressed in NASA POR via NISAR (in partnership with ISRO) and GEDI
HyspIRI	Objectives would be met with Surface Biology and Geology
ASCENDS	Objectives partially addressed in POR and recommended as a candidate for Earth System Explorer (Greenhouse Gases)
SWOT	Implemented by NASA in partnership with CNES, in POR
GEO-CAPE	Partially addressed by TEMPO in POR and by Aerosols in the Designated program element
ACE	Key objectives could be provided by a combination of Aerosols and Clouds, Convection, and Precipitation
LIST	Recommended under Incubation (Surface Topography and Vegetation)
PATH	Recommended under Incubation (Planetary Boundary Layer)
GRACE-II	GRACE-FO, implemented by NASA in partnership with GFZ, meets key objectives, as does Mass Change in the Designated program element, which seeks to ensure continuity
SCLP	Recommended as a candidate for Earth System Explorer (Snow Depth and Snow Water Equivalent)
GACM	Recommended as a candidate for Earth System Explorer (Ozone and Trace Gases)
3D-Winds (Demo)	Recommended as a candidate for Earth System Explorer and for Incubation (Atmospheric Winds)
NOAA-DIRECTED	
GPSRO	Implemented by NASA, NOAA, NSF, and international partners, in POR
XOVWM	Recommended as a candidate for Earth System Explorer (Ocean Surface Winds and Currents)
JOINT NASA-NOAA	
CLARREO	Partially implemented by NASA, in POR

ACHIEVING AN INSPIRATIONAL PROGRAM

The challenges of observing Earth from space naturally inspire innovation. As we look forward to the decade ahead, we seek to harness such inspiration to provide the bold but credible program the nation needs for making rapid progress in space-based Earth observation. This report's proposed program establishes a realistic, structured framework within which inspired progress can be made over the next decade. However, as noted in Chapter 2 (see the section "Programmatic Impediments and Vulnerabilities"), the committee also recognized the existence of numerous impediments to success. In response, the recommended program embraces the role of competition, strengthens the critical leveraging of international and commercial partnerships, ensures focused incubation of needed measurements that have been languishing through existing programmatic channels, and introduces robust guidance for maintaining science priorities. Through such changes, it seeks to break the mold of "business as usual" and achieve new, more effective ways of pursuing science and applications. In particular:

- Through the new competitive Earth System Explorer program element, the NASA Earth Science Program will be able to address previously identified high-priority Target Observables, leveraging the latest innovations and ideas available to proposers at the time of solicitation, and in full consideration of the domestic and international POR at the time. This will create opportunities for new competitors and spur innovations in Earth observations from space, capitalizing on the full potential of the aerospace and Earth science communities. It will also enable the programmatic flexibility NASA needs to optimize its flight program throughout the decade as domestic and international programs evolve.

- The Venture-Continuity line will incentivize reductions in the cost to maintain long-term measurement records, as will the recommended increase in ESTO funding for game-changing technology development (Chapter 4). Lower cost capabilities for measurement continuity will help reduce the inherent tension between long-term continuous measurements and the emergence of new observations, creating more fertile ground for Earth observation capabilities. These elements provide a much-needed programmatic mechanism to incentivize innovation in favor of cost efficiency rather than improved performance.
- The recommended Incubation program will make possible development of capabilities that are difficult to achieve through one-off competitive calls, something long sought by managers of Earth observation programs at NASA.
- The establishment of decision rules (Chapter 4) ensures that community guidance with respect to science priorities is well understood when adjustments to the NASA flight program are required due to budgets that are greater or less than anticipated, or when unanticipated events alter plans.

The committee believes this program changes the existing programmatic paradigm, enabling innovation while constraining cost and managing risk. The program rises to the Community Challenge presented in Chapter 1, ensuring effective use of resources to accomplish outstanding science and enable valuable applications over the coming decade and beyond.

REFERENCES

Ablain, M., J.F. Legeais, P. Prandi, M. Marcos, L. Fenoglio-Marc, H.B. Dieng, J. Benveniste, and A. Cazenave. 2017. Satellite altimetry-based sea level at global and regional scales. *Surveys in Geophysics* 38(1): 7-31.

ACE Science Study Team, A. da Silva, R. Swap, H. Maring, M. Behrenfeld, R. Ferrare, and G. Mace. 2016. *ACE 2011-2015 Progress Report and Future Outlook*. September. https://acemission.gsfc.nasa.gov/documents/ACE_5YWP-FINAL_Redacted.pdf.

Andela, N., D.C. Morton, L. Giglio, Y. Chen, G.R. van der Werf, P.S. Kasibhatla, R.S. DeFries, et al. 2017. A human-driven decline in global burned area. *Science* 356:1356-1362.

Asner, G.P., G.V.N. Powell, J. Mascaro, D.E. Knapp, J.K. Clark, J. Jacobson, T. Kennedy-Bowdoin, et al. 2010. High-resolution forest carbon stocks and emissions in the Amazon. *Proceedings of the National Academy of Sciences* 107:16738-16742.

Asner, G., R. Martin, D. Knapp, R. Tupayachi, C. Anderson, F. Sinca, N. Vaughn, and W. Llactayo. 2017. Airborne laser-guided imaging spectroscopy to map forest trait diversity and guide conservation. *Science* 355:385-389.

Asrar, G.R., J.W. Hurrell, and A.J. Busalacchi. 2013. The World Climate Research Program strategy and priorities: Next decade. In *Climate Science for Serving Society: Research, Modeling and Prediction Priorities*, eds. G.R. Asrar and J.W. Hurrell. Dordrecht: Springer SBM.

Baker, W.E., R. Atlas, C. Cardinali, A. Clement, G.D. Emmitt, B.M. Gentry, R.M. Hardesty, et al. 2014. Lidar-measured wind profiles: The missing link in the global observing system. *Bulletin of the American Meteorological Society* 95:543-.564.

Bauer, P., A. Thorpe, and G. Brunet. 2015. The quiet revolution of numerical weather prediction. *Nature* 525:47-55.

Bony, S., B. Stevens, D.M. Frierson, C. Jakob, M. Kageyama, R. Pincus, T.G. Shepherd, S.C. Sherwood, A.P. Siebesma, and A.H. Sobel. 2015. Clouds, circulation and climate sensitivity. *Nature Geoscience* 8(4):261-268.

Brown, S., P. Focardi, A. Kitiyakara, F. Maiwald, L. Milligan, O. Montes, S. Padmanabhan, R. Redick, D. Russel, V. Bach, and P. Walkemeyer. 2016. Demonstrating a low-cost sustainable passive microwave sensor architecture: The Compact Ocean Wind Vector Radiometer Mission. Pp. 5561-5564 in *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*.

Chen, J.L., C.R. Wilson, B.D. Tapley, and S. Grand. 2007. GRACE detects coseismic and postseismic deformation from the Sumatra-Andaman earthquake. *Geophysical Research Letters* 34(13):L13302.

Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, et al. 2013. Carbon and other biogeochemical cycles. Pp. 465-570 in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, et al. Cambridge: Cambridge University Press.

Davis, J.L., L.H. Kellogg, J.R. Arrowsmith, B.A. Buffett, C.G. Constable, A. Donnellan, E.R. Ivins, et al. 2016. *Challenges and Opportunities for Research in ESI (CORE)*. Report from the NASA Earth Surface and Interior (ESI) Focus Area Workshop. Arlington, VA, November 2-3, 2015.

Devred, E., K.R. Turpie, W. Moses, V.V. Klemas, T. Moisan, M. Babin, G. Toro-Farmer, M.H. Forget, and Y.H. Jo. 2013. Future retrievals of water column bio-optical properties using the Hyperspectral Infrared Imager (HyspIRI). *Remote Sensing* 5(12):6812-6837.

Dieng, H.B., A. Cazenave, B. Meyssignac, and M. Ablain. 2017. New estimate of the current rate of sea level rise from a sea level budget approach. *Geophysical Research Letters* 44:3744-3751.

Dietz, A.J., C. Kuenzer, U. Gessner, and S. Dech. 2012. Remote sensing of snow—A review of available methods. International *Journal of Remote Sensing* 33(13):4094-4134.

Drewry, D.J., E.M. Morris, G.D.Q. Robin, and G. Weller. 1992. The response of large ice sheets to climatic change. *Philosophical Transactions of the Royal Society B* 338:235-242.

Farahmand, A., and A. AghaKouchak. 2013. A satellite-based global landslide model. *Natural Hazards Earth System Sciences* 13:1259-1267.

Fasullo, J.T., C. Boening, F.W. Landerer, and R.S. Nerem. 2013. Australia's unique influence on global sea level in 2010-2011. *Geophysical Research Lett*ers 40:4368-4373.

Forsythe, M. 2007. "Atmospheric Motion Vectors: Past, Present, and Future." Presented at the ECMWF Seminar on Recent Development in the Use of Satellite Observations in NWP, September 3-7. https://www.ecmwf.int/sites/default/files/elibrary/2008/9445-atmospheric-motion-vectors-past-present-and-future.pdf.

Frankenberg, C., C. O'Dell, J. Berry, L. Guanter, J. Joiner, P. Köhler, R. Pollock, and T.E. Taylor. 2014. Prospects for chlorophyll fluorescence remote sensing from the Orbiting Carbon Observatory-2. *Remote Sensing of Environment* 147:1-12.

Fretwell, P., H.D. Pritchard, D.G. Vaughan, J.L. Bamber, N.E. Barrand, R. Bell, C. Bianchi, et al. 2012. Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere* 7:375-393.

Gonzalez, P., G.P. Asner, J.J. Battles, M.A. Lefsky, K.M. Waring, and M. Palace. 2010. Forest carbon densities and uncertainties from Lidar, QuickBird, and field measurements in California. *Remote Sensing of Environment* 114:1561-1575.

Gregg, W., and C. Rousseaux. 2017. Simulating PACE global ocean radiances. *Frontiers in Marine Science* 4:60.

Hammerling, D.M., A.M. Michalak, and S.R. Kawa. 2012. Mapping of CO_2 at high spatiotemporal resolution using satellite observations: Global distributions from OCO-2. *Journal of Geophysical Research: Atmospheres* 117(D6).

Han, S.C., J.M. Sauber, and F. Polllitz. 2016. Postseismic gravity change after the 2006-2007 great earthquake doublet and constraints on the asthenosphere structure in the central Kuril Islands. *Geophysical Research Letters* 43(7):3169-3177.

Hansen, M.C., P.V. Potapov, R. Moore, M. Hancher, S.A. Turubanova, A. Tyukavina, D. Thau, et al. 2013. High-resolution global maps of 21st-century forest cover change. *Science* 342:850-853.

Hinkel, J., D.P. van Vuuren, R.J. Nicholls, and R.J.T. Klein. 2013. The effects of adaptation and mitigation on coastal flood impacts during the 21st century. An application of the DIVA and IMAGE models. *Climatic Change* 117(4):783-794.

Hofmann, D.J., J.H. Butler, E.J. Dlugokencky, J.W. Elkins, K. Masarie, S.A. Montzka, and P. Tans. 2006. The role of carbon dioxide in climate forcing from 1979-2004: Introduction of the Annual Greenhouse Gas Index. *Tellus* 58(5):614-619.

Houborg, R., M. Rodell, B. Li, R. Reichle, and B. Zaitchik. 2012. Drought indicators based on model assimilated GRACE terrestrial water storage observations. *Water Resources Research* 48:W07525.

IPCC (Intergovernmental Panel on Climate Change). 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. Cambridge: Cambridge University Press.

IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. Core Writing Team, R.K. Pachauri, and L.A. Meyer. Geneva: IPCC.

Ivins, E.R., T.S. James, J. Wahr, E.J.O. Schrama, F.W. Landerer, and K.M. Simon. 2013. Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. *Journal of Geophysical Research: Solid Earth* 118(6):3126-3141.

Johnson, G.C., and D.P. Chambers. 2013. Ocean bottom pressure seasonal cycles and decadal trends from GRACE Release-05: Ocean circulation implications. *Journal of Geophysical Research: Oceans* 118(9):4228-4240.

Kavaya, M.J., J.Y. Beyon, G.J. Koch, M. Petros, P.J. Petzar, U.N. Singh, B.C. Trieu, and J. Yu. 2014. The Doppler aerosol wind (DAWN) airborne, wind-profiling coherent-detection lidar system: Overview and preliminary flight results. *Journal of Atmospheric and Oceanic Technology* 31(4):826-842.

Kay, J.E., and A. Gettelman. 2009. Cloud influence on and response to seasonal Arctic sea ice loss. *Journal of Geophysical Research: Atmospheres* 114 (D18).

Kelly, E.C., and M.B. Schmitz. 2016. Forest offsets and the California compliance market: Bringing an abstract ecosystem good to market. *Geoforum* 75:99-109.

Lang, T.J., S. Pédeboy, W. Rison, E.S. Cerveny, J. Montanyá, S. Chauzy, D.R. MacGorman, et al. 2017. WMO world record lightning extremes: Longest reported flash distance and longest reported flash duration. *Bulletin of the American Meteorological Society* 98(6):1153-1168.

Le Quéré, C., R.M. Andrew, J.G. Canadell, S. Sitch, J.I. Korsbakken, G.P. Peters, A.C. Manning, T.A. Boden, P.P. Tans, and R.A. Houghton. 2016. Global carbon budget 2016. *Earth System Science Data* 8(2):605-649.

Leuliette, E.W., and R.S. Nerem. 2016. Contributions of Greenland and Antarctica to global and regional sea level change. *Oceanography* 29(4):154-159.

Llovel, W., J.K. Willis, F.W. Landerer, and I. Fukumori. 2014. Deep-ocean contribution to sea level and energy budget not detectable over the past decade. *Nature Climate Change* 4(11):1031-1035.

Lythe, M.B., D.G. Vaughan, and the Bedmap Consortium. 2001. BEDMAP: A new ice thickness and subglacial topographic model of Antarctica. *Journal of Geophysical Research* 106:11335-11351.

Maschhoff, K.R., J.J. Polizotti, and J. Harley. 2015. MISTiCTM Winds, A Micro-Satellite Constellation Approach to High-Resolution Observations of the Atmosphere Using Infrared Sounding and 3d Winds Measurements. Presented at the 29th Annual AIAA/USU Conference on Small Satellites, Logan, UT, August 8-13.

Montzka, S.A., E.J. Dlugokencky, and J.H. Butler. 2011. Non-CO_2 greenhouse gases and climate change. *Nature* 476:43-50.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2016a. *Next Generation Earth System Prediction: Strategies for Subseasonal to Seasonal Forecasts*. Washington, DC: The National Academies Press.

NASEM. 2016b. *The Future of Atmospheric Chemistry Research: Remembering Yesterday, Understanding Today, Anticipating Tomorrow*. Washington, DC: The National Academies Press.

Nerem, R.S., B.D. Beckley, J.T. Fasullo, B.D. Hamlington, D. Masters, and G.T. Mitchum. 2018. Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the National Academy of Sciences U.S.A.* 115(9):2022-2025.

NOAA (National Oceanic and Atmospheric Administration). 2001. *U.S. Detailed National Report on Systematic Observations for Climate: U.S. Global Climate Observing System (U.S.-GCOS) Program*. August. https://www.ncdc.noaa.gov/gosic/global-climate-observing-system-gcos/us-gcos-program.

NRC (National Research Council). 1999. *Adequacy of Climate Observing Systems*. Washington, DC: National Academy Press.

NRC. 2008. *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring*. Washington, DC: The National Academies Press.

NRC. 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Washington, DC: The National Academies Press.

NRC. 2015a. *Continuity of NASA Earth Observations from Space: A Value Framework*. Washington, DC: The National Academies Press.

NRC. 2015b. *The Space Science Decadal Surveys: Lessons Learned and Best Practices*. Washington, DC: The National Academies Press.

Penner, J.E., M.J. Prather, I.S.A. Isaksen, J.S. Fuglestvedt, Z. Klimont, and D.S. Stevenson. 2010. Short-lived uncertainty? *Nature Geoscience* 3(9):587-588.

Reillon, V. 2017. "Securing the Copernicus programme—Why EU Earth Observation Matters." European Parliamentary Research Service. http://www.copernicus.eu/sites/default/files/library/EPRS_BRI_Copernicus_matters.pdf. Accessed August 4, 2017.

Rignot, E., W.A. Salas, and D.L. Skole. 1997. Mapping deforestation and secondary growth in Rondonia, Brazil, using imaging radar and thematic mapper data. *Remote Sensing of Environment* 59:167-179.

Rignot, E., I. Velicogna, M.R. Van Den Broeke, A. Monaghan, and J. Lenaerts. 2011. Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters* 38(5):L05503.

Riva, R.E.M., J.L. Bamber, D.A. Lavallée, and B. Wouters. 2010. Sea-level fingerprint of continental water and ice mass change from GRACE. *Geophysical Research Letters* 37(19):L19605.

Rodell, M., H.K. Beaudoing, T.S. L'Ecuyer, W.S. Olson, J.S. Famiglietti, P.R. Houser, and E.F. Wood. 2015. The observed state of the water cycle in the early twenty-first century. *Journal of Climate* 28(21):8289-8318.

Save, H., S. Bettadpur, and B.D. Tapley. 2016. High resolution CSR GRACE RL05 mascons. *Journal of Geophysical Research: Solid Earth* 121:7547–7569.

SCC (Social Cost of Carbon, U.S. Government, Interagency Working Group). 2010. *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis—Under Executive Order 12866*. https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf.

Sherwood, S.C., S. Bony, O. Boucher, C. Bretherton, P.M. Forster, J.M. Gregory, and B. Stevens. 2015. Adjustments in the forcing-feedback framework for understanding climate change. *Bulletin of the American Meteorological Society* 96(2):217-228.

Simmons, A., J.L. Fellous, V. Ramaswamy, K. Trenberth, G. Asrar, M. Balmaseda, J.P. Burrows, et al. 2016. Observation and integrated Earth-system science: A roadmap for 2016-2025. *Advanced Space Research* 57(10):2037-2103.

Sneed, M., J.T. Brandt, and M. Solt. 2014. *Land Subsidence, Groundwater Levels, and Geology in the Coachella Valley, California, 1993-2010*. No. 2014-5075. U.S. Geological Survey, Reston, VA.

Tapley, B.D., S. Bettadpur, J.C. Ries, P.F. Thompson, and M.W. Watkins. 2004. GRACE measurements of mass variability in the Earth system. *Science* 305(5683):503-505.

Treuhaft, R.N., B.E. Law, and G.P. Asner. 2004. Forest attributes from radar interferometric structure and its fusion with optical remote sensing. *AIBS Bulletin* 54(6):561-571.

Tucker, S.C., C. Weimer, M. Adkins, T. Delker, D. Gleeson, P. Kaptchen, B. Good, M. Kaplan, J. Applegate, and G. Taudien. 2015. Optical Autocovariance Wind Lidar (OAWL): Aircraft test-flight history and current plans. *Proceedings of SPIE* 9612(96120E).

U.S. Commission on Ocean Policy. 2004. *An Ocean Blueprint for the 21st Century*. Final Report. Washington, DC.

Velicogna, I., T.C. Sutterley, and M.R. Van den Broeke. 2014. Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time variable gravity data. *Geophysical Research Letters* 41(22):8130-8137.

Voigt, F., F. Giulio-Tonolo, J. Lyons, J. Kucera, B. Jones, T. Schneiderhan, G. Platzeck, et al. 2016. Global trends in satellite-based emergency mapping. *Science* 353(6296):247-252.

Von Schuckmann, K., M.D. Palmer, K.E. Trenberth, A. Cazenave, D. Chambers, N. Champollion, J. Hansen, et al. 2016. An imperative to monitor Earth's energy imbalance. *Nature Climate Change* 6(2):138-144.

Warrick, F. 2016. *NWP SAF AMV Monitoring: the 7th Analysis Report (AR7)*. Document NWPSAF-MO-TR-032, Version 1.0 http://nwpsaf.eu/monitoring/amv/nwpsaf_mo_tr_032.pdf.

Zeng, X., S. Ackerman, R.D. Ferraro, T.J. Lee, J.J. Murray, S. Pawson, C. Reynolds, and J. Teixeira. 2016. Challenges and opportunities in NASA weather research. *Bulletin of the American Meteorological Society* 97(7):ES137-ES140.

Zhang, C. 2013. Madden-Julian Oscillation: Bridging weather and climate. *Bulletin of the American Meteorological Society* 94(12):1849-1870.

Zilberman, N., and G. Maze. 2015. *Report on the Deep Argo Implementation Workshop*. http://www.argo.ucsd.edu/DAIW1report.pdf.

4

Agency Programmatic Context

Chapter 3 described the committee's recommended decadal research strategy to advance Earth system science. Ultimately, our goal is to understand Earth as a system in ways that provide benefit and value to society. Achieving such an understanding requires programs that translate Earth observation data into applications that meet user needs—the subject of the first part of this chapter. The "programmatic context" in which research at the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and U.S. Geological Survey (USGS) is carried out and applied is the subject of the second part of this chapter.

This chapter is not intended as a general review of all programmatic elements within these agencies (which is beyond the committee's statement of task). Instead, it focuses on those programmatic elements that are specifically related to the space-based observing system and that the committee felt required particular discussion. Many important programmatic elements, such as workforce, education, and outreach—and even some (such as product generation processes and computational advances such as machine learning) that are more closely related to the observing system itself—are not included. Programmatic topics not directly discussed within this chapter may be addressed to some extent by the guidance in the strategic framework presented in Chapter 2.

MULTIAGENCY CONTEXT

Some contextual issues are specific to the implementing agencies, but many are common. The topics presented in this section represent opportunities for each agency to advance individually as well as prospects for cross-agency sharing of best practices to advance together.

Advancing the State of Applications

Applications are often viewed in the context of "practical things that get done with scientific knowledge." Gradually, this perception is expanding as we come to appreciate the intellectual and practical challenges of ensuring applied impacts from the fundamental science that has been the core of the community's work. Applications challenges are many, from how to understand the world's multiplicity of use cases to more rapidly transitioning knowledge into practical use. These challenges certainly reflect many practical problems, but they also embody a set of intellectual problems that are every bit as important as the foundational Earth science from which they are built.

Importance of an Applications Perspective

The first decadal survey for Earth sciences and applications (ESAS 2007; NRC, 2007) promoted the proposition that the application of scientific knowledge about the Earth system was as important as acquiring it in the first place. This was not a new insight about the Earth sciences, but it was important to articulate it clearly to NASA, NOAA, and USGS. The current decadal survey (ESAS 2017) reinforces this view. The benefits to society of Earth science research are the partners of scientific discovery and progress; they are more than serendipitous by-products of basic research, but are often co-equal in importance. Their impacts on society, from safety to economics (Box 4.1) can be enormous. Conversely, scientific discoveries in the Earth sciences also generate important insights for the use of that new knowledge.

Each of the agencies whose programs and interests we are examining in this survey has a long history of promoting the applications of their science. For USGS, applying their research to land management issues within the Department of Interior, and to mapping for exploration, planning, and management is part of their intrinsic mission. NOAA has both research and policy/operational components under one roof, from the National Weather Service to the National Marine Fisheries Service, and has experience with transitioning knowledge from research to operations and policy. NASA has no *formal* role in operations (with specific exceptions, notably its formal role in ozone monitoring), but it is actively involved in promoting applied uses of its research and in providing policy-relevant information for global environmental issues, such as tropical deforestation, stratospheric ozone depletion, and climate change.

Valuing information for climate-related purposes is particularly challenging, given the extent to which impacts occur in the far future. Nevertheless, the community is making progress on economic tools. A major challenge for valuing information within any global climate observing system is illustrated through the example of seasonal- to decadal-scale prediction. Current climate studies most often rely on observations designed not for climate but for weather or basic research. The former often lack the accuracy needed for decadal time scale climate change, while the latter struggle to achieve continuity of multidecade climate change records (NRC, 2007; NASEM, 2015; Weatherhead et al., 2017; Trenberth et al., 2013). Lack of accuracy of observations on decade time scales has also been shown to delay detection of anthropogenic climate change trends by decades (Leroy et al., 2008; Wielicki et al., 2013).

These delays indicate a substantial societal value for the international community to design and implement an observing system designed specifically to meet climate change requirements. Recent studies have estimated the economic value of a more accurate and rigorous global climate observing system at US $10 trillion to $20 trillion (Cooke et al., 2014, 2016b; Hope, 2015; Weatherhead et al., 2017). Return on investment of a tripling of the current global investment in climate research is estimated at $50 to $100 for every $1 invested (Cooke et al., 2014, Weatherhead et al., 2017). At these levels, even a factor of 5 uncertainty in the economic analysis does not change the final conclusion: development of a more accurate and complete global climate observing system, climate system analysis, and climate modeling is a very effective economic investment. Several reports have also discussed improved methods for the design of a more rigorous climate observing system (Dowell et al., 2013; NASEM, 2015; Weatherhead et al., 2017).

These recent reports and studies suggest a need to consider the appropriate level of investment in Earth observations and suggest that the most cost-effective approach would be a much higher level of investment than current national and international levels. For climate change in particular, society will

BOX 4.1 THE FINANCIAL AND NONMONETARY VALUE OF EARTH OBSERVATIONS

The breadth of use of Earth science for societal benefit is well documented (see NSTC, 2014; NRC, 2001, 2002, 2003, 2007, 2012, 2013; NASA, 2014; Macauley, 2009; Macauley and Laxminarayan, 2010; CCSP, 2008; among other studies). These studies tend to frame societal benefit as, for example, "the data helped in deployment of disaster relief" but provide less insight into why the data were useful, such as "the availability of data within two hours at 10 km resolution allowed deployment of disaster relief twice as fast as without the data and enabled an estimated *x* percent more lives to be saved." But defining the counterfactual is very challenging.

The value of information (VOI), developed in the 1960s (see Savage, 1954; Hirshleifer and Riley, 1979; McCall, 1982; Bikhchandani et al., 2013), provides an answer to the question "by how much has information influenced a decision to take (or not take) an action?" The canonical example is a weather forecast, with the likelihood of rain influencing decisions about when to harvest and the "value" of the information is derived directly from the value of the decision—in this case, the value of the forecast is derived directly from the value of the harvest. A large body of literature uses VOI for natural resource management, including weather and crop forecasting (Adams et al., 1995; Babcock, 1990; Considine et al., 2004; Katz and Murphy, 1997; Lazo and Waldman, 2011; Nordhaus, 1986; Nelson and Winter, 1964; Roll, 1984; Sonka et al., 1987; Bradford and Kelejian, 1977; Lave, 1963) and geologic mapping (Bernknopf et al., 1997).

A growing body of literature uses VOI specifically to value Earth science satellite data (Table 4.1.1), with applications from insurance, agriculture, forestry, water quality, drought, human health, disaster relief, and carbon pricing. VOI is not limited to financially denominated values. VOI methods can also integrate nonmarket values including nonuse values, option values, and existence values (Freeman, 2003; Bernknopf and Pearlman, 2016).

TABLE 4.1.1 Examples of the Use of Value of Information (VOI) Methodology to Value Earth Science Satellite Data

Value of Information Methodology	Earth Science Satellite Data Use
Price- and cost-based	Weather data for weather insurance (Osgood and Shirley, 2012) Drought and land-use information for index insurance (Skees et al., 2007) Losses averted from vector-borne disease (Hartley, 2012) Forest carbon sequestration (Macauley and Sedjo, 2011; Sedjo and Macauley, 2011; Macauley, 2010; Richardson and Macauley, 2012; Macauley and Richardson, 2011)
Probabilistic	Bayesian belief networks (Kousky and Cooke, 2012)
Regulatory cost-effectiveness and policy evaluation	Nonpoint source groundwater pollution (Bernknopf et al., 2012) Monitoring water quality (Bouma et al., 2009) Social cost of carbon (Cooke et al., 2014, 2016a, 2016b)
Econometric modeling and estimation	Productivity (agriculture; Tenkorang and Lowenberg-DeBoer, 2008) Forestation (Pfaff, 1999)
Simulation modeling and estimation	Land use and climate change (Fritz et al., 2012)

manage Earth's environment indefinitely into the future. An international observing system designed for this purpose appears to be the most cost-effective approach.

Definition of Applications in This Report

A variety of functions could be expressed by the term "applications." For the purposes of this report, we focus primarily on two of these:

Direct use of remote sensing products in an operational context. This is probably the most commonly understood use of the term applications—data products from remote sensing are used more or less directly in an operational program. They may be used directly to initialize models for numerical weather forecasting, for example. But remote sensing data products can also be used as part of an operational program without necessarily being used for parameter estimation. The use of vegetation index data products, for example, is an essential feature of the Famine Early Warning System,[1] which is a collaboration involving NASA, NOAA, and USGS. Remote sensing products are increasingly used in a large variety of ways to improve decision making by government agencies and nongovernment end-users, as well as individuals who make use of a reliable stream of this type of information in their daily lives.

Using remote sensing information in support of decision- and policy-relevant issues. Objective measurements are of critical importance to build understanding of issues around which policy questions are debated and to support decisions made by individuals, businesses, and government organizations. The ability to measure the loss of humid tropical forest in an objective and replicable way through Landsat data has become an extremely powerful tool for understanding the magnitude of tropical deforestation, and more generally, rates of land-cover and land-use change on global scales. In Brazil this measurement capability has become part of the government's operational program for enforcing laws forbidding deforestation in some areas of the Amazon. Measurements of Earth's radiation budget, total column ozone, sea-level rise, or ice extent and mass balance have similar roles. They are not necessarily immediately incorporated into operational models or used in operational programs, but they are crucial for a more complete understanding of Earth science issues that are actively discussed and debated in policy forums. One of the earliest examples is the observations of the ozone hole over Antarctica, which led to the 1987 Montreal Protocol. Measurements that fall into this category are also of high value from a purely scientific standpoint—there is little to differentiate their scientific value from their applications value from an information perspective. This is a type of application that is very common in the NASA Earth Science portfolio.

Operations and applications are not identical, and it is often important to make a clear distinction between the two terms. For example, NOAA has a clear operations mandate that is quite different from NASA's support for applications of data from its scientific satellites. In general, this report does not focus on that distinction. Both operations and applications are considered to be applied uses for observations, in contrast to scientific uses. This distinction is generally reflected in the report rather than that between operations and applications, except in specific instances when the latter is relevant to a particular discussion.

Examples of Current and Potential Applications

Table 4.1 shows the wealth of both existing and potential future applications from the interdisciplinary panels' responses to a survey from the steering committee. Several important points emerge that are

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[1] Information on FEWS-NET is available at https://www.fews.net/.

TABLE 4.1 Examples of Issues Addressed with Remote Sensing, as Responses to a Survey of the Panels

Societal Issue	Climate	Earth Surface and Interior	Hydrology	Marine and Terrestrial Ecosystems	Weather and Air Quality
Food security	Y		Y	Y	Y
Human health	Y		Y	Y	Y
Greenhouse gases management	Y			Y	Y
International environmental agreements and treaties	Y	Y		Y	Y
Markets for ecosystem services			Y		Y
Environmental conservation, protection			Y	Y	Y
Extreme events and hazard prediction and response	Y	Y	Y	Y	Y
Urbanization and other demographic change		Y	Y		Y
Internet applications		Y			Y
Improved weather prediction	Y		Y		Y

relevant to NASA, NOAA, and USGS. All the panels have salient examples of products that could fit in each of the two preceding categories. None of the panels perceived that the goal of being able to apply the measurements was in conflict with being scientifically interesting and important.

Barriers to Improving Applications

ESAS 2007, as well as many other studies, identified a number of barriers to improving the applications use of remote sensing data and science. The most studied examples are those in the research-to-operations challenges exemplified in the relationship between NASA and NOAA vis-à-vis measurements that eventually find themselves being used in operational forecast products.

The National Academies of Sciences, Engineering, and Medicine itself has examined these issues in many reports over the past decade. There are barriers due to funding constraints, which force choices between new and sustained capabilities. These arise from the understandable and often justifiable conservatism of operational agencies taking on new research products, from technical evolution being too rapid for operations, and from research not taking sufficiently into account the known applications. In nonoperational realms, much of the difficulty stems from resources, and from not appreciating the many different ways in which Earth system measurements might be applied. In addition, the technical requirements for accessing and analyzing remote sensing data can still be overwhelming to many user communities, because they require technical skills that are not often widespread. Lack of standard products with simple documentation can also be a large impediment, requiring users to be satellite experts in order to apply the data. If applications are viewed as an add-on requirement, to be satisfied only if all scientific requirements can be addressed, then they will inevitably be curtailed when budget constraints are inevitably encountered.

Opportunities for Future Investment

NASA has chosen to create and fund a separate Applications program, although there are clearly applications of its remote sensing throughout its program. NOAA has created process teams and collaborations with NASA and its own operational users, to improve communications and intake of research data into operational contexts. USGS, through its sponsorship of the Landsat Science Team, has internalized applications and research in a more seamless manner, although its task is substantially simpler by being primarily concerned with only one data stream.

All three agency programs would benefit from a longer-term, strategic view of how the applications perspective might be improved. There is limited opportunity in these three agencies for research on the science of how to make applications easier and more effective to achieve. Individual projects and "case study" approaches can be successful, but a more structured assessment process is needed to ensure that lessons learned from one project are transferable to future initiatives. In the context of global change science, the National Academies has written a number of reports that are immediately relevant to this problem in the context of use-based science, decision support, co-production of knowledge, and similar issues. NASA, NOAA, and USGS can benefit from substantially improving research-to-operations, applications development, and other aspects of the general process for gaining applied benefits from science.

Applications are often viewed as an engineering problem—constructing an approach for using or disseminating knowledge generated through scientific exploration. Increasingly, the applications field is becoming associated with a science of its own (Dozier and Gail, 2009) related to generating new knowledge about how to effectively apply scientific results, how to rapidly transition science to societal benefits, who potential users are and how to reach them, ways to achieve the broadest possible impacts of science, and much more. NASA, NOAA, and USGS can all benefit by embracing this deeper view of the academic challenges associated with effective applications.

The final missing piece of applications research in the agencies is the very initial phase of creating applications—supporting studies that have an idea about how an application might work, and then attempting to create a community for it, and demonstrate its utility. To expand the potential applications of Earth observations, it would be beneficial to support "proof-of-concept" application studies. Investigators could propose research to evaluate potential data applications, whether a preliminary idea, or a more mature approach to expand the use of remote sensing data.

Finding 4.1: NASA, NOAA, and USGS applications-oriented programs have successfully transitioned remote-sensing-based research into applications of societal, economic, and operational value, but much more is both needed and possible. The transition has recognized barriers: (1) conservatism by operational agencies that is often justified but may also make them slow to adopt advances; (2) lack of early involvement in the research component of the research-to-applications process by operational agencies; (3) a shortage of specific funds and well-defined responsibilities for ensuring the rapid and effective realization of applications from research; and (4) insufficient academic focus on the science of applications.

Recommendation 4.1: NASA, NOAA, and USGS should reduce barriers to applied uses of remote-sensing research and seek innovative ways to accelerate the transition of scientific research into societal benefits.

End-to-End Information Systems

Effective use of Earth information increasingly requires viewing that information within the context of an end-to-end system, involving many elements beyond observations alone. This concept is widely understood but often still poorly implemented, both for science and for applications. Technological advances, including those available through commercial services, have enabled much of this just within the last decade. In many ways, this systematic connection of observing systems to intermediate data processing steps and ultimately to scientific and practical end-uses constitutes an information infrastructure. Elements of this infrastructure exist in isolation, but to a growing extent this infrastructure is integrated at local, national, and even international levels. Such integration presents exciting new opportunities as well as challenges. It requires its own investments by the nation, led by this report's sponsoring agencies, consistent with the strategic framework outlined in Chapter 2.

The topic of end-to-end information is critical to both scientific and applications progress over the next decade. Breakthrough science will be done by virtual science teams collaborating through complex, multiobservation data sets. Important new applications will emerge as advanced data systems enable the fusion of multiple, diverse data sources and the rapid communication of decision-support information to governments, businesses, and individuals. However, comprehensive treatment of the topic is outside the statement of task of this committee. For that reason, discussion of this topic is limited within the report.

Modeling and Prediction

Satellite observations are instrumental to development and continued improvement of numerical weather prediction (NWP) and Earth system models (ESMs). These models incorporate our best understanding of the Earth system, integrate the best available satellite and in situ observations, help us interpret the observations to improve our understanding, and provide the best tools for making valuable forecasts of the future. A seamless ESM prediction system connecting weather to climate time scales is fast becoming a reality (Palmer et al., 2008; Hoskins, 2013; Bauer et al., 2015). The growing emphasis on prediction at subseasonal-to-seasonal (S2S) scales increases the importance of resolving couplings within the Earth system. Increasing use of satellite data in NWP has improved weather forecast quality, and satellite observations provide critical data for the verification and improvement of ESMs. The spatial resolution of these models steadily increases, and the range of interacting Earth system variables that they describe steadily expands to serve scientific and applications needs.

Satellite observations now provide more than 90 percent of all data for global NWP model initialization, though nonsatellite sources remain critically important as well. Sustained satellite observations have provided critical data for climate model evaluation. They include, for example, two decades of global precipitation[2] and surface winds[3] and three decades of infrared and microwave (following the launch of TRMM in November 1997) sea-surface temperature measurements[4] (e.g., Buckley et al., 2014; Banzon et al., 2016). Satellite data for atmospheric composition from instruments on Terra, Aqua, and Aura, in combination with advanced atmospheric models, have provided the basis for quantifying the global burden of disease from air pollution (Bauer et al., 2015). The NASA Global Modeling and Assimilation Office (GMAO) has made major contributions to assimilate satellite data to improve the global mapping of

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[2] From instruments on the NASA-Japan Aerospace Exploration Agency [JAXA] Tropical Rainfall Measuring Mission [TRMM] and Global Precipitation Measurement [GPM] satellites.

[3] From the NASA scatterometer (NSCAT) carried on the Japanese Advanced Earth Observing Satellite (ADEOS); the wind scatterometer carried on the European Remote Sensing Satellite, generation 2 (ERS-2); Quick Scatterometer (QuikSCAT); and the advanced scatterometer (ASCAT) carried on MetOp (Meteorological Operational satellite programme), a series of polar-orbiting meteorological satellites developed by the European Space Agency and operated by EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites).

[4] For example, infrared observations via the Along-Track Scanning Radiometer (ATSR) series of instruments that began in 1991 and the multichannel sea surface temperature (SST) data from the Advanced Very High Resolution Radiometer (AVHRR) series. Microwave measurement of SST have been made by the TRMM Microwave Imager (TMI) and the Advanced Microwave Sounding Radiometer (AMSR)-E.

ozone (Wargan et al., 2015) and polar stratospheric clouds (Stajner et al., 2007), and has provided analysis and reanalysis data for atmospheric chemistry models in NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA and MERRA-2). The user community has been served well by NASA's commitment to being an "end-to-end" agency where satellite observations are carried to their ultimate scientific applications using advanced numerical models.

Earth System Modeling

ESMs have evolved over the last 20-30 years from uncoupled atmospheric NWP and climate models to coupled atmosphere-ocean-land-ice models with complex model physics (e.g., Puri et al., 2013). Recent advances in high-performance computing and computer technology such as the Earth Simulator over the last decade have made it possible to experiment with global cloud-permitting (3-5 km grid resolution) simulations in the Japan Meteorological Agency (JMA) Nonhydrostatic Icosahedral Atmospheric Model (NICAM) and the National Center for Atmospheric Research Model for Prediction Across Scales (MPAS), and the NASA Goddard Earth Observing System Version 5 (GEOS-5). GEOS-5 has the capability of simulation of global weather at 1.5 km resolution and detailed simulation of atmospheric chemistry with c720 cubed-sphere resolution (~12 km). Improvements in ocean modeling (e.g., Griffies et al., 2016; Rocha et al., 2016), in ice-sheet modeling (e.g., Larour et al., 2012), in the representation of the coupled ice-ocean system (e.g., Buehner et al., 2017), and in ocean state estimation (e.g., Forget et al., 2015; Penny et al., 2015; Stammer et al., 2016) have also played critical roles in advancing Earth system modeling. Research investments by the National Science Foundation (NSF) and Office of Naval Research (ONR) in cloud-resolving (~1 km) coupled atmosphere-ocean-land regional models over the last 20 years have contributed to the development of global cloud-permitting coupled NWP and ESMs, which are expected to become operational at the European Centre for Medium-Range Weather Forecasts (ECMWF), JMA, the UK Met Office, and other operational centers in the coming decade.

The plan for the national Next-Generation Global Prediction System (NGGPS), initiated by NOAA, in collaboration with the U.S. Navy and NASA, focuses on improving model prediction that could extend weather forecast lead-time from 1-2 weeks to a month. NGGPS will include a global cloud-permitting capability in ESMs. Although coordination of distributed activities among agencies is a good start (Carman et al., 2017), realizing the NGGPS vision requires strong commitment and funding support by NOAA and other agencies.

Data Assimilation

Data assimilation systems associated with NWP models now weave multiple threads of global satellite and in situ observations into the best available estimate of the detailed state of the Earth system for prediction and analysis. Assimilation of satellite observations has played a leading role in extending the range of weather forecasts over the past two decades. Assimilation of chemical observations from satellites is being used to initialize air quality forecasts. The analysis fields produced through data assimilation, by merging satellite and in situ observations and model information, provide us with continuous global information on the state of the Earth system, which is used in a wide range of Earth system science and applications.

Three important developments over the last two decades have led to significant improvements in model initialization and predictions (Bauer et al., 2015). First, the implementations of 4DVar data assimilation at operational centers, started at ECMWF in 1997 and followed by Meteo-France, the UK Met Office, JMA, Environmental Canada, and the U.S. Naval Research Laboratory, have set a milestone for NWP. Second, this approach is further improved by direct assimilation of satellite data in their native state by including a forward model to predict the native satellite data from the model state. Third, the recent trend toward using flow-dependent, ensemble-based estimates of background error covariances and hybrid ensemble and variational data assimilation have been the main advances of atmospheric data assimilation in recent years (Bonavita, 2014; Bonavita et al., 2015), which is also used in current Observing System Experiments (OSEs) for assessing satellite data impact on NWP.

There are many examples of assimilations of new Earth observations in operational analysis systems. Assimilation of Soil Moisture Active-Passive (SMAP) Tb observations in the ensemble-based NASA GEOS-5 land-surface data assimilation system at GMAO has produced the Level 4 surface and root zone soil moisture product for a broad range of applications (Reichle and De Lannoy, 2015). Janiskova (2015) describes the assimilation of CloudSat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) radar and lidar data into the ECMWF operational system and impact on the global analysis. NOAA directly assimilates satellite- and ground-based cloud data into its regional models (Benjamin et al., 2016). NASA, NOAA, and NSF have supported the development of ocean models and ocean data assimilation (e.g., Forget et al., 2015; ECCO Consortium, 2017a,b), which will eventually provide the ocean component for subseasonal-to-seasonal (S2S) NWP and for ESMs.

The next-generation ESMs will weave the coupled atmosphere-wave-ocean-land-sea ice components with data assimilation systems. Augmented satellite observations of the atmospheric variables (e.g., moist physical and dynamic processes, atmospheric composition, wind, and planet boundary layer [PBL] structure) together with observations of the ocean, land, biosphere, and cryosphere will be critical for development of physically based coupling of the components of the Earth system. The resolution and scope of ESMs will also continue to increase, resulting in more explicit representation of important Earth system processes and more effective coupled assimilation of a wide range of satellite data. A truly integrated Earth system modeling and analysis system will make the seamless weather-climate prediction a reality.

Reanalysis

Reanalysis products are widely used in Earth sciences (Kalnay et al., 1996). Numerous reanalysis projects have been undertaken to assimilate observations from a variety of sources—ground-based stations, ships, airplanes, and satellites—and forecasts from NWP models. Reanalysis efforts began in the atmospheric community and have since been extended to oceans (Balmaseda et al., 2013) with steps developed toward consistent reanalyses of the coupled climate system (Bosilovich et al., 2015).

Reanalysis products are commonly created using a stable data assimilation system that blends observations and model-based forecasts to produce gridded fields representing hundreds of variables with synoptically consistent spatial and temporal coverage extending over multiple decades. This combination of space-time uniformity and long time series of variables that include many not available from observations directly is attractive and makes the reanalyses relatively straightforward to handle. However, it is important to note that reanalysis products are blends of observations and models—not observations themselves. Some warn that reanalysis data cannot be equated with "real" observations and measurements (e.g., Schmidt, 2011; Bosilovich et al., 2013), while others argue the differences from actual observations are smaller than might be expected (Parker, 2016). The value of reanalysis versus observations is a complex issue, and for a given variable it depends in part on how well relevant physical processes are represented in the models used. Box 4.2 provides two examples of reanalysis.

BOX 4.2 THE IMPORTANT ROLE OF REANALYSIS IN UNDERSTANDING THE EARTH SYSTEM

Figures 4.2.1 and 4.2.2 provide two examples of the use of reanalysis, one highlighting the advantages of reanalysis and the other underscoring its challenges.

Figure 4.2.1 shows trends in 2 m land-surface temperature derived from reanalysis. Land-surface temperature trends from direct in situ observations suffer from a number of complicating factors such as station siting, instrument changes, changing observing practices, urban effects, land cover, land-use variations, and statistical processing, which have all been hypothesized as introducing artifacts on trends presented by the Intergovernmental Panel on Climate Change (IPCC) and others. Compo et al. (2013) ignore all air temperature observations and infer the land-surface temperature from observations of barometric pressure, sea-surface temperature (SST), and sea-ice concentration using a physically based data assimilation system referred to as the 20th Century Reanalysis (20CR) (Compo et al., 2011). As the 20CR does not use temperature observations from land stations, it is entirely independent of those observations. Nevertheless, the time variations of TL 2 m (TL 2m refers to near-surface (2 m) air temperature over land) in the 20CR are very similar to those previously reported in the station-based data sets over both the 1901 to 2010 period and the more rapidly warming 1952 to 2010 period.

Figure 4.2.2 shows the trends in the atmospheric column integrated water vapor over a 30-year period over oceans expressed as a sensitivity of percent change in column water vapor per degree of SST warming. This sensitivity is thought to be a fundamental metric of the water vapor feedback that contributes the majority of the warming to forced changes of climate. Four independent observational records (in red) are shown being close to the theoretical guidance of Clausius-Clapeyron theory ranging between 6 and 7 percent/K (horizontal lines). This same trend is derived from six different reanalysis data records that are widely used in Earth science research. The trends in reanalysis vary over an order of magnitude from 2.5 percent/K to 25 percent/K.

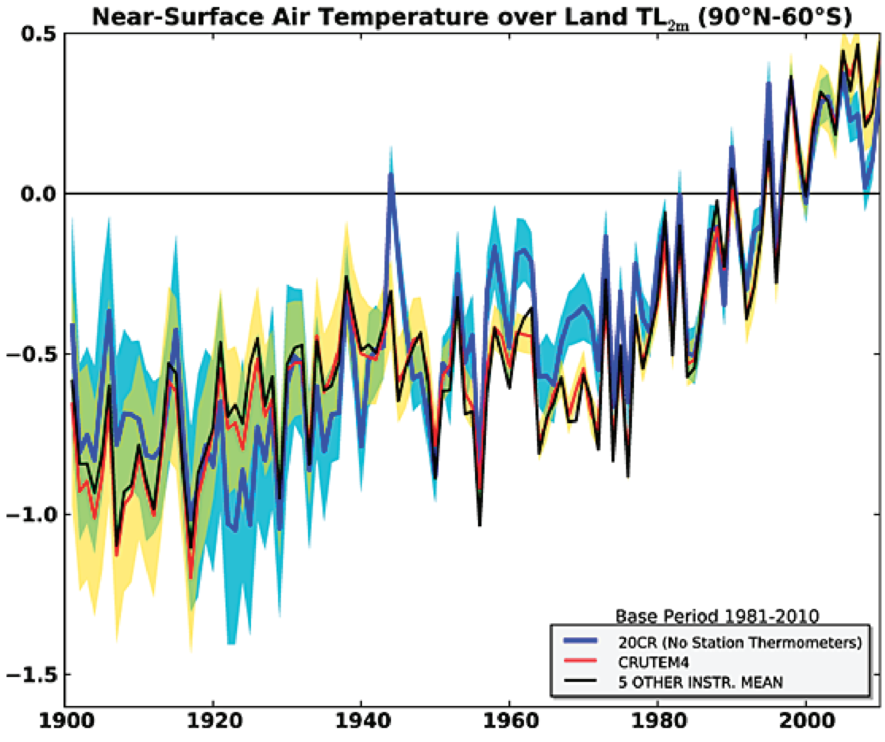

FIGURE 4.2.1 Temporal comparison of near-global land (90 degrees N to 60 degrees S) 2 m air temperature anomalies between 20CR and station-temperature-based estimates. Red curve: global anomaly series from in situ data (CRUTEM4, [Jones et al., 2012]); black curve: the average of five additional station-temperature data sets; and blue curve: the 20CR. Uncertainty ranges of 95 percent are shown for CRUTEM4 (yellow fill) and 20CR (blue fill) and their overlap (green fill). SOURCE: Compo et al. (2013).

BOX 4.2 Continued

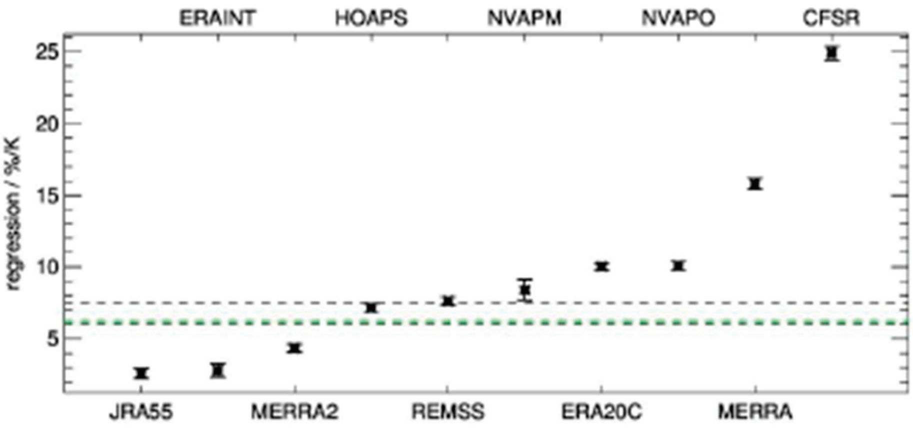

FIGURE 4.2.2 The trends in column-integrated oceanic water vapor from JRA55, ERA interim, MERRA2, ERA20C, MERRA, and CSFR reanalyses. NOTE: Acronyms defined in Appendix G. SOURCE: Schröder et al. (2017).

The observational program proposed connects to these ongoing reanalysis activities in several important ways:

- Many of the observations proposed relate to processes whose representation today remains challenging in global model and assimilation systems. Advancing the representation of these processes will further advance the utility of reanalysis.
- Many of the observations proposed provide an important independent source of data for assessing variables derived from reanalysis.

Finding 4.2: The integration of satellite data with models provides significant opportunities to advance scientific understanding, prediction skill, and applications. A key factor contributing to the success of global weather prediction over the last two decades is data assimilation systems that optimize the impact of satellite data in NWP models. Assimilation has also enhanced modeling efforts for other aspect of the Earth system and could lead to advances in Earth system models (ESMs). Progress in modeling the Earth system requires a combination of scientific, observing, and computational advances, including a concerted investment in each of these elements. With the expected continuing improvement in NWP and ESMs, and growing societal needs to develop information on finer scales and for a broader suite of Earth system variables, the coupling between the component models for the Earth system and the coupled data assimilation of satellite-based observations will be a focus for advancing Earth system science and applications.

Recommendation 4.2: To ensure continued advances in modeling in conjunction with Earth observation:

- **NASA should develop a long-term strategic plan for a strong sustained commitment to Earth system modeling in concert with observations. Success in observation-driven modeling holds the key for**

maintaining the end-to-end capability that has served NASA well in its effectiveness and service to society.

- **NASA, in collaboration with NOAA, should take a leadership role in developing fully coupled ESMs that assimilate comprehensive satellite, aircraft, ground-based, and in situ observations to advance understanding of the Earth system.**
- **NOAA should develop a close partnership with NASA and other agencies to lead the Next-Generation Global Prediction System (NGGPS) effort in developing the next-generation cloud-permitting, fully coupled ESMs with advanced data assimilation and NOAA's sustained global ocean observing system for enabling subseasonal-to-seasonal (S2S) forecasting and seamless weather-climate prediction.**

Data and Computation in the Cloud

Investments in data, data science, and computation are critical to enabling a future that allows faster development of knowledge and applications. New technologies are appearing rapidly, and the agencies and their supported research communities need to keep abreast. For example, cloud computing has the potential to benefit the community by avoiding data downloading and local management of data. Open source tools to analyze data can potentially enhance the transparency of analytical techniques and attract users to cloud computing and analytics. These benefits become particularly evidence when working with data at large scales.

It is clear that large amounts of data can be analyzed efficiently and made available within a cloud computing environment, but there may also be different cost models for this service, and policy issues surrounding archiving and access to data will be important to get right. NASA and NOAA are both evaluating the use of big data in a manner that facilitates the development of new knowledge and applications, but in very different ways. The European Space Agency (ESA) is also investigating how it might proceed.

NOAA has established Cooperative Research and Development Agreement (CRADA) contracts that enable partnerships with private contractors or universities, to enable greater access to its data. Among early successes was the provision of Next-Generation Radar (NEXRAD) data on Amazon's commercial cloud services. When Amazon established those services, usage of the NEXRAD data increased by 2.3 times at no net cost to the U.S. taxpayer. Data access that previously took 3+ years to complete now requires only a few days. Cost recovery strategies in the longer run are unclear, as is whether or not there would be a similar increase in usage if larger amounts of satellite data were to be made available or whether other types of data were available (e.g., ocean). Nevertheless, the success of the NEXRAD services makes clear that these types of opportunities and engagement with the private sector should be further explored.

NASA is studying whether to put their data on the cloud, and how best to provide analytical tools and computational resources to facilitate their use. It has established the NASA Earth Exchange as a virtual collaborative to bring scientists together in a knowledge-based social network to provide computing tools, computing power, and access to big data. NASA also has available a Climate Model Diagnostic Analyzer with web-based tools running on the Amazon cloud. This provides data set and analysis services, allowing users to download original data sets or higher-level data products.

NASA's 2015 Technical Capability Assessment Team (TCAT) review recommended developing prototypes to explore costs and benefits of using private-sector cloud environments, before moving forward. Longer-term decisions will depend on the outcomes of shorter-term studies. Issues under investigation include (1) getting locked in to a single vendor, (2) unknown future storage cost, (3) potentially uncapped costs for terminating a vendor, (4) security restrictions, and (5) trust in the network access technologies. By resolving these issues academic and government users should achieve benefits similar to those obtained by many commercial users of cloud resources.

Nevertheless, in the near term NASA is examining the feasibility of operating Distributed Active Archive Centers (DAACs) and Earth Observing System Data and Information System (EOSDIS) core services using cloud services providers. But many questions remain, such as whether private cloud services offer a cost-effective method of ensuring that publicly owned data are curated and archived properly for future use, and whether reproducing the DAAC architecture in the cloud is really the best model for the future. The present DAAC structure offers one feature that should, somehow, be maintained. Each DAAC is hosted in an institutional setting that has resident discipline experts committed to being good stewards of that data. They have assumed responsibility for maintaining the integrity of its data; this sense of ownership should not be lost but rather nurtured when considering any move to the cloud.

ESA is developing a new mode of operating in response to technological advances (e.g., cloud computing, citizen science). Starting from January 2017, ESA has designated that 25 percent of research funding will be oriented toward new research practices, focusing on interdisciplinary work and pairing big data analytics experts with Earth scientists who can interpret the results. ESA has determined that it is necessary now to invest in training existing and future scientists to use big data.

The majority of U.S. Earth science students and researchers do not have the training that they need to use cloud computing and big data. The barrier to entry can be overwhelming to Earth scientists not trained in data sciences, and it would be valuable for data centers (National Centers for Environmental Information/DAACs) to lead efforts to train the community at major meetings, online meet-ups, and other venues. Moreover, innovation may come from places far outside academia. This is not just “citizen science,” but rather anyone with a network connection and computer will be able to access and analyze enormous quantities of data.

With Geostationary Orbit Environmental Satellite-R Series (GOES-R) data having become available in early 2017, a rapid engagement of the (external) scientific community is needed to use the opportunity for leveraging advances in data science. GOES-R presents an opportunity to explore open-source, version control, workflow documentation, data provenance, security, and quality control details. This “experiment” can be possible at little cost/risk for NOAA but will help all agencies (both in the United States and international) define metrics for success.

Recommendation 4.3: NASA, NOAA, and USGS should continue to advance data science as an ongoing priority within their organizations in partnership with the science/applications communities by (1) identifying best practices for data quality and availability; (2) developing data architecture designs that are effective and agile; and (3) exploring new data storage/dissemination strategies to facilitate more interdisciplinary collaborations.

Complementary Observations

Investments in observations from space are considerably enhanced by complementary, and generally far less costly, observations from in situ, airborne, and other vantage points. These observations are used for a variety of purposes: (1) complementing space-based measurements within model data assimilation, (2) calibration/validation of space-based measurements, (3) algorithm development/refinement, and (4) providing fine-scale complements to more coarse space-based measurements for process studies, and more. Box 4.3 provides an example from the highly successful Operation IceBridge.

Sensors on commercial aircraft already provide important contributions to the global observing system, with significant opportunities for further contributions. New technologies and methodologies promise sub-

BOX 4.3 OPERATION ICEBRIDGE

NASA's Operation IceBridge (OIB) airborne mission[1] (Figure 4.3.1) was implemented in 2008 to acquire surface elevation data across the 9-year gap between NASA's laser-altimeter carrying satellite, ICESat (2003-2009) and the follow-on mission ICESat-2 (planned for launch in 2018). Only uninterrupted monitoring of land ice provides a multidecadal record of change, and the continuous nature of such observations is critical. Data acquisition periods are every spring for each hemisphere, and from multiple airborne platforms (P-3B, DC-8, B-200, HU-25, BT-67, DHC-3, G-V, C-130H), and will operate two more campaigns (one Greenland, one Antarctica) after the ICESat-2 launch in 2018.

Because an airborne program cannot match the spatial and temporal coverage of a satellite, the primary focus of OIB was on key regions of the ice sheets that were already known to be changing rapidly, including the coastal regions of the Greenland Ice Sheet, as well as outlet glaciers flowing into the Amundsen Sea, adjacent to the vulnerable West Antarctic and on the Antarctic Peninsula. OIB has successfully added data to the surface elevation time series in these key regions. These data are useful for interpolating between continuous time series, for creating Digital Elevation Models (DEMs), for cross-calibration between various altimeter missions, and for validating the data from the CryoSat-2 mission.

Complementing the altimetry, OIB's airborne platform also provided an opportunity to measure critical parameters of the ice sheet that cannot be measured from space: ice thickness, stratigraphy, and near-surface ice and snow properties. OIB gravity and magnetics have provided new bathymetry for many Greenland fjords and some of the major West Antarctic ice shelves and ice streams, providing data for more accurate bathymetric maps near the grounding line that are essential for estimating discharge of land ice. OIB uses different ice-penetrating radar systems to investigate the subglacial environment and near-surface snow and ice layers on both land ice and sea ice. On land ice, these data have proved to be invaluable to our understanding of ice-sheet mass balance and ice dynamics, resulting in more robust constraints for ice-sheet models that predict ice-sheet contributions to sea-level rise, and have led to improved bedrock maps, grounding line positions, and so on, providing critical information for improving estimates of Antarctica's ice discharge. For sea ice, the radar data provide essential information for interpreting the satellite altimetry signals, which require knowledge of the overlying snow cover.

stantial advances in these areas. Drones can make airborne measurements far cheaper and more readily available than some ground-based observations or those from conventional aircraft. Their use for scientific campaigns is growing rapidly. Citizen science and community observing networks, such as the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS),[5] have proven enormously valuable for filling space-time scale gaps—increasing the space-time density of observations beyond what is available from institutional networks.

Reference systems that enable quality observations are often forgotten or neglected during observing system development, as they generally play more of a supporting role to those missions built primarily to observe geophysical variables. One critically important example is the Terrestrial Reference Frame, which provides essential information about Earth coordinates that enable a wide variety of observing systems. It is a system-of-systems: (1) Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) are needed to provide center of mass, orientation, scale, and Earth rotation; (2) a large and international Global Navigation Satellite System (GNSS) network is needed to provide accurate orbits not only for users

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[5] A more complete description of CoCoRaHS is available at https://cocorahs.org.

BOX 4.3 Continued

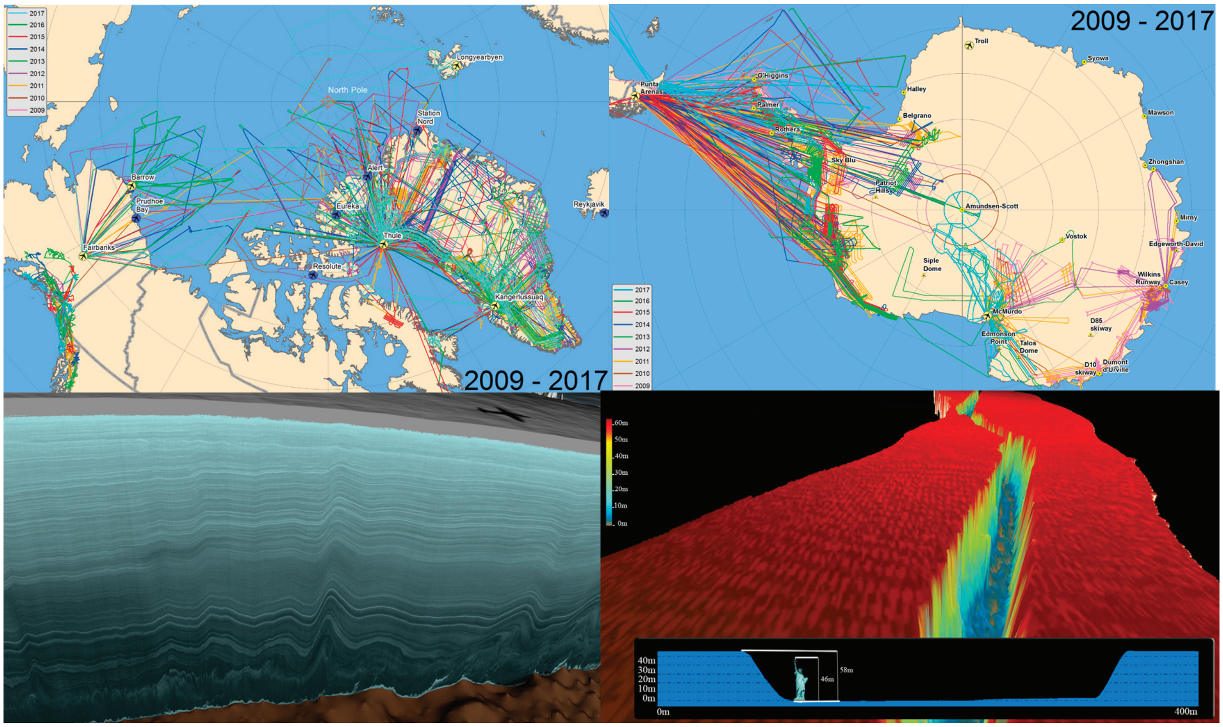

FIGURE 4.3.1 *Top panels:* Flightlines of NASA's Operation IceBridge campaigns over the Arctic (left) and Antarctica (right) from 2009 to present. SOURCE: NASA, https://icebridge.gsfc.nasa.gov/?page_id=1010. *Bottom-left panel:* Layers in radargram data collected by one flight made by Operation IceBridge across the Greenland Ice Sheet on May 2, 2011. SOURCE: MacGregor et al., 2015. *Bottom-right panel:* Three-dimensional representation of airborne topographic mapper (ATM) data on rift in Antarctica's Pine Island Glacier. SOURCE: NASA/Goddard Space Flight Center/Scientific Visualization Studio.

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[1] See http://science.sciencemag.org/content/351/6273/590; http://onlinelibrary.wiley.com/doi/10.1029/2011GL049216/full; http://onlinelibrary.wiley.com/doi/10.1029/2011GL049026/full; http://onlinelibrary.wiley.com/doi/10.1002/2013GL059010/full; http://www.nature.com/ngeo/journal/v7/n6/abs/ngeo2167.html; and http://science.sciencemag.org/content/341/6143/266.

of GNSS ground data, but also to allow satellite and aircraft missions access to the International Terrestrial Reference Frame (ITRF); and (3) GNSS is also used to measure Earth rotation and is the key technique for defining tide gauge datums in ITRF.

A substantial amount of science reliant on the ITRF is at risk if the ITRF is not properly maintained and advanced.

Recommendation 4.4: NASA should complete planned improvements to its Global Geodetic Observing System sites during the first half of the decadal survey period as part of its contribution to the establishment and maintenance of the International Terrestrial Reference Frame.

International Partnerships

International partnerships have made, and continue to make, a significant contribution to the U.S. Earth science program (e.g., CNES/ESA/European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)/EC and the JASON series, EUMETSAT and its polar and geosynchronous satellites, JAXA and TRMM/GPM, DLR and GRACE, ISRO and NISAR). Not only do they reduce U.S. costs, but they also engage a larger and more diverse community of scientists (Box 4.3). The priorities of this report would be very different without the critical contributions to Earth measurement from our foreign partners. While partnerships pose a challenge in differing management styles and governance structures, one partner can support the other in challenging times.

The implementation and impact of these partnerships is different for NOAA than for NASA, but they are no less important to each agency. NOAA has enjoyed the benefits of numerous international agreements. These have included accords with Japan for backup satellite coverage from geostationary orbit, with Europe for backup coverage from polar orbit, and with the international Coordination Group for Meteorological Satellites (CGMS), whose members include Japan, China, Russia, India, the European Meteorological Satellite Organization and the World Meteorological Organization.[6]

NOAA and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), in particular, have long maintained a strategic collaboration in the field of operational meteorological satellite observations that has delivered full, free, and open data sharing essential to meeting NOAA's commitment to protecting lives and property in the United States. On December 2, 2015, NOAA and EUMETSAT signed the Joint Polar System (JPS) agreement for the period 2020 to 2040. Building on the 2013 Agreement on Long Term Cooperation, the JPS follows the Initial Joint Polar-orbiting Operational Satellite System (IJPS), EUMETSAT's Meteorological Operational Satellite Program (MetOp), and NOAA's Polar Operational Environmental Satellites (POES) and Suomi-NPP satellites, with assurance of observations from a pair of complementary morning and afternoon orbits to include each nation's new generation of polar-orbiting satellites: the EUMETSAT Polar System-Second Generation (EPS-SG) and the Joint Polar Satellite System (JPSS).[7]

This is only a partial description of NOAA's international agreements and partnerships, but it illustrates their critical importance. In today's environment of constrained resources, an issue shared by our partners, effective use of partnerships is more important than ever. Extending and leveraging these partnerships is central to NOAA's progress. Expanding them to include the larger life-cycle aspects of future capabilities, starting with the science that seeds future operational system priorities, is one possibility.

Science has no boundaries, but policy constraints limit possible partnerships. China is one potential international partner whose capabilities are not available to some U.S. federal agencies by law (see the discussion of legislative guidance in the "Toward a National Strategy" section of Chapter 2). As the world's largest nation with a robust space program, China (notably the Chinese Meteorological Administration [CMA]) has the potential to fill gaps in our own program. As a specific example, in 2018 CMA is expected to shift at least one (FY-3E) of its polar orbiting meteorological satellites to an early morning orbit in response to international coordination at the World Meteorological Organization (WMO), thereby better complementing its counterpart satellites of NOAA and EUMETSAT to provide improved global coverage. In a time of constrained resources, access to all data, including from nations such as China, can enable a

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[6] See W. Ferster, "Gary Davis, Former NOAA Satellite Executive, Dies," *SpaceNews.com*, October 13, 2014, http://spacenews.com/42170gary-davis-former-noaa-satellite-executive-dies/.

[7] It is important to note that the two systems operate in distinctly different orbit planes, each designed to preserve its relationship with the Sun such that every orbit for a given satellite passes over Earth at the same local time every day. Due to the nature of these low-Earth orbits, a point on Earth may experience an overpass of the -EPS-SG in midmorning, followed by the midafternoon JPSS overpass. Each of these satellites then flies over the same area some 12 hours later at night.

more robust U.S. program at lower cost to the United States. Those opportunities go unrealized when there are restrictions on federal agencies regarding engaging China and making use of its assets. An example of an opportunity concerning the continuity of microwave imagery and the multiple purposes it serves is provided in Box 4.4.

Finding 4.3: NASA, NOAA, and USGS have successfully relied on international partnerships to enhance their programs. Partnerships potentially lower the overall cost to the United States of space-based observations and enable more of this decadal survey's priorities than could otherwise be achieved. In certain cases, current restrictions on potential international partnerships hinder access to observations and thus limit opportunities to reduce U.S. cost or enhance science and applications.

Recommendation 4.5: Because expanded and extended international partnerships can benefit the nation:

- **NASA should consider enhancing existing partnerships and seeking new partnerships when implementing the observation priorities of this decadal survey.**
- **NOAA should strengthen and expand its already strong international partnerships, by (1) coordinating with partners to further ensure complementary capabilities and operational backup while minimizing unneeded redundancy and (2) extending partnerships to the more complete observing system life cycle that includes scientific and technological development of future capabilities.**
- **USGS should extend the impact of the Sustainable Land Imaging (SLI) program through further partnerships such as that with the European Sentinel program.**

Technology Innovation, Infusion, and Obsolescence

Progress in space-based observations is being enabled by the technological advances that are being developed both in programs within the federal agencies that are sponsoring or supporting ESAS 2017, as well as those outside government (Box 4.5). The ESAS 2017 recommended program is designed to provide the flexibility and responsiveness needed to leverage new opportunities and technological advances throughout the decade. Rather than locking in specific mission implementation recommendations based on technologies, implementation methods, and known opportunities available at the time of the decadal survey, the committee has provided a set of priority Targeted Observables for the decade. This approach allows for the program implementation to evolve and be optimized throughout the course of the decade at the time each mission is started and/or selected.

Over the past few decades, the space sector has evolved greatly. With an influx of ideas and flight demonstrations of disaggregation, small spacecraft, and constellations, there are now multiple viable approaches to accomplishing many Earth science measurement objectives. In addition to spacecraft and sensor technology, significant advances in software, data analytics, and advanced computational techniques offer the potential of extracting new knowledge and additional accuracy from space-based measurements of Earth. In these domains, commercial and national security interests have resulted in significant investment in industry and academia.

Cutting-edge Earth science relies on continuous innovation, and critical technology developments are now spread across small business, established industry organizations, new entrants, academia, and the NASA Centers. As such, it is important that NASA (as well as NOAA and USGS, where appropriate) not only invest in technology but also identify and build partnerships that import as much innovation as possible into the Earth science enterprise. Mechanisms that offer the potential to improve the performance and efficiency of NASA flight programs include data buys, block buys, standard bus, public-private partnerships, crowdsourcing and citizen science, use of commercial assets, and partnerships with philanthropists,

BOX 4.4 INTERNATIONAL CONTINUITY OF MICROWAVE IMAGING—A POTENTIAL GAP

Microwave imaging typifies the issues, often complex, that must be faced when maintaining climate data records. Microwave imaging also typifies issues associated with the transition from what has been a U.S. endeavor for much of the past, to one that requires partnerships with the international community in the future.

Benefits. The Defense Meteorological Satellite Program (DMSP) and its Special Sensor Microwave Imager (SSMI) family of sensors—building on the record initiated by the Scanning Multichannel Microwave Radiometer (SMMR) aboard Nimbus-7 in 1978—have provided a continuous, reliable source of global microwave imagery for almost four decades. This has been of enormous benefit to the civilian Earth science community, serving multiple interests:

- *Numerical Weather Prediction (NWP) Assimilation.* Microwave imagery is routinely assimilated in weather forecast systems with demonstrable positive impact on forecast accuracy and skill (Cardinali and Prates, 2011; Kazumori et al., 2016; Geer, 2016).
- *Climate Data Records.* This microwave imagery enables (1) climate data records of changing snow cover on land and the diminishing Arctic sea ice cover (Callaghan et al., 2011; Walsh et al., 2017); (2) Global Precipitation Climatology Project climatologies of water vapor, cloud liquid water, and sensible and latent heating fluxes (O'Dell et al., 2008; Santer et al., 2009; Clayson et al., 2013; Elsaesser et al., 2017); and (3) when using Advanced Microwave Scanning Radiometer (AMSR) or Global Precipitation Measurement (GPM) with their lower frequencies, all-weather sea-surface temperature (Wentz et al., 2000).

Potential Gap. While the Earth science community has been served with continuous coverage up to the present, it faces a potential gap if and when the last of the current microwave radiometers reaches the end of its life, assuming that happens prior to the launch of the next generation of radiometers in 2021-2022. Figure 4.4.1 illustrates when this gap might occur.

Status of Current Coverage. The three current DMSP radiometers are all well beyond their 5-year design life. The spacecraft for the most recent mission, F-19, failed on orbit, rendering the radiometer data unavailable; and a decision was made in November 2016 not to launch F-20, but to tear it down. At 14 years, Windsat is well beyond its design life. Megha-Tropiques, with a 20-degree inclination, offers only low-latitude coverage. GPM, with a 65-degree inclination, lacks high-latitude coverage.

Prospects for Future Coverage. Table 4.4.1 highlights the capabilities of the current and future microwave radiometers. For the future, only WSF, EPS-2G-B, and FY-3 are operational, continuing series with follow-on satellites planned for a specified period of coverage. The frequency bands, and hence capabilities, of the WSF—the follow-on to DMSP—are unknown at this time. The frequency bands of EPS-2G-B are not optimal for detecting sea-ice cover. While the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) is distributing FY-3 data via its EUMETCast and both the European Centre for Medium-Range Weather Forecasts (ECMWF) and the UK Met Office are using them, policy issues have precluded access to Chinese satellite data (discussed elsewhere); hence the data quality and reliability have not been assessed in this country.

Compact Ocean Wind Vector Radiometer (COWVR) is a technology demonstration with a minimal set of frequencies; hence minimal capabilities. The Japanese had been planning for NOAA to provide a scatterometer as an additional instrument to complement the Advanced Microwave Scanning Radiometer (AMSR-2) in the Global Change Observation Mission-Water (GCOM-W1) payload, but NOAA was unable to do so. The Japan Aerospace Exploration Agency (JAXA) is now unlikely to fly a GCOM-W2, and the next opportunity to fly an AMSR-2 sensor will be on the Greenhouse Gas Observing Satellite (GOSAT) in 2022, but the prospect of AMSR being among its payload is uncertain.

Looking to the Future. Improved coordination between the U.S. civil and military environmental satellite programs would be beneficial. Addressing policy issues that preclude access to Chinese satellite data, especially from the Chinese Meteorological Administration, would be helpful. Improved coordination with the Committee on Earth Observation Satellites (CEOS), perhaps forming a Microwave Radiometry Constellation, would be a step in the right direction. Helping the Japanese find a flight opportunity for an AMSR might be beneficial.

BOX 4.4 Continued

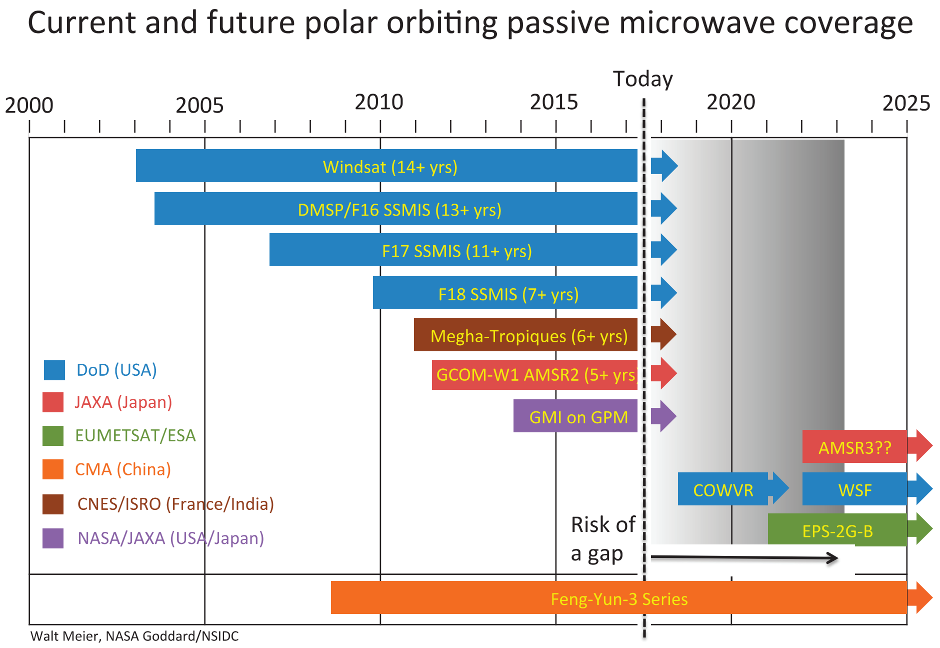

FIGURE 4.4.1 A chronology of current and future microwave radiometers; many are listed in the Program of Record (POR). As noted, a potential gap in coverage may occur prior to 2021-2022, when EPS-2G-B is launched.

TABLE 4.4.1 Projected Capabilities of Current and Future Microwave Radiometers

Current and Future Polar-Orbiting Microwave Radiometer Capabilities

	Useful for Observing					
Satellite/Sensor	**SST**	**Sea Ice and Snow**	**Atmosphere**	**(First) Launch**	**Follow-on**	**Coverage Until**
DMSP/SSMI/SSMIS		✓	✓	1987		?
WindSat	✓	✓	✓	2003		
FY-3/MWI	✓	✓	✓	2008	✓	2023
MeghaTropiques			✓	2011		
GCOM-W1/AMSR2	✓	✓	✓	2012		
GPM/GMI	✓		✓	2014		
OR-6/COWVR			✓	2018		
EPS-2G-B/MWI		?	✓	2022	✓	2040
WSF/MWI	?	?	?	2022	✓	?

NOTE: The three Useful for Observing columns reflect capabilities that are based on the frequency bands of the particular microwave radiometer on each satellite; the Follow-on column indicates an operational series; and the Coverage Until column indicates its planned period of coverage. SST = all-weather sea-surface temperature; Sea Ice and Snow = sea ice and snow-on-land cover; Atmosphere = rain rate, columnar water vapor, cloud liquid water, and wind speed over ocean.

BOX 4.5 THE PROMISE OF TECHNOLOGY INNOVATION

The high cost of observing Earth from space has by necessity resulted in an observing strategy built around measurements of relatively few "essential" variables (e.g., Bojinski et al., 2014; Simmons et al., 2016). This works against developing a more integrated observing strategy, which is further exacerbated by rising costs of operational observing systems in times of flat or declining budgets. Technology innovation promises the potential to drive down costs of sensors, platforms, and accessibility to space and in turn to change the way we currently think about Earth observations.

Much of the current discussion about technology innovation of spaceborne systems seems to revolve around discussion of cubesat capabilities (NASEM, 2016b) and the affordable access to space that such capabilities offer. The cubesat development has forced a de facto standardization that, in concrete terms, provides design principles with specifications on the power/weight/volume into which sensors have to fit. Miniaturization of a number of "U-class" sensors that potentially can address a range of important measurements is developing. For example, Figure 4.5.1 highlights four U-class sensors that have been developed under the NASA Earth Science Technology Office (ESTO) program that are to be demonstrated in space in 2018.

There are both opportunities and challenges associated with smallsats and cubesats. On the positive side, smallsats and cubesats have encouraged development of smaller sensors and enabled creative alternative design solutions that can be very capable, even at lower cost. They also offer the possibility to explore the trade space between constellations of small sensors (to provide higher temporal resolution) versus single, larger, more capable platforms. Smaller sensors and associated satellite systems have opened the door to nontraditional vendors and providers within both the government and the private sector. The ability to produce small satellite systems at universities has positively impacted the vitality of the Earth observing enterprise. However, there are also risks that must be acknowledged and accepted, as would be the case with any evolving technology in its early stages of realization. Risks in performance, stability, measurement availability, system reliability, and mission lifetime must be understood and weighed for each particular application.

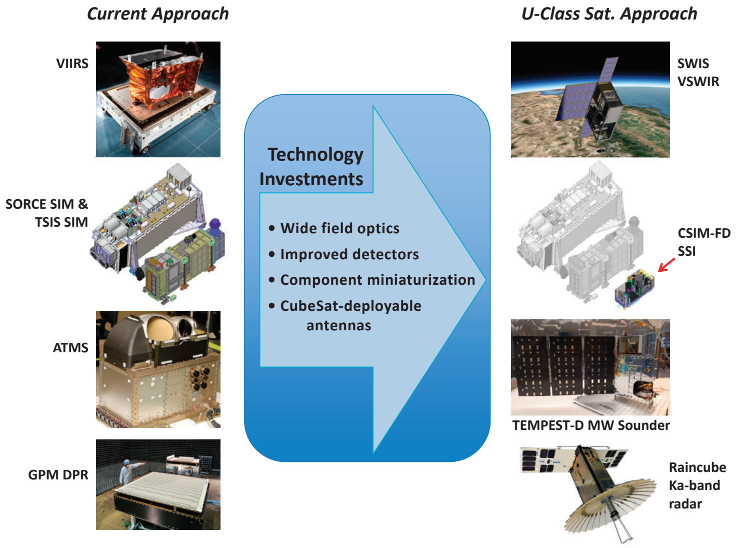

FIGURE 4.5.1 Sensor miniaturization and cost reductions are happening as a result of investments in key technologies (center). Four examples of U-class sensor miniaturization that are to be demonstrated in space in 2018 via the NASA Earth Science Technology Office (ESTO) In-Space Validation of Earth Science Technologies (InVEST program) are shown to the right of the central figure. The sensors to the left are the counterpart sensors that map to the U-class defined to the right. The NASA InVEST program has been an important incubator of technology innovation and provides a pathway to demonstrate miniaturized sensor performance in space.

nonprofits, and the defense community.[8] Technology investment in sensors, low size, mass and power electronics, small satellites, small launch vehicles, and secondary payload and rideshare transportation elements remain critical. When possible, such technology investments should be made through competitive means, potentially in partnership with NASA's Space Technology Mission Directorate.

Within NOAA flight programs, GOES-16 and JPSS-1 both benefited from block buys of instruments and spacecraft, with an expected service life continuing through the time frame covered by this decadal survey. However, system replenishment in the following decade (2028-2037) will require decisions and investments in this decade in order to maintain and potentially improve the quality of the data used for both research and operational forecasting. These systems have significant positive impact on U.S. economic competitiveness, national security, and quality of life. The National Environmental Satellite Data and Information Service (NESDIS) plan is to "develop a space based observing enterprise that is flexible, responsive to evolving technologies and economically sustainable" (Volz, 2016) by moving away from stand-alone space and ground programs and identifying low-cost and rapidly deployable space systems that meet future needs.

While this committee agrees with the NESDIS strategic goal, we suggest an incremental approach in which commercial system and data opportunities demonstrate an "equal or better" performance baseline established by existing GOES and JPSS systems, as suggested in the NESDIS Independent Review Team report (IRT, 2017). This risk of moving to new commercial systems must be balanced against the technology availability risk of these legacy systems, particularly in areas related to critical sensor technologies.

The continuity needs of Landsat data products also suggest that USGS implement a balanced strategy that weighs moving toward commercial systems and employing innovative approaches to advance system capability and reduce cost against the technology availability risk of legacy systems. As such, the committee suggests that both NOAA and USGS make the needed investments in both existing and new technologies to ensure the sustainment and improvement of the measurements required for weather forecasting and continuation of critical climate measurements. In the coming decade it is expected that each of these critical Earth observing systems will move toward further use of commercial systems and data opportunities, while the importance and benefit of federal investment in space technology will continue to increase.

NASA PROGRAMMATIC CONTEXT

NASA's contextual issues range from programmatic balance to technology innovation. Successfully addressing each of these topics is essential to effective implementation of the ESAS 2017 science and applications priorities and associated observation plan.

NASA Programmatic Balance and Scope

The NASA Earth Science Division (ESD) has a broad mandate to develop measurement technology, to advance scientific discovery, to apply measurements and science for societal benefit, and to educate and inspire citizens and a next generation of scientists. Within its budget, NASA ESD must seek an optimal balance to achieve this broad mission in the most effective and efficient way possible. NASA ESD must support a world-class scientific research program that will both guide the development of the missions and will fully realize the value of the resulting data. While developing improved technology and addressing

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[8] One critical trade-off is between "block buys" (purchase of multiple instruments or spacecraft to achieve cost savings) and technology advances. Block buys can reduce cost, but they constrain the ability to leverage newer technologies as they arise within the time duration of a block.

novel science questions, NASA also must optimally utilize its existing fleet of satellites that continue to collect important data.

In addition to scientific discovery, NASA has a congressionally directed mission to monitor the stratosphere, and is also the de facto agency responsible for continuing satellite measurements critical to climate science (see the discussion of agency roles in the "Toward a National Strategy" section of Chapter 2). It is also important for NASA to foster the translation of this information to societal benefit through applications of the data, partnering with operational agencies and transferring mature tools to these agencies.

Robustness and Resilience

A major purpose of striving for balance is to achieve programmatic robustness and resilience. To guide the balance discussion, the committee identified characteristics of a robust and resilient observational program, including both flight and nonflight issues.

Finding 4.4: A robust and resilient ESD program has the following attributes:

- A healthy cadence of small/medium missions to provide the community with regular flight opportunities, to leverage advances in technologies and capabilities, and to rapidly respond to emerging science needs;
- A small number of large cost-constrained missions, whose implementation does not draw excessive resources from smaller and more frequent opportunities;
- Strong partnerships with U.S. government and non-U.S. space agencies;
- Complementary programs for airborne, in situ, and other supporting observations;
- Periodic assessment of the return on investment provided by each program element; and
- A robust mechanism for trading the need for continuity of existing measurement against new measurements.

Elements of an Overall Balanced Program

A properly balanced program needs to reflect multiple aspects of balance. In general, these aspects cannot be viewed in isolation. Doing so may result in optimal balance for that particular aspect of the NASA program, but suboptimal balance for the program as a whole. The important aspects of NASA's overall balance are discussed in this section, with specific topics regarding the flight program covered in the following section.

Balance Between Flight and Nonflight Elements

Figure 4.1 shows the annual ESD expenditures for flight missions and mission support from 1996 to 2017. This figure shows actuals through 2016 and estimates, based on a simple inflation adjustment, during the decade 2017-2027. Total expenditures in constant dollars are currently about 75 percent of expenditures in the late 1990s. In recent years, the ratio of flight to nonflight expenditures has been about 60 to 40 percent. The number of beneficial Earth observations that NASA ESD can make has expanded, but the purchasing power of its budget has declined.

Balance Between ESD Program Elements

Figure 4.2 shows detail on how NASA-ESD expenditures (since 2007) are apportioned among six program element categories. The total ranges of these categories are given in Table 4.2. The proportions have been fairly constant in recent years.

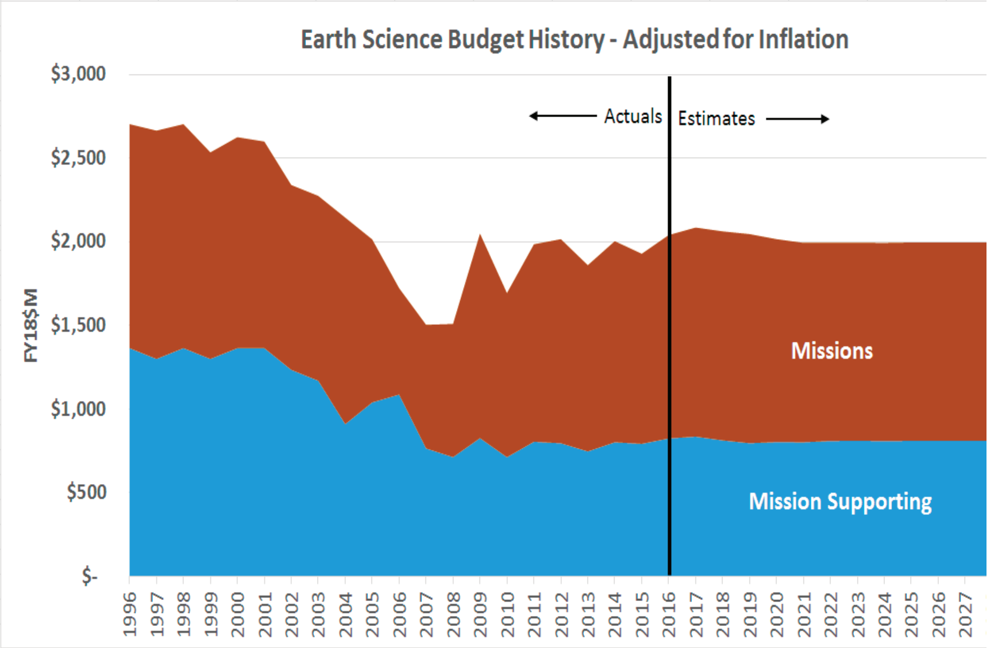

FIGURE 4.1 The NASA Earth Science budget 1996-2016+ ($ FY 2017), showing both mission and nonmission contributions. For the period following known budget requests, a simple inflation-adjusted increase is assured.

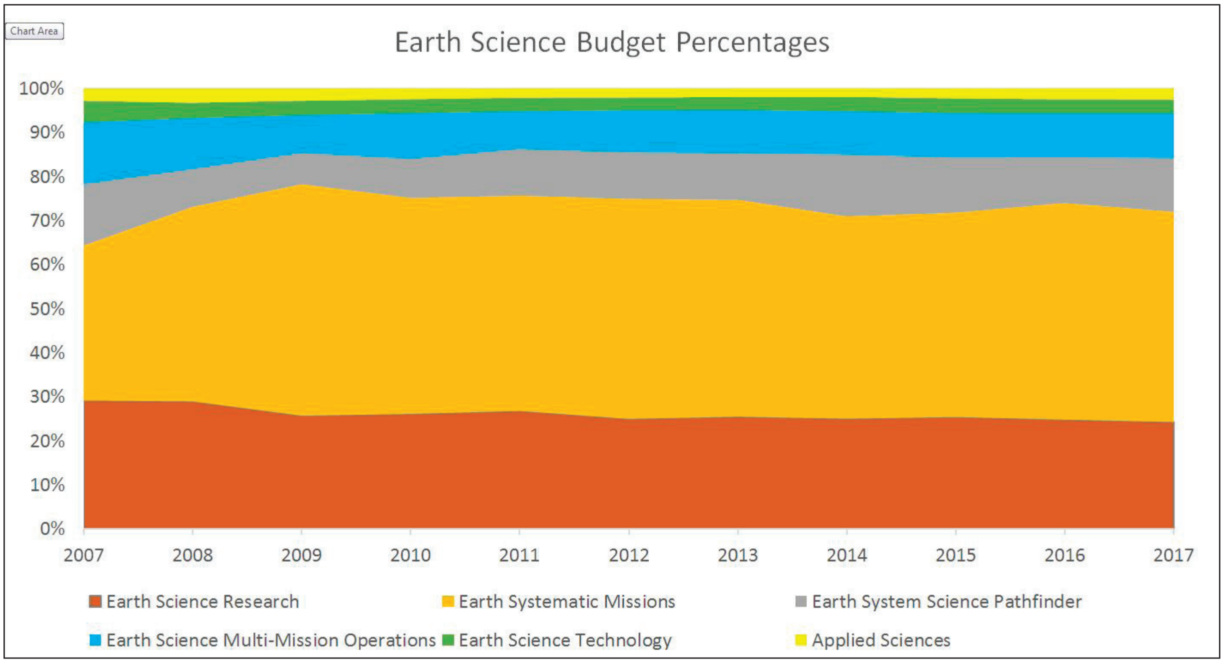

FIGURE 4.2 Percentage of Earth Science Division (ESD) budget devoted to Science Research, Systematic Missions, Earth System Science Pathfinder missions (includes Venture), Multi-Mission Operations, Technology, and Applied Sciences from 2007 to 2017.

TABLE 4.2 Percentage Ranges of Expenditure Categories Since 2007

Expenditure Category	Low %	High %
Earth Science Research	24	29
Earth Systematic Missions	35	52
Earth System Science Pathfinder	7	14
Earth Science Multi-Mission Operations	9	14
Earth Science Technology	3	5
Applied Sciences	2	3

Figure 4.2 and Table 4.2 show that since 2007 a large fraction of the budget has been spent on systematic missions. In 2016 about 47 percent of the budget is for large missions and 12 percent for Earth System Science Pathfinder and Venture missions. Large directed missions are justified if they are needed to address a particularly difficult but important problem, or to collect the complement of measurements needed to address critical interdisciplinary problems (NASEM, 2016a). However, an appropriate balance for the broader community also requires a cadence of opportunity for principle investigator (PI)-led and Venture class missions that is frequent enough to sustain a culture of innovation and creativity among the Earth observations from the space community.

Balance Between Mission Investment and Science Investment

As stated previously, a balanced NASA program requires a strong scientific research and applications program to plan and utilize remote sensing measurements of Earth. In 2016 about 18 percent of the total ESD budget was directed toward Earth Science Research and Analysis; 3 percent to computing, including the across-NASA High-End Computing Capability (HECC) Project; and 3 percent to administration. Balance requires sufficient support for Earth science research and analysis to effectively develop and utilize the space-based measurements. A balanced Earth science and applications program supports a robust community applying space-based measurements of Earth to benefit society for a broad range of purposes including research, forecasting, public safety, and business.

Balance of Responsibilities to Partner Agencies

NASA ESD has a variety of responsibilities to other agencies. Three core responsibilities are listed here:

- *NOAA Operational Satellite Development.* NASA Goddard Space Flight Center (GSFC) has responsibility for developing and procuring satellites for NOAA NESDIS, under direct agreement between NOAA and GSFC going back many years. This is not included within the ESD budget, and is not under ESD management authority. A separate NOAA partnership for the on-orbit Suomi National Polar-Orbiting Partnership (S-NPP) mission, initiated during the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) program, was carried within the NASA ESD development budget, although operations are now the responsibility of NOAA.
- *Sustainable Land Imaging (SLI).* NASA ESD has responsibility for developing and procuring the Landsat satellite series, under its SLI partnership with USGS. The budget for this partnership project is included within the ESD systematic mission budget line.

- *Satellite Needs Working Group (SNWG).* SNWG provides a means for multiple government agencies to provide input on national needs that could guide priorities for new NASA observations and ensure more effective applied use of current observations throughout the U.S. government.[9]

NASA's obligation to the first two of these is well-defined, with clear expectations and budget obligations. The third is quite flexible, with NASA given discretion as to whether and how needs from other agencies get reflected in ESD priorities. In general this SNWG process has proven both less burdensome to ESD and more beneficial to partner agencies than might be anticipated. The balance (between partner needs and ESD's own needs) achieved by ESD in each of these areas appears appropriate, in that those partner needs complement ESD's missions without being disruptive and do not dominate ESD budgets.

Balanced Applications to Society

NASA ESD measurements are critical to advancing understanding and prediction of the Earth system, which carry tremendous benefit to humanity. The science program at NASA ESD is designed to perform this function. In addition, space-based measurements of Earth can be applied more locally and in other ways to benefit communities and businesses. The Applications program at NASA ESD is designed to translate NASA Earth observations and science to the benefit of communities and businesses. In a balanced program, measurements of Earth from space are translated into human benefit.

Elements of a Balanced Flight Program

Beyond general programmatic balance, the ESD Flight program has additional balance issues that are critical to address (Box 4.6 provides an example of the trade-offs inherent in achieving balance):

Balance Between Large and Small Flight Missions

A mix of large, medium, and small flight missions will best advance progress in Earth remote sensing science at NASA. More expensive missions with more capable instruments or multiple instrument packages may be the best option for addressing certain critical science questions. Smaller, less expensive missions can address many science questions and provide more frequent opportunities to innovate and engage the science and engineering communities through a higher cadence of mission opportunities. Achieving the right balance among large, medium, and small flight missions is critical. Large missions cannot be allowed to consume too much of the budget and thereby stifle the innovation fostered by frequent opportunities for smaller, competed missions. Large missions, especially, should be cost constrained (NRC, 2012, p. 5).

Balance Among Technology Development Phases

Investments in innovation are critical to the success of this new program. Earth system science and applications rely on long-term (sustained) observations of many key aspects of the Earth system. Yet, there

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[9] "The Satellite Needs Working Group (SNWG) was chartered as an interagency working group by action of the National Science and Technology Council (NSTC), Committee on Environment, Natural Resources, and Sustainability (CENRS), U.S. Group on Earth Observations (USGEO) Subcommittee. The SNWG supports an annual Satellite Needs process by which federal departments and agencies can communicate their Earth observation satellite measurement or product needs to NASA and other providers of satellite observations. The SNWG federal high-priority satellite needs collection was initiated in response to the President's Budget for Fiscal Year 2016, which reflects the decision to make NASA responsible for the acquisition of the space segment for all U.S. government-owned civilian Earth-observing satellites except National Oceanic and Atmospheric Administration (NOAA) weather and space weather satellites. The Administration further recognized that user agencies will continue to need satellite data from NASA, and that their needs should serve as input to NASA decisions on which measurements to transition from experimental to sustained observations." From "USGEO Satellite Needs Working Group Reporting Federal High-Priority Satellite Needs," available at https://remotesensing.usgs.gov/rca-eo/documents/Satellite_Needs_Collection_Survey.pdf.

BOX 4.6 ACHIEVING BALANCE IN FLIGHT PROGRAMS: PERFORMANCE, COST, AND RISK

A healthy Earth science flight program requires careful consideration of the appropriate balance between the three interrelated parameters of performance, cost, and risk. Increasing performance (i.e., through increasing scope or tightening technical requirements) generally implies an increase in cost or risk. Costs can be lowered by accepting more risk or reducing performance (e.g., by relaxing technical requirements or reducing the scope of a mission). Similarly, low tolerance to risk can increase costs as funding is expended to, for example, improve parts selection, complete additional analyses, and hold in-depth reviews.

Which of the three parameters are actively managed versus allowed to vary as a function of the others has program-wide implications. Low tolerance to risk coupled with tight technical requirements results in higher mission costs, which can limit the scope of the overall program as the number of missions implemented decreases in response to the increase in individual mission costs. Acceptance of high levels of risk may lower a mission's cost, but it may also result in increased incidences of mission failures or shorter mission lifetimes. The program-level requirement for a mission's success or its ability to tolerate reduced performance or limited mission duration should be used to determine its appropriate risk posture for a given mission. Higher levels of risk are expected to be acceptable, for example, within the Venture Program than in the Designated program element.

ESAS 2017's recommended program includes a variety of program elements that serve to enable active consideration of the balance between cost, performance, and risk while providing flexibility throughout the decade to evolve as new opportunities emerge, technologies are developed, scientific discoveries are made, and the international contributions to the Program of Record evolve.

is at present no mechanism to fund early-stage innovation that might lead to lowering the cost of providing for long-term observations. Instead, teams are currently incentivized to improve upon state-of-the-art to qualify for consideration in competitive funding solicitations that are targeted to new scientific investigations. Put simply, there is no incentive to drive for efficiency. The committee therefore proposes that ESTO establish a competitive call to incentivize development of game-changing technologies to lower the cost and risk associated with provision of sustained observations needed for Earth system science. The ESTO budget is currently at the low end of its historical range as a percentage of ESD's budget. The committee recommends (Recommendation 4.6) that the ESTO budget be increased to 5 percent of the ESD budget, which remains within the historical range of ESTO funding (Table 4.2).[10]

Balance of Mission-Enabling Investments versus Flight Missions

NASA must balance its Earth science technology efforts across broadly based investments that reduce cost across multiple programs and focused mission technologies. In particular, broadly based investments that reduce the cost or improve the resiliency of space launch are critical (including small launch vehicles, standard bus architectures, and secondary payload and rideshare approaches). NASA also has the critical role of continuing to advance Earth system science sensor technology. As the Earth science community works to improve the accuracy of its measurement and prediction capabilities and translate this knowledge into applications that impact U.S. economic competitiveness, national security, and quality of life, NASA must continue to keep the Earth science sensor community at the cutting-edge. As a means to provide this

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[10] As noted in Chapter 3, a portion of the Incubation program's budget is expected to flow to the Earth Science Technology Office (ESTO) commensurate with its role in the maturation of instrument and technology concepts. The remaining funding to support the recommended increase in ESTO's budget is obtained through decreases in other program elements consistent with the report's recommendation to maintain those other program elements within their historical funding ranges.

balance, new technology funds are included in the coming decade for both broadly based investments and focused technology investments through the Incubation program element. In addition to focused technology investments for priority instruments and missions, this program element also includes an Innovation Fund to enable program-level response to unexpected opportunities that occur on subdecadal scales.

Balance Between Heritage Technology and New Technology

The development of advanced technology can provide novel measurement capabilities and the ability to make needed measurements at reduced cost. Less expensive measurement technologies are critically important if NASA ESD is to innovate to obtain the most critical measurements within its expected budget. In a balanced program, new technology is continuously introduced into space-based measurements, and innovation to improve existing measurements and measure new variables of importance is implemented. New technologies do require investment, however, and their successful adoption requires demonstrated capabilities to achieve measurement objectives. In the meantime, heritage technologies are essential for the achievement of observation objectives until such time as reliable transition to new capabilities can be accomplished.

Balance Between Extended Operations and New Missions

Valuable data can be collected from missions that remain functional beyond their designed lifetime, but this data collection requires resources that might be used for other purposes. Extending the operational phase of successful space missions beyond their design lifetime generally provides valuable data at a low cost, relative to new instruments and launches. The recent NASEM (2016a) report (*Extending Science—NASA's Space Science Mission Extensions and the Senior Review Process*) states that the present method of "senior review" to evaluate mission extensions is working well.

Balance Between Continuity of Existing and Novel Measurements

Some satellite data records have been established for which continuation (continuity) of the record in time carries significant scientific and practical benefits (Box 4.7). Achieving the appropriate balance between investments to maintain continuity versus the development of new measurement capabilities is a longstanding challenge,[11] one that is complicated further when the line between a continuity measurement and a novel measurement is blurred. For example, this survey's recommended Surface Deformation Targeted Observable could be justified on the basis of continuity, extending the record to be initiated by NISAR. However, this Targeted Observable's new emphasis on temporal versus spatial resolution implies some novelty to address needs for both continuity and new measurements, so it is hard to make a clear distinction.

The committee emphasizes that many continuity measurements are provided by the national and international Program of Record (POR), especially the European Copernicus, perhaps making the proposed set of measurements appear skewed toward new measurements. However, if those POR measurement continuity capabilities did not exist, the proposed measurements recommended by the committee would have involved a different mix.

Execution of the national and international POR and the recommendations of this decadal survey, taken together, will provide for the continuation of many key satellite records through most of the next decade. The planning and preparation to continue such measurements beyond the next decade is urgently needed. International collaboration is required to ensure continuity, given individual agency resource constraints. The recent agreement between NASA, NOAA, ESA, EUMETSAT, and the European Union (via its Copernicus

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[11] A recent report from the National Academies of Sciences, Engineering, and Medicine (NASEM, 2015) sought to establish a more quantitative understanding of the need for measurement continuity and the consequences of measurement gaps.

BOX 4.7 THE NEED FOR CONTINUOUS MEASUREMENTS

Satellite remote sensing of Earth grew rapidly in the 1970s, and many measurements became indispensable for Earth science and applications and are continuing. These measurements are used both for immediate applications and to establish long-term records that are essential for understanding Earth system behavior on longer time scales. A 2015 report of the National Academies of Sciences, Engineering, and Medicine (NASEM, 2015) identifies key evaluation factors and puts forward a decision-making framework that quantifies the need for measurement continuity and the consequences of measurement gaps for achieving long-term science goals. It is important for Earth science and applications that these measurements be improved and continued, including observations that meet climate quality standards.

A partial list of key variables for which continuity of measurement is important is provided in Table 4.7.1. Table 4.7.1 is not a complete list of all relevant measurements and it is not a priority listing. The committee has assessed the likely continuity of these and other measurements through the end of the coming decade, based upon the Program of Record (POR) (Appendix A) and the Observing System Priorities table (Table 3.4), to identify potential gaps as it developed its recommended program.

Two Targeted Observables (Mass Change and Surface Deformation and Change) are included in the Designated program element specifically to ensure continuity; several of the Targeted Observables listed in Table 3.6 (Greenhouse Gases, Ozone and Trace Gases, and others) are recommended for competition in the Earth System Explorer program element in part to provide continuity; and others may be addressed via the recommended Venture-Continuity competition strand described in Chapter 3. The provision of continuous measurements of such critical variables by the international community, which allowed the committee to focus its attention on new or missing observations, underscores the importance of the POR as the foundation upon which the committee's recommendations were established. If the POR and the program priorities recommended here are executed as planned by NASA, NOAA, USGS, and our international partners, then it is likely that many (but not all) of these critical records will continue to be available for science and applications in the United States.

TABLE 4.7.1 Examples of Observations Associated with Potential Continuity Needs

Observation	Purpose	Start of Record	Description
Land-Surface Conditions	Monitor land-surface conditions.	1972—Landsat I	Global visible and IR imaging of land at high spatial resolution.
Ocean Color	Measure near-surface ocean color for fisheries and ocean biology and chemistry.	1978—CZCS	Multiwavelength visible imager.
Sea-Ice Concentration	Important for navigation, fisheries and climate monitoring.	1978—Nimbus 7 SMMR	Multiwavelength microwave imager.
Precipitation	Microwave imager provides estimate of precipitation over ocean.	1978—SMMR 1997—TRMM radar	Multiwavelength microwave imager. Precipitation radar.
Temperature and Humidity Profiles	Needed for weather forecasting and measuring change.	1978—Microwave and thermal IR sounding begins	Thermal IR and microwave sounders for all-weather data.
Ocean Vector Winds	Useful for weather forecasting and seasonal prediction.	1978—Seasat, *but record not continuous*	Radar scatterometry or polarimetric microwave radiometry.
Cloud Cover and Optical Properties	Cloudiness is a key weather variable, and clouds are also a key climate variable.	1978—AVHRR; geostationary imaging	Multiwavelength visible and IR imaging.

BOX 4.7 Continued

Observation	**Purpose**	**Start of Record**	**Description**
Solar Irradiance	Total solar irradiance is the energy source for Earth; the ultraviolet radiance influences stratospheric ozone.	1979—Nimbus 7 ERB 2003—SORCE	Total irradiance from the Sun. Total and spectral irradiance from the Sun.
Earth Radiation Budget	Measures changes associated with clouds, temperature trends, or volcanic eruptions.	1979—Nimbus 7 ERB	Absolutely Calibrated Broadband solar and terrestrial radiance at the top of the atmosphere.
Ozone and Trace Gases	Reactive chemicals affect UV radiation, air quality, and climate.	1979—SAGE I, Nimbus 7, TOMS, SBUV 1995—GOME	Solar backscatter, solar occultation, thermal IR, and microwave sounding.
Aerosol Optical Depth	Aerosols affect air quality, weather, and climate.	1999—MODIS, MISR	Solar backscatter.
Sea-Surface Temperature	Needed for weather forecasting and monitoring ocean change.	1981—AVHRR on NOAA-7	Thermal infrared and microwave imaging.
Vegetation Greenness Index	Estimation of the photosynthetic activity indicates health and productivity of land vegetation.	1981—AVHRR NDVI	Multiwavelength reflected solar imager.
Sea-Surface Height	Global measurements of sea-surface height are useful for quantifying sea-level rise, diagnosis and forecasting of El Niño, and determining ocean heat storage.	1992—TOPEX and JASON	Radar altimetry.
Mass Change	Gravity measurements can be used to monitor ocean mass, land-surface total water storage, and land-ice mass changes.	2002—GRACE	Spatial and temporal anomalies of gravity field.
Ice Elevation	Changes in land-ice volume are an important potential source of large sea-level changes.	2003—ICESat	Laser altimetry.
Cloud/Aerosol Vertical Profiles	The vertical structures and properties of cloud and aerosol layers are important for weather and climate.	2006—CloudSat 2006—Calipso	Radar and lidar profiling of cloud and aerosol structure.
Greenhouse Gases (CO_2, Methane)	Important in understanding the factors controlling carbon fluxes and atmospheric concentrations.	2009—GOSAT 2014—OCO-2 2002—SCIAMACHY	Reflected solar spectrometer.

NOTE: Not in any priority order. These examples, and others not included in this sample, should undergo formal review, as described in the report *Continuity of NASA Earth Observations from Space: A Value Framework* (NASEM, 2015), to plan for continuity needs.

program) to continue high-precision ocean altimetry measurements via the Sentinel-6 program provides an example of international collaboration. As noted in Recommendation 2.2, NASA should continue to work with international partners to develop an international strategy for maintaining key satellite measurements and establish data-sharing agreements among the nations making the measurements.

Finding 4.5: Maximizing the success of NASA's Earth science program requires balanced investments across its program elements, each critically important to the overall program. The *flight* program provides observations that the *research and analysis* program draws on to perform scientific exploration, the *applied sciences* program transforms the science into real-world benefits, and the *technology* program accelerates the inclusion of technology advances in flight programs. The current balance across these four program elements is largely appropriate, enabling a robust and resilient Earth science program, and can be effectively maintained using decision rules such as recommended in this report. Some adjustment of balance within each program element is warranted, as recommended in this report.

Recommendation 4.6: NASA ESD should employ the following guidelines for maintaining programmatic balance:

- ***Decision Rules*. Needed adjustments to balance should be made using the decision rules included in this report.**
- ***Flight versus Nonflight*. Flight programs should be approximately 50-60 percent of the budget.**
- **Within Nonflight:**
  - ***R&A Program*. Maintain at its current level of the ESD budget.**
  - ***Technology Program*. Increase from its current level of 3 percent to 5 percent of the ESD budget.**
  - ***Applications Program*. Maintain at its current level of the ESD budget.**
- **Within Flight:**
  - ***Program Elements*. Ensure that no flight program element is compromised by overruns in any other element.**
  - ***New versus Extended Missions*. Continue to use the present method of "senior review," consistent with guidance from the National Academies of Sciences, Engineering, and Medicine (NASEM, 2016a).**
  - ***New Measurements versus Data Continuity*. Lead development of a more formal continuity decision process (as in NASEM, 2015) to determine which satellite measurements have the highest priority for continuation, then work with U.S. and international partners to develop an international strategy for obtaining and sharing those measurements.**
  - ***Mission-Enabling Investments versus Focused Missions*. Other than additional investments in the Technology program and the new Incubation program element, no change in balance is recommended.**

Scope Within Nonflight Program

As noted throughout this section, NASA's nonflight programs are essential to its overall mission. These programs are performing well and are all in approximately correct balance at the current time. Two small scope adjustments are recommended:

Recommendation 4.7: NASA should make the following scope changes to its program elements:

- ***Technology Program*. Establish a mechanism for maturation of key technologies that reduce the cost of continuity measurements.**

- ***Applications Program.* Redirect a small portion to new funding opportunities that focus specifically on taking early-stage ideas and exploring how to move them into applications, including co-sponsorship with NOAA and USGS.**

Balance and Scope Within the Venture Program

The Earth Venture Program was established to "create space-based observing opportunities aimed at fostering new science leaders and revolutionary ideas" (NRC, 2007). To achieve this, NASA implemented three strands of Earth Venture elements. The first is the Earth Venture Mission (EV-M) opportunity, which solicits stand-alone space missions with a cap of $150 million. The second is the Earth Venture-Instrument (EV-I) opportunity, which solicits instrumentation for which NASA assumes the responsibility of identifying a launch opportunity. EV-I is solicited at approximately 18 month intervals. Last, the Earth Venture Suborbital (EV-S) opportunity solicits suborbital studies with an approximately 4-year cadence, selecting approximately five investigations per cycle, cost-capped at $30 million each, lasting 5 years each. Through the implementation of this program, NASA has provided two opportunities in the past decade for missions, six for instrumentation, and two for suborbital proposals.[12] The result has been that the program has succeeded in fostering innovation and stimulating a vibrant Earth science community through the provision of multiple opportunities for large-scale observation capabilities.

Even though the Earth Venture program was initiated nearly a decade ago, only one EV-M has been launched (CYGNSS), none of the EV-I missions has been flown yet, and one cycle of the EV-S has been completed. As a result, the relative benefits of these programs are still not fully understood. The committee fully supports the continuation of the Earth Venture program in its present form, but after several of the EV-I missions and the contributions from Cyclone Global Navigation Satellite System—Earth Venture Mission (CYGNSS) are better understood, a cost-benefit analysis of the EV investments would help inform the amount and distribution of future investments in the program.

Finding 4.6: The Earth Venture program has provided increased opportunities for innovation in scientific Earth observations. However, it is too early in the program, with too little history, to assess the benefits of modifying the present three-strand Venture structure or adjusting cost caps beyond the recommended addition of a Venture-Continuity strand.

Recommendation 4.8: The Midterm Assessment, with a longer program history than is available to ESAS 2017, should examine the value of each Venture strand and determine whether the cadence or number of selections of any strand should be modified. In particular, the Venture-Suborbital strand should be compared to the approach of executing comparable campaigns through the research and analysis program to assess which approach serves the community better.

Budget Guidance and Decision Rules for Maintaining Balance

The committee's suggested decision rules have two components. First are guidelines for how to allocate funding that becomes available as current flight missions are completed (referred to as the "funding wedge"). Second are guidelines for ensuring various aspects of balance in the program's overall budget. The assumption, used throughout this report, is that future budgets correspond to the FY 2016 budget adjusted for inflation. Computation of the funding wedge is described in detail in Chapter 3. The conclu-

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[12] Information on NASA's Venture-class program can be found at https://essp.nasa.gov/projects/.

sion was that the cost to complete the POR (the NASA-baseline missions already "in implementation") was estimated to be $3.6 billion and the "funding wedge" for new missions advocated in this report was estimated to be $3.4 billion.

Overall Program Balance

To maintain program balance, the committee recommends (Recommendation 4.6) that ESD budget components should be approximately consistent with historical budgets. For the entire ESD budget, the following guidelines are recommended.

- *Earth Science research* should be maintained at approximately 24 percent of the budget (within the range 22-26 percent). (This value of 24 percent includes 18 percent for openly competed research and analysis, and approximately 3 percent each for computing and administration.)
- *The Applications program* should be maintained at 2-3 percent of the budget.
- *The Technology program* should be increased from its current 3 percent to about 5 percent.
- *Flight programs*, including Venture, should be 50-60 percent of the budget.
- *Mission operations* should be 8-12 percent of the budget.

Allocation of the Funding Wedge Within Flight

As general guidance for allocating the funding wedge within flight programs, an appropriate distribution of the ESD investment is 35-45 percent in large missions, 40-50 percent in medium and small missions, and 10-15 percent in technology-related aspects of flight development. No single mission should consume more than 25 percent of the funding wedge.

Managing Budgets

Decision rules are most effective when budgets are managed carefully across ESD. Mission development, with its large costs and uncertainties, traditionally results in significant budget management challenges. Recommendation 3.3 provides specific guidance concerning the cost-aware management of missions in development.

Decision Rules for Budget Changes

The committee expects that budgets will be different from the nominal assumptions made in accordance with the committee's statement of task. A critical purpose of decision rules is to maintain the scientific and technical capacity for a robust space-based Earth science program when budgets change. Maintaining capacity is important, since that capacity takes a long time to build (in some cases, longer than the mission development time scale) and is easily disrupted.

The committee places the highest priority on continuity of critical missions, followed by competitive opportunities in the Earth System Explorer and Earth Venture lines, followed by the large missions. However, because the highest overarching priority is a balanced portfolio, it is important that no one aspect of the portfolio be reduced excessively, to keep others intact.

As a result, in managing potential *budget reductions* that impact the scope or cadence of the new measurements of this decadal survey:

- Reductions should first be accommodated by delaying the large missions.
- If additional reductions are required, the medium-size Designated missions should be delayed, unless these delays threaten the continuity of data sets that require continuous measurement.

- Should continuity be threatened, the cadence of medium-size competitive missions should be reduced but not to fewer than two competitions in the decade. The budgets for Venture and research and applications should not be reduced by more than 5 percent from their historical averages.

These decision rules are intended to apply to the new missions recommended in this decadal survey. Because of the fraction of the budget consumed by the POR in the first half of the decade, there is very little flexibility to absorb budget reductions with the missions recommended in this survey until the second half of the decade. Should cuts to the POR be required to address budgetary challenges in the first half of the decade, then the science priorities identified in the Science and Applications Priorities table (Table 3.2), in conjunction with the preceding decision rules—which prioritize continuity and seek to absorb cuts first by reducing large missions, then medium missions, then competitive missions—should be used as guidance to inform such reductions.

Large changes to the Decadal program (those that exceed the capacity of the preceding decision rules to address, in particular decisions that must balance continuity and the cadence of competition) should be made only subsequent to additional review by the National Academies Committee on Earth Science and Applications from Space (CESAS). In particular, NASA ESD should consult its standing scientific advisory committees if (1) the projected cost of the POR grows to consume more than $3.6 billion in the coming decade, (2) more than one mission in this decadal survey is delayed more than 3 years, or (3) a mission in the POR or required to meet the new measurements of this decadal survey is lost prematurely. In such cases the preceding decision rules provide guidance to CESAS, but need not be strictly adhered to, as more flexibility may be needed to manage unforeseen events.

In managing situations where *additional budget* becomes available, the additional funds should be used to increase the cadence of the new measurements and associated missions recommended in this survey. In particular, expanding the breadth of observational objectives should be prioritized, potentially by increasing the number of Earth System Explorer competition opportunities. The ESAS 2017 Science and Applications Traceability Matrix (SATM) should be consulted for guidance on the scientific priorities when augmentations are possible.

NOAA PROGRAMMATIC CONTEXT

This section provides guidance for NOAA's observing system priorities, in accordance with the committee's statement of task, which specified primary tasks to include "(1) how new technology may enhance current operations, and (2) what new science is needed to expand current operations, either to enable new opportunities or to include new areas of interest."

NOAA's Role in Civil Observing System

NOAA's role with regard to space-based observations is specified in the 2014 *National Plan for Civil Earth Observations* (NSTC, 2014). NOAA's primary responsibilities fall within "Sustained Satellite Observations for Public Services," in contrast to NASA's responsibilities, which fall largely within the categories "Sustained Satellite Observations for Earth System Research" and "Experimental Satellite Observations." Within the category, specific NOAA responsibilities are called out.

These distinctions have been further clarified through additional policy directives, such as the Office of Management and Budget (OMB) guidance accompanying the 2016 Federal Budget, as well as the Appropriations Committee Reports for the 2016 and 2017 Federal Budgets, which direct NOAA to prioritize satellite programs directly related to weather forecasting (as described in the "Toward a National Strategy" section of Chapter 2). This focus reflects a new budget reality for NOAA. Issues regarding the role of observations in support of NOAA's non-NWS mission are discussed separately in this section.

NOAA's observing system role is thus distinct and different from NASA or USGS. Key distinctions, for the purpose of this discussion, include the following:

- *Operational responsibility for high-reliability observations.* As noted in the statement of task, NOAA has "a critical requirement for continuity of observations and delivery of services and information to the public and commercial sectors." This strong requirement has corresponding implications for observing system design, programmatic implementation methodologies, and new capabilities development.
- *Multidecade development cycle*. NOAA's stringent availability requirements have led to observing system architectures with very long life cycles. The current development paradigm involves multidecadal cycles and impacts any development approaches or partnerships. It has also constrained NOAA's agility for introducing new capabilities.
- *International operational obligations, and mandated international data sharing*. NOAA has formal obligations for data sharing through agreements such as WMO-40 and the Joint Polar System (JPS) with EUMETSAT. This has implications for its use of commercial and alternate data sources, since their acquisition may imply obligations for sharing beyond NOAA.

For these reasons and others, ESAS 2017 is not intended as a primary planning activity for NOAA space-based observations. Instead, ESAS 2017 was requested to provide guidance largely associated with opportunities for improving NOAA's system beyond its baseline plan.

Needs and Challenges

The report of the NOAA NESDIS Independent Review Team (IRT, 2017) provides an important perspective on the needs and challenges of NOAA's space-based observations. The report's objective is "independent assessment of NESDIS path forward and the capability of the enterprise to embark on that path." Key conclusions relevant to ESAS 2017 include the following:

- The IRT concluded that NESDIS has a positive path forward and is "capable of embarking on that path."
- NESDIS has a critical mission to protect lives and property, with high-reliability space-based observations an essential element.
- NASA plays an important role in weather science, with relevance to NOAA. NASA (in particular, the NASA Goddard Space Flight Center) also plays a complex and evolving role in NOAA system development, recently including both JPSS and GOES-R, which face ongoing challenges such as potential coverage gaps. Better definition and strengthening of the NOAA-NASA relationship is needed. The NESDIS strategic plan (NOAA, 2016) provides a framework for improving the partnership.
- NESDIS has developed a strong strategic plan, which recognizes the value of use-inspired science for advancing the NESDIS mission. However, the strategic plan suffers from being an "internally focused document, which limits its utility."

Science and Applications

NOAA's primary planning activity at this time is an internal study called the NOAA Satellite Observing System Architecture (NSOSA) performed within the Office of Systems Architecture and Advanced Planning (OSAAP), supported by a NOAA-chartered community study performed by the Space Platform Requirements Working Group (SPRWG). Both studies were ongoing at the time of ESAS 2017 and briefed to the committee on several occasions. Several ESAS 2017 members were also SPRWG members. Although NOAA's mission includes space weather, it was not a part of the ESAS 2017 study.

NSOSA, in consultation with SPRWG, developed a formalized quantitative evaluation methodology to assess the cost and benefit of individual observations within the overall NOAA architecture (including the benefits/costs of relative improvements among observations), driven primarily by operational (rather than scientific) needs. The process is intended to inform NOAA management, which will make final decisions on observing system requirements.

The current NOAA satellite system is expected to be replenished through the late 2020s or early 2030s without substantial changes. This POR system is referred to as POR 2025. The charter of NSOSA/SPRWG is to plan for changes to that system that could be implemented during the 2030s and persist into the 2050s. To accomplish that, NSOSA/SPRWG prioritized possible changes to the system and identified those achieving the best cost-benefit performance as candidates for inclusion in the post-2030 system. In doing this, NSOSA/SPRWG also identified a set of "unsatisfied priorities" that reflect high-priority NOAA requirements involving observations not selected for inclusion due to cost or technology readiness issues. Assessing these unmet needs is somewhat subjective, as it depends highly on unknown budget availability 10-30 years in the future.

Recognizing this reservation, NOAA provided the committee with a preliminary summary of expected unsatisfied priorities, as identified by the NSOSA/SPRWG advisory process (which was ongoing at the time this report is being written). These are listed in Table 4.3, along with corresponding priorities identified by ESAS 2017. From this table, it is clear that there are well-defined unmet needs that correspond closely to ESAS 2017 priorities. There are notable exceptions, as well, such as the low-medium priority for regional IR and microwave sounding; the Weather and Air Quality Panel felt that diurnal sounding capability is a high priority, and GEO-based sounding is one way to accomplish that. The table thus presents opportunities for NASA development activities that match NOAA's "unsatisfied" priorities.

Finding 4.7: The NOAA observations system plan for 2035-2050 currently is anticipated to have unsatisfied priorities for global 3D fields of winds, global precipitation, and other observables, along with a general need for observing system cost reduction. With some exceptions, these unsatisfied NOAA priorities generally align well with the ESAS 2017 recommendations to NASA.

Programmatics

Providing guidance for advancing NOAA's observing system requires starting with an understanding of how this has been accomplished historically. Appendix D of *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey* (NRC, 2012) has an abbreviated history. Its general features include an initial strong interaction with NASA in terms of instrument and satellite development that has become less strongly linked over time.

Today, NOAA faces challenges to an effective process for advancing their observing systems. These include the following:

TABLE 4.3 Opportunities for Improving the NOAA Operational Observing System

Expected NOAA "Unsatisfied Priorities"	Expected NOAA Priority and Rationale	Related ESAS 2017 Programs or Targeted Observables
Instrument Cost Reduction	*High*—Reducing cost of any system element enables greater system capability. NOAA has limited capacity to invest in development activities that eventually reduce production cost.	Incubation program element NASA ESTO
3D Winds in Troposphere and Lower Stratosphere	*High*—High cost and low technology readiness impede inclusion in NOAA operational system.	Atmospheric Winds
Global Precipitation Rate	*High*—High cost and low technology readiness impede inclusion in NOAA operational system.	Clouds, Convection, and Precipitation
Subseasonal to Seasonal (S2S) Forecasting	*Medium*—Multiple new and often difficult observations needed, notably upper ocean and ocean-atmosphere coupling, along with assurance of continuity and ongoing cost reduction for existing observations.	Many ESAS 2017 Targeted Observables
Ocean Surface Vector Winds	*Medium*—Coverage is likely to be less than desired, with high-volume coverage presently costly.	Ocean Surface Winds and Currents
Global Atmospheric Soundings	*Medium*—Expect future systems to have more soundings of at least moderate precision/accuracy levels as compared to today, but high-precision/accuracy IR and microwave soundings may be lacking.	Planetary Boundary Layer
GEO-based Regional IR and Microwave Sounding	*Low to Medium*—Useful for forecaster nowcasting, but generally considered less valuable than global sounding.	Planetary Boundary Layer

NOTE: Based on a preliminary assessment of unsatisfied observing system priorities identified within the NSOSA/SPRWG process (intended to inform NOAA management, which will determine final observing system requirements). Related ESAS 2017 priorities are included for comparison.

1. *Balancing Reliability Against Advancement.* How should the need to advance be weighed against NOAA's requirements for "continuity of observations and delivery of services," given that advance is necessary to provide expected new observations and services in the future?
2. *Determining Acceptable Risk.* How much risk is acceptable to accommodate needed advances across observing system generation (block) changes? How much risk is acceptable to accommodate advance within observing system generations? How can on-ramps be integrated to accomplish this?
3. *Selecting Prioritization Methodologies.* How should development advances be selected and prioritized? Some options include community-based input (e.g., SPRWG and National Academies' studies), and NASA/NOAA-provided Observing System Simulation Experiments (OSSEs) and Observing System Experiments (OSEs).
4. *Accelerating Adoption of New Capabilities.* How can NOAA make more rapid use of observing system advances, avoiding internal bottlenecks in adoption, assimilation, and algorithms?[13]
5. *Leveraging External Sources.* How can external advances in observing systems and data sources be integrated more rapidly?
6. *Deciding Between Make or Buy.* Should observing system advances be accomplished within NOAA, implemented by commercial partners through the procurement process, or pursued through partnerships?

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[13] NOAA has recently introduced a policy referred to as *NAO 216-105B: Policy on Research and Development Transitions* to better address this issue. It more clearly defines NOAA's research-to-operations transition, including applications and commercialization. The text of this policy is available at http://www.corporateservices.noaa.gov/ames/administrative_orders/chapter_216/216-105B.html.

NOAA has internal policies that comprehensively address these issues, but they are in many cases insufficient to address the growing challenges NOAA faces. The result is an ineffective strategy for how to rapidly advance its observing systems so as to meet the nation's evolving needs. Most fundamental is the first of these, by which NOAA's appropriate commitment to reliability eventually becomes an impediment to needed advances. All of these issues could be directly addressed by a NOAA policy that formally defines a coherent strategy and prioritization for advancing the observing system, in addition to the critical mission assurance requirements.

Observations for NOAA's Non-NWS Capabilities

NOAA NESDIS has a broad range of real and potential users that extends well beyond its traditional (and most important) customer, the National Weather Service (NWS) and its provision of atmospheric weather forecasts, warnings, and services. These users include the remaining NOAA line offices, other agencies, international partners, commercial users (Box 4.8), academia, and private citizens. As examples, their needs include detecting and forecasting harmful algal blooms, understanding fish stock variability, forecasting high-seas wind and wave conditions, estimating rainfall for the Pacific Islands, planning responses to coastal inundation, detecting coral bleaching, and sea-ice forecasting, along with performing reanalyses of various physical phenomena.

At the same time, many (both real and potential) users across the agency have expressed frustration with using data from satellites. Many see large weather satellite costs coming at the expense of their modest-by-comparison budgets. A common complaint is that a user has to be a satellite expert to understand and use the data. In general, users need help accessing satellite data and turning them into useful

BOX 4.8 OCEAN SURFACE WIND MODELING FOR MARITIME OPERATIONS

The Meteorological Operational Satellite Program (MetOp) 50 km advanced scatterometer (ASCAT) ocean surface winds, along with in situ observations, presently serve as one of the primary drivers for the Global Forecast System (GFS) model that provides atmospheric forcing for NOAA's WaveWatch III wave model (Bi et al., 2011). This wave model has a global domain of approximately 1.25 degrees × 1.0 degrees resolution, with nested regional domains for the Northern Hemisphere oceanic basins at approximately 0.5 degree × 0.25 degree and approximately 0.25-degree resolution.[1] This wave model serves seaport cargo activity, which accounts for 26 percent of the U.S. economy.[2]

One of its most critical applications is for operations at the Port of Long Beach, California. The Port of Long Beach, combined with the Port of Los Angeles, is the busiest port in the United States. Fifty percent of California's oil comes in through this port, with only a 5-day storage capacity. With the longer 1100-1300 ft vessels, entrance to the port is constrained by the draft of the ship. The vessels must have 10 percent clearance under their keel. If the waves approach on the stern, the vessels will start to pitch, losing 9.6 ft of draft for each 1 degree of pitch. Presently, five oil companies engage in offshore transfers of petroleum products onto smaller oil tankers that can then enter the port. The cost is $100,000-$200,000 per day to hold a tanker offshore.

In 2014, the port, in partnership with Tesoro, California, Oil Spill Prevention and Response, Jacobsen Pilots, the Marine Exchange of San Pedro, NOAA's National Ocean Service, the National Weather Service, the Army Corps of Engineers' Coastal Data Information Program, and California Parks and Recreation, contracted a company in Rotterdam, Protide, to calculate and provide the "go, no-go" status to the Long Beach Pilots. This status is based on many parameters, such as wave models, tides, and bathymetry. The WaveWatch III model has a key role in providing initializations and boundary conditions for higher-resolution nested models that produce the swell information used by the Protide application. At this time the WaveWatch III model could benefit by

BOX 4.8 Continued

higher temporal (presently updates every 3 hours) and spatial resolution of the wind forecast to help improve forecast accuracy. At the Long Beach location, the WaveWatch III model is known for either underpredicting or overpredicting the swell (Figure 4.8.1). Improving the existing satellite winds, which would result in higher wave model accuracy, will have societal economic, environmental, and safety benefits.

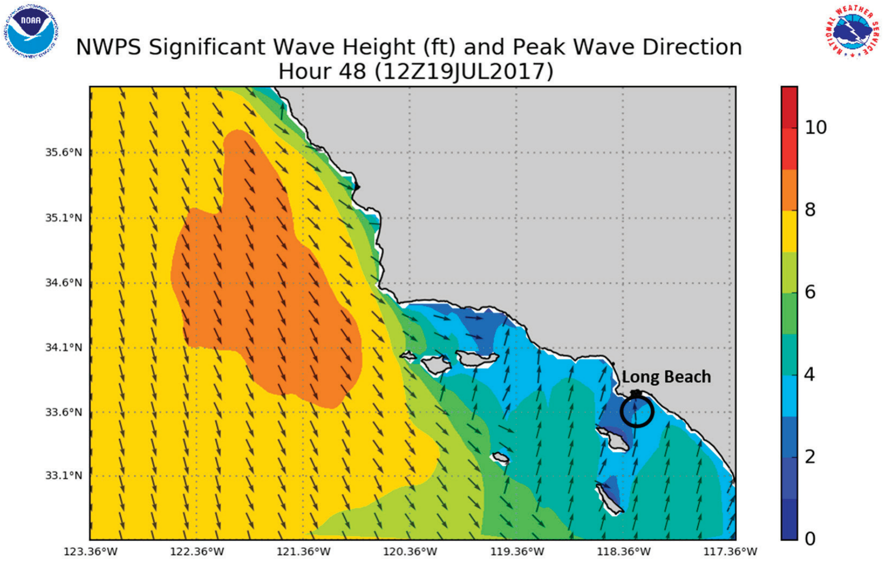

FIGURE 4.8.1 Nearshore Wave Prediction System (NWPS) model illustrating island sheltering and corresponding bimodality of wave approach. The black circle at the Port of Long Beach represents the critical area of vessel transit during an energetic south swell. SOURCE: Courtesy of NOAA/National Weather Service.

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[1] See, NOAA National Weather Service, "NOAA WAVEWATCH III: NWW3 Implementations," last modified November 15, 2012, http://polar.ncep.noaa.gov/waves/implementations.shtml.

[2] See, American Association of Port Authorities, "FY2017 Omnibus Appropriations Bill Will Help America's Ports," News Release, May 4, 2017, http://www.aapa-ports.org/advocating/PRDetail.aspx?ItemNumber=21678.

information, combining them with in situ observations, and applying a combined product to meet a particular need—whether answering a societally relevant research question or feeding into an operational environmental forecast.

The origin of this issue is an *institutional framework* within NOAA that systematically acquires, processes, and distributes satellite data from its own and foreign-partner satellites in support of NWS operational weather forecasting needs, which provides a degree of *vertical integration.* A corresponding institutional framework is lacking for the most part in support of other (non-NWS) NOAA needs; data must be acquired from various satellites (some NOAA, but mostly NASA and international), appropriate products derived, and then distributed to a diverse user community spread across the agency.

Meeting diverse NOAA needs—beyond the NWS—for satellite data involves acquiring satellite data from various NASA and foreign sources, generating suitable products, distributing them to users, and then working with those users to meet their needs and demonstrate benefits. Some user needs require timely access to near-real-time products, others require higher-level retrospective products at later times. There are costs associated with this process. And if funds are not available to demonstrate the utility of the satellite data, it is difficult to justify a budget increase to provide a corresponding new operational service to society. Since much of the satellite data come from outside NOAA, this results in lost opportunities, being unable to take advantage of other agencies' and nations' substantial investments in satellites in order to exploit their resulting data.

Forecasting harmful algal blooms (HABs) is an example of one of those needs. HAB forecasts in the western end of Lake Erie—which serves as the water supply for Toledo and a dozen surrounding communities in Ohio and Michigan—determine those times when the water must either have a significant level of additional treatment or, in extreme situations, not be used at all for drinking. Similar forecasts in the eastern (around Tampa, Florida) and western (north of Brownsville, Texas) Gulf of Mexico determine those times when shellfish beds must be closed. Both of these HAB events typically are annual events and may last for one to several months in duration.

Within NESDIS, the Center for Satellite Applications and Research (STAR) is responsible for accessing various satellite sources and generating and distributing near-real-time products, while the National Centers for Environmental Information (NCEI, the former national data centers) are responsible for generating and distributing retrospective products. These two organizations can be part of the solution by recognizing, engaging, and partnering with the broad user base across NOAA. This could take the form of an internal Users' Working Group, such as is employed at the NASA DAACs. Such a group would help interested users understand the variety of sources of satellite data products potentially available—both near-real-time and retrospective, and then empower those users to provide feedback to STAR and NCEI to help prioritize which sources to access, what products to generate, and how to access those products. This would show users that STAR and NCEI are committed to helping those users meet their needs, thereby demonstrating a responsive service attitude. This is a step that can be taken today.

Finding 4.8: NOAA has diverse communities of real and potential users with needs for satellite data that extend well beyond those associated with the provision of weather forecasts and warnings. These users would benefit by having more timely and easier access to user-friendly derived products that incorporate data from multiple sources. Such access would enable each user to work with those satellite products of interest and combine them with data from selected in situ sources to meet specific operational and use-inspired research needs.

Recommendation 4.9: NESDIS, working through its Center for Satellite Applications and Research (STAR) and National Centers for Environmental Information (NCEI) should establish an internal Users' Working Group (including cooperative institutes and other NOAA partners) to (1) recognize the breadth of the potential user base beyond the National Weather Service that would benefit from improved access to satellite data products; and (2) work in partnership with those users to prioritize requirements and how they might best be met.

Leveraging Non-NOAA Observations

NOAA has a long and successful history of sharing its observations with international partners and likewise benefiting from access to their data. Yet more is possible.

Other Governmental and International Sources

Data sources from other governmental and international sources offer an opportunity for increased information and value for a minimal investment; however realizing those benefits requires that such data actually be incorporated into the operational and research framework, which for a variety of reasons, often does not happen. One impediment is the long and tedious process of understanding alternate data sources, ensuring their quality, and establishing that using them to improve forecasts or meet other needs. NOAA has established processes for doing this with new systems of its own. For example, both JPSS and GOES-R each include a budget line (labeled "Proving Ground for Risk Reduction") to demonstrate product utility in a user setting; this enables the development of new and refinement of existing products for these two operational NOAA satellite programs. The associated funding for each is in the range of ~$10 million+ in the early years of a program to a few million dollars in later years.

These budget lines are critical for the NWS to be able to successfully exploit the data coming from their new systems. But there is no analogous funding opportunity for similar work on data from non-NOAA sources such as NASA and foreign satellites (especially Copernicus), particularly to serve non-NWS needs. For example, while the United States has access to observations of ocean-surface vector winds from SCATSAT, the Indian scatterometer satellite, funds are not available for the Ocean Prediction Center to actually utilize this data, or the wind data that will be available from its successor—Oceansat-3—when it is launched in 2018.

Making the transition from NASA research (or foreign) missions to NOAA operations also requires management support. Both sides must recognize the importance of transitioning. It is important that NOAA leadership has a fundamental understanding and appreciation of what NASA has to offer, as well as the potential offered by non-NOAA satellite sources.

Recommendation 4.10: NOAA should further leverage use of NASA, USGS, and international satellite observations to meet diverse needs of its line organizations, including those unrelated to weather—and thus not lose the opportunity to capitalize on substantial investments made by other organizations. As one step to accomplish this, NOAA should establish a budget line (similar to what is done for JPSS and GOES-R) in order to (1) facilitate access to and use of data from these non-NOAA sources and (2) demonstrate resulting benefits through broadened collaboration with the NASA Applications and similar programs.

Commercial and Other Nongovernmental Sources

NOAA, to its credit, has recognized the potential benefit of commercial satellite data and is proceeding with projects to explore the opportunities. Indeed, NOAA/NESDIS's 2016 Strategic Plan suggests that, as an integral part of providing a comprehensive and trusted set of products to serve users' needs, NOAA will "Continue to diversify our portfolio by ingesting, validating and certifying data and information from within NOAA, our interagency and international partners and potential commercial sources based on established priorities and requirement needs.[14]

The recent NOAA Commercial Weather Data Pilot awards are demonstration projects to evaluate and demonstrate the quality of commercial data and its impact to weather forecast models. The awards to Spire Global and GeoOptics suggest the potential for small satellite launches to provide radio occultation data into NOAA's operational weather prediction models. MISTiC Winds (Maschoff et al., 2016) is a proposed

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[14] See NOAA, *Strategic Plan: NOAA's National Environmental Satellite, Data, and Information Service*, https://www.nesdis.noaa.gov/sites/default/files/asset/document/the_nesdis_strategic_plan_2016.pdf.

27U CubeSat mission designed to improve short-term weather forecasting based on a miniature high-resolution, wide-field, thermal emission spectrometry instrument that will provide global tropospheric vertical profiles of atmospheric temperature and humidity at high (3-4 km) horizontal and vertical (1 km) spatial resolution. Formations of three sequential spacecraft in one or multiple orbit planes could provide global 3D horizontal vector wind retrievals. Key remaining technical risks are being reduced through laboratory and airborne testing under NASA's Instrument Incubator program.

With time, both the potential benefits and the risks are coming to be better understood. To be viable within NOAA's operational system, NOAA insight is generally needed into data generation processes, calibration, validation, and other data quality characteristics. In some cases this need conflicts with the needs of commercial providers to keep information proprietary for competitive purposes. This need also requires the commercial providers to have done substantial calibration and validation on their own, sometimes beyond what is needed for other customers. Commercial providers are similarly challenged by some of NOAA's use-rights expectations, including sharing of data with all international partners. All of these issues, and more like them, reflect impediments to NOAA use of commercial data, something not surprising given that the availability of commercial space-based data sources is still in its infancy. With efforts on both sides, impediments can often be overcome.

Given the critical operational role of NOAA, robustness of data sources is essential. To be viable within NOAA's operational system, commercial and alternative data sources must be robust against loss of any single source/provider, if essential to NOAA core functions. To ensure recoverability in the event of lost sources/providers, NOAA can either engage multiple providers or develop protocols for managing such losses.

A full review of the potential benefits and risks of commercial data sources was beyond the scope of this committee, but we recognized the potential opportunity presented by this emerging data source for NOAA.

Recommendation 4.11: NOAA should establish itself among the leading government agencies that exploit potential value of commercial data sources, assessing both their benefits and risks in its observational data portfolio. It should innovate new government/commercial partnerships as needed to accomplish that goal, pioneer new business models when required, and seek acceptable solutions to present barriers such as international partner use rights. NOAA's commercial data partnerships should ensure access to needed information on data characteristics and quality as necessary and appropriate, and be robust against loss of any single source/provider if the data are essential to NOAA core functions.

NASA Development Partnership

NOAA's partnership with NASA has been long and often productive. Several decades ago, NASA provided extensive development and flight prototyping support for advancing NOAA's operational satellite systems (see Appendix D of NRC, 2012, for a more detailed description). Today, NOAA's needs and NASA's capabilities are well matched. A strong partnership can be very productive for both organizations (Box 4.9). This holds for both technology and scientific advancement.

Technological Opportunities

Technology is advancing at a rapid pace in the space community, driven in large part by commercial and academic innovation. NOAA can benefit from these advances. The upcoming decade will likely enjoy an exponential growth in microSat, nanoSat, and CubeSat instrumentation, flights, and observations, with a commensurate explosive surge in collective contribution to Earth system science, application, and operations—from space weather to hydrology, spanning the atmosphere, ocean, and land surface.

BOX 4.9 OPPORTUNITIES AND CHALLENGES INHERENT TO A NASA-NOAA DEVELOPMENT PARTNERSHIP: CASE STUDY OF GEOSTATIONARY IR SOUNDING

The high temporal sampling of geostationary hyperspectral sounders allows for rapidly evolving weather to be observed from space to improve the forecasting of severe weather events, and will also support air quality monitoring and atmospheric chemistry observations. NOAA once had plans to include a hyperspectral IR sounder on its Geostationary Operational Environmental Satellites (GOES), but chose not to move forward with the plans. Part of the reason cited by NOAA was lack of NASA development for such instruments. The history of this observational capability illustrates the opportunities and challenges involved in a NOAA-NASA development partnership.

In its evolution of environmental remote sensing capabilities, NOAA (earlier the Environmental Science Services Administration [ESSA]) has often relied on new technology demonstrations by NASA that were subsequently transferred into NOAA missions. The polar-orbiting Nimbus satellite series had a number of scientific firsts, such as the High-resolution Infrared Sounder (HIRS) that flew on Nimbus 6 and led to the HIRS operational sounder on the TIROS-N. NASA research and engineering also supported the development of the operational geostationary satellite program. The SMS-1 (Synchronous Meteorological Satellite) was a NASA-developed, NOAA-operated spacecraft. SMS-1 and SMS-2 paved the way for the GOES satellite program, which included the multispectral imagery from the Visible and Infrared Spin-Scan Radiometer (VISSR).

In 1980 NASA added a sounding capability to the NOAA geostationary imager, the VISSR Atmospheric Sounder (VAS). The VAS demonstration was successful in producing hourly soundings, but research and applications pointed to the need for increased spectral resolution to better resolve the vertical changes in temperature and moisture. NOAA introduced an operational broadband infrared (IR) geostationary sounder in 1994 with GOES-8. This 19 spectral band sounder successfully produced hourly observations over extended regions, including over the data-sparse oceans. These soundings complemented the twice-daily international suite of radiosondes and helped depict rapid changes in regional temperature, water vapor, and cloud cover for nowcasting severe weather.

However, information content analyses have demonstrated that broadband sounders still have limited vertical information and accuracy for atmospheric profiling, when compared with hyperspectral IR sounders.

The mainstream emergence of "U-class" miniaturized satellites will significantly transform how we plan and conduct future Earth and space science research and operations, but only if the agencies are poised to take advantage of them. These spacecraft have masses no more than 1.33 kg per unit ("U") and are composed of multiple of 10 × 10 × 10 cm cubic units (e.g., 1U, 3U, 27U). They typically feature commercial off-the-shelf (COTS) components and are deployed on-orbit via previously planned—for example, through International Space Station resupply missions or accommodated as secondary (auxiliary) payloads on other launch vehicles such as NASA's Educational Launch of Nanosatellites (ELaNa) and CubeSat Launch initiative (CSLI).

One option is to exploit the proven capabilities offered by the NASA Earth Science Technology Office (ESTO), through a multiagency funding and coordination mechanism. The intent would be to resurrect an interagency technology maturation process to provide atmospheric observing technology "on-ramps" that would account for the strengths of the two agencies: NOAA's low-risk and sustainable measurement set evolving as NASA matures new observing technologies to a high-technology readiness level. Today, ESTO's limited budget only allows for limited technology maturation. Through the addition of NOAA's future observing system needs, suitably supported, it would become possible for ESTO to oversee a technology maturation process that would deliver high Technology Readiness Level (TRL) instruments that

BOX 4.9 Continued

To address this, NOAA planned to swap the broadband GOES sounder for a high spectral resolution (hyperspectral) sounder on the third GOES (GOES-10), but the implementation of the Geostationary High-resolution Interferometer Sounder (GHIS) never materialized. During the systems design of the follow-on GOES-R series, an Advanced Baseline Sounder (ABS) was studied to replace the GOES sounder. The ABS measurements were to enable monitoring of the evolution of detailed temperature and moisture structures in clear skies with higher accuracy (better than 1 K temperature and 15 percent relative humidity root mean square) and improved vertical resolution (about 1 km) over the GOES broadband sounder. However, NOAA determined that a geostationary Earth orbit (GEO) advanced hyperspectral infrared sounder, without a prior technology demonstration, would offer unacceptable risk to an operational agency, and the ABS was removed from the GOES-R series.

In the 1990s NASA developed a high spectral resolution infrared sounder intended for geostationary testing; the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) was built, but never launched. In response to the de-scoping of the Hyperspectral Environmental Suite (HES) intended for the next generation of NOAA GOES satellites, ESAS 2007 recommended that NOAA develop a strategy to make high-temporal and high vertical resolution measurements of temperature and water vapor from geosynchronous orbit, however this was not accomplished. The agency has cited the lack of a prototype as one reason there is currently no hyperspectral IR sounder on its current (GOES-R series) geostationary platforms.

Other organizations have developed and are flying IR sounders of the type interesting to NOAA. China successfully launched the Geosynchronous Interferometric Infrared Sounder (GIIRS) in December 2016. The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) is developing GEO advanced hyperspectral IR sounders to fly operationally as a part of Meteosat Third Generation (MTG-3) in 2023. The GIIRS and IRS will provide detailed vertical layer-by-layer information on wind, temperature, and humidity that improves the capability to nowcast and to initialize regional and global NWP models.

Is development of a hyperspectral IR sounder of sufficient importance to NOAA to support development? Does NASA retain an interest in doing so? Is a flight prototype needed, given other experience with such instruments? These are questions that a robust NOAA-NASA partnership needs to be able to address.

would surpass a significant barrier to an operational agency: beyond prototype demonstration in a relevant environment (TRL6) to a system prototype demonstration in an operational environment (TRL7).

The ESTO In-Space Validation of Earth Science Technologies (InVEST) program element, intended to reduce the risk of new technologies in future Earth science missions, is incubating many of these satellites—for example, CubeSat Radiometer Radio Frequency Interference Technology Validation (CubeRRT); Compact Infrared Radiometer in Space (CIRiS); CubeSat Infrared Atmospheric Sounder (CIRAS); and a precipitation profiling radar in a CubeSat (RainCube). Initiatives from academia and industry are also breaking ground. The Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats (TROPICS) mission comprises 12 3U CubeSats in three low-Earth orbital planes. These capabilities demonstrate the potential efficacy of NASA and other organizations maturing new and innovative technologies to meet some of NOAA's observational needs.

Programmatic Opportunities

The programmatic history of NASA support for NOAA's operational system is described in Appendix D of NRC, 2012, with a particular example illustrated in Box 4.9. An often-cited element of this partnership is the Operational Satellite Improvement Program (OSIP).[15] While OSIP was a successful model for its time, it is not likely the right model for today. NASA and NOAA budgets are not matched to the OSIP roles, and the need for NOAA pathfinder development has been reduced. There is a need, however, to replicate much of the benefit that NOAA achieved through OSIP.

The 2017 NESDIS Independent Review Team (IRT, 2017) noted that NOAA and NASA "could together define an R&D program specifically designed to develop and transfer technology to NOAA programs." This committee concurs, as long as the resource contributions of each agency are matched to the benefits derived by each.

However, the committee believes that no single programmatic approach like OSIP is sufficient in today's environment. The needs are more diverse, the opportunities are broader, and the expectations are higher. Instead, NOAA can benefit from pursuing multiple programmatic approaches to both direct advances to its observing system and access advances that occur external to NOAA. NASA is clearly a central partner for pursuing system advances. As summarized in Recommendation 4.12, NOAA and NASA should establish a framework within which opportunities for advance are readily identified and pursued on an individual basis, as each opportunity has unique programmatic needs. This framework should enable implementation of specific project collaborations, each of which may have its own unique requirements, ensuring the following:

1. *Clear roles,* with both agencies contributing their expertise.
2. *Mutual interests*, in which NOAA's benefits are complemented by NASA benefits.
3. *Life-cycle interaction*, from the earliest program phases for identifying opportunities, to the latest phases for ensuring successful transition of lessons and knowledge.
4. *Multidisciplinary methodologies*, which may include contributions from requirements assessments, modeling, algorithm development, and even flight system alterations, and so on.
5. *Multielement expertise*, which may involve several elements of NOAA (e.g., NESDIS and NWS) and NASA (e.g., ESTO and ASP) as well as established joint mechanisms such as Joint Center for Satellite Data Assimilation (JCSDA).
6. *Appropriate budget mechanisms*, including transfers that provide full support for any share of collaborations, thus aligning resources with responsibility for execution.

Finding 4.9: In order for NOAA to continue meeting user needs, advances in observing system capability should receive priority comparable to the core objective of mission reliability.

Recommendation 4.12: NOAA should establish, with NASA, a flexible framework for joint activities that advance the capability and cost-effectiveness of NOAA's observation capabilities. This framework should enable implementation of specific project collaborations, each of which may have its own unique requirements, and should ensure (1) clear roles, (2) mutual interests, (3) life-cycle interaction, (4) multidisciplinary methodologies, (5) multielement expertise, and (6) appropriate budget mechanisms.

USGS PROGRAMMATIC CONTEXT

This section provides guidance for USGS's observing system priorities, in accordance with the committee's statement of task, which specified primary tasks to include "(1) how new technology may enhance

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[15] See NRC (2012).

current operations, and (2) what new science is needed to expand current operations, either to enable new opportunities or to include new areas of interest."

USGS Role in Civil Observing System

The USGS is a research agency, embedded in a large and complex Interior Department. USGS advances scientific understanding and provides basic monitoring of natural hazards, water, energy and minerals, status of ecosystems and the environment, and the effects of climate and landuse change (Box 4.10).

In addition to their scientific programs, therefore, the USGS also has had extensive experience in archiving and managing remote sensing data, distributing data to a wide variety of research, management, and private users, and providing information on land-cover and land-use change for many different policy clients across the U.S. government. USGS has a long history with NASA and other U.S. government agencies in providing the main archive for Land Surface Imaging. Landsat, however, augmented by MODIS imagery in the Land Processes DAAC, has been the main concern for decades.

USGS responsibility for managing the Landsat archive has taken many forms over the years of the Landsat missions. Early technological limitations on downloads from the satellites, augmented by a failure of a recorder on a later mission, meant that in practice, much of the global archive of Landsat data was

BOX 4.10 LANDSLIDE MAPPING TO SAVE LIVES AND PROPERTY

Volcanic activity, earthquakes, intense or long-duration rainfall or snowmelt, fire, progressive hillslope steepening by canyon cutting rivers, and anthropogenic disturbance (e.g., road construction, deforestation) all may cause discrete areas of landscapes to suddenly or progressively move as a landslide. These areas can be less than a meter or greater than a kilometer in width. Susceptibility to landsliding depends especially on steepness of the slope and the strength of the potential failure material (e.g., soil, bedrock, and artificial fill). The initial failure material may mobilize as a rapidly flowing mixture of debris that can travel more than a kilometer, entrain more material, and become highly destructive, especially if landslides head down canyons. Other landslides may move slowly, accelerating during rainy periods and slowing during droughts. Local topography tends to direct runoff, concentrating water that elevates pressure in the ground, reducing its strength. Landslides also can leave topographic scars that can last thousands of years, and thus provide a visible record of potentially unstable areas. Hence, the most important surface feature to document at high resolution is the surface topography. All landslide models rely on topographic data.

On March 22, 2014, after a 3-week period of heavy rainfall, the massive Oso landslide mobilized as a debris flow and traveled across a river, burying a small community of 35 single-family residences and killing 43 people in Snohomish County, Washington. This 8 million cubic meter landslide is the deadliest landslide in the history of the continental United States. Figure 4.10.1 shows the landside and a series of maps based on lidar surveys of the area. Lidar light penetration enables both the mapping of the canopy structure of trees and the detection of the "bare earth" wherever laser light can penetrate to the ground. The maps show the bare-earth topography (all the vegetation digitally removed), revealing the numerous large ancient landslide scars that are otherwise hidden by the dense forest cover. The shock of this deadly landslide and the clear evidence of past landslide activity in the area has led the state of Washington to institute a program of lidar mapping across the state for hazard detection (http://lidarportal.dnr.wa.gov/). If high-resolution satellite-based lidar can be advanced, such surveys could be done globally and repeatedly, providing a means not only to map landslide scars but also to use the topographic data to make forecasts about landslides. Such data would be a revolution in the field of hazard detection and prediction.

held in foreign archives. USGS was responsible for managing the relationships among the global data archives, but the unavoidable outcome was that the United States did not hold a complete global archive throughout most of the history of the measurements. With the return of Landsat to the public sector with Landsat 7, and with the rapid development of information technology, however, USGS began the herculean task of coming up to date with both technological advancements and the changing goals of the Landsat mission. These included a complete revision of the processing system, reacquiring data for the U.S. archive that previously existed only overseas, and revamping the cost of data to the users from both current acquisitions and the archive.

With the advent of the U.S. government's commitment to a Sustainable Land Imaging (SLI) capability, USGS's responsibilities for Landsat data evolved as well. USGS is now responsible for the entire operational and ground segments of the Landsat mission; NASA is responsible for the planning, design, procurement, and launch of the satellite—which also gives it a primary responsibility for technological evolution of the measurements. In addition, USGS supports a Landsat Science Team, which considers technological design issues and evolution, changes to algorithms for data processing and distribution, and the design of standard data products to enable easier use of the data.

BOX 4.10 Continued

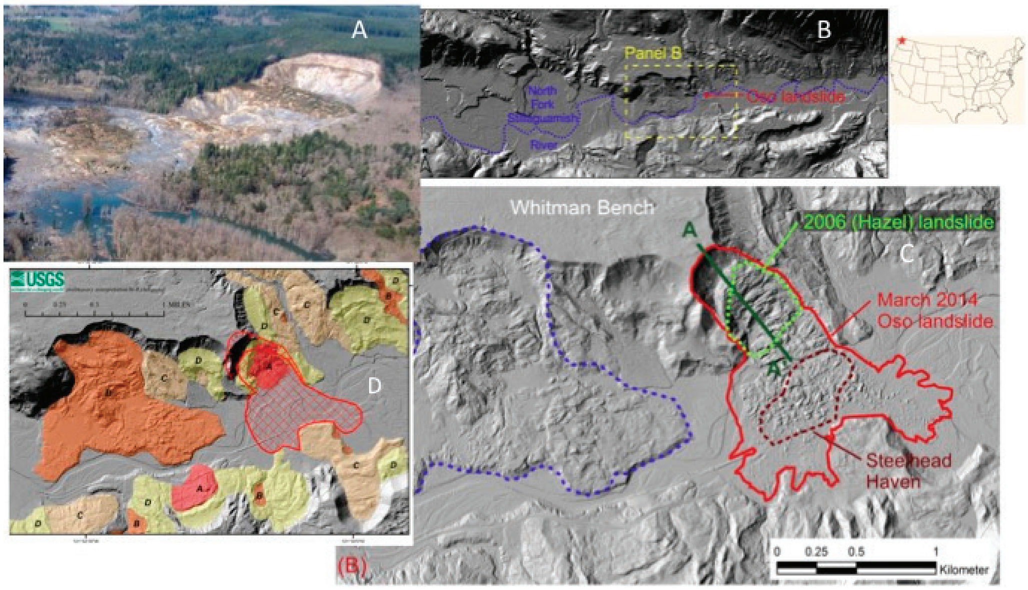

FIGURE 4.10.1 The Oso landslide of March 22, 2014, killed 43 people and caused more than $120 million in economic loss. A: Aerial photograph of landslide. B: Bare-earth shaded relief image derived from airborne lidar of river valley. C: Outline of 2014 landslide and earlier landslides. D: Youngest (A) to oldest (D) landslides revealed by the high-resolution lidar imagery. SOURCE: Panel A from M. Reid, in Iverson et al. (2015); panels B and C from Wartman et al. (2016); panel D from Haugerud (2014).

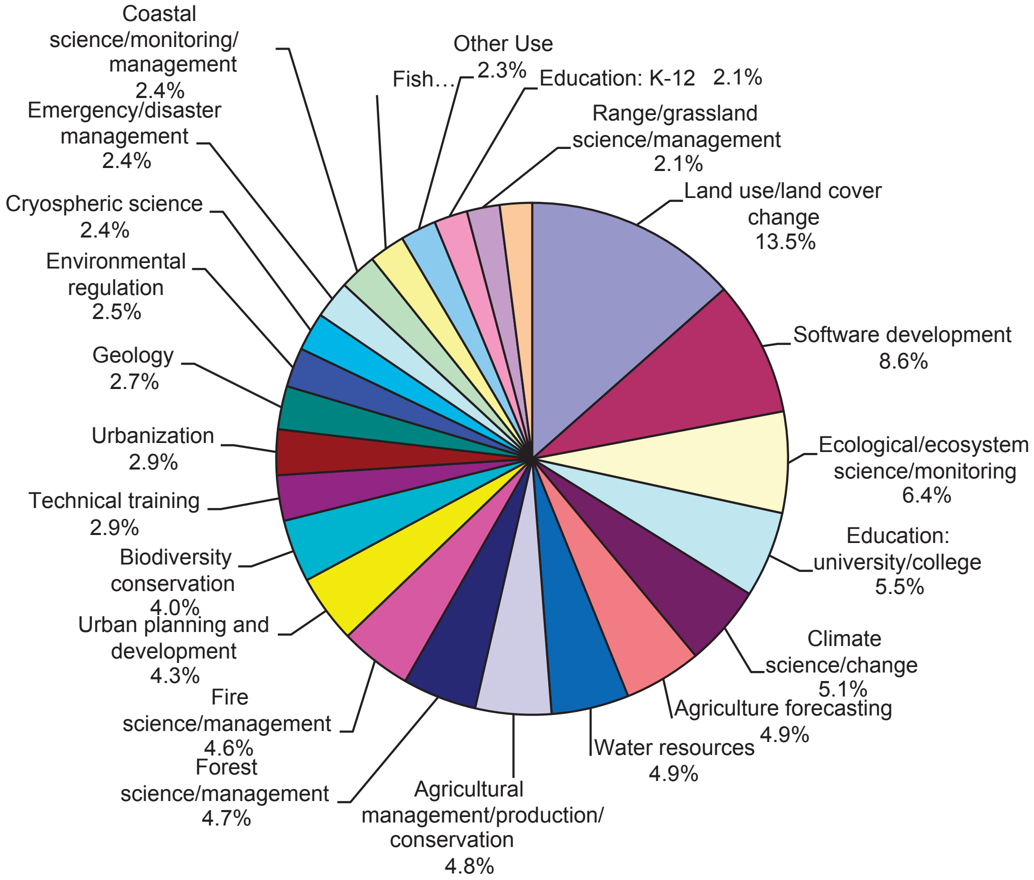

FIGURE 4.3 Landsat (federal and nonfederal government) usage by purpose and sector for a recent 1-year period (October 1, 2015-September 30, 2016).

NASA, USGS, and the European Space Agency (ESA) are now producing “harmonized” 30 m global multispectral imagery with an equatorial revisit frequency of 3.7 days, from the union of Landsat-8, Sentinel-2a, and Sentinel-2b multispectral data. This revisit frequency will drop to 3.0 days when Landsat-9 joins the team in 2020. These “harmonized” data will move land surface research and applications to 30-60 m from the current 500-1000 m spatial resolution of the Moderate-Resolution Imaging Spectroradiometer (MODIS). ESA had a “block buy” of four Sentinel-2 imagers and has two imagers in reserve ready to be launched when needed. NASA may want to consider Landsat-10 and Landsat-11 to follow the example of Sentinel-2 for a block buy of two imagers with a wider-swath (300 km) and multispectral visible, near-infrared, shortwave infrared, and thermal data, which would increase the equatorial revisit frequency to 2.0 days for the harmonized data. Time series 30 m data will be invaluable for many research and application purposes (Fisher et al., 2017; Li and Roy, 2017).

In addition, the excellent Landsat-8 and Landsat-9 multispectral imagers are and will be the intercalibration means for the commercial company Planet (formerly Planet Labs) to produce 5 m daily global

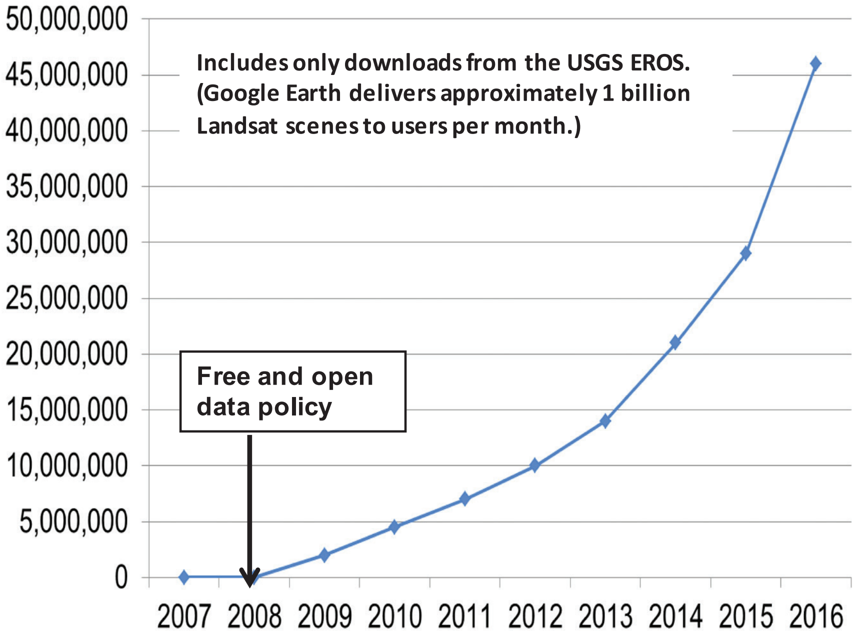

FIGURE 4.4 Cumulative Landsat image downloads from the Earth Resources Observation and Science (EROS) Center.

data time series from constellations of cubesats. This "Landsat-based" inter-calibration service will be a major contribution of NASA and USGS to the development of the commercial remote sensing sector at the few meter spatial scale.

Through this combined capability, involving international and commercial partnerships, for the first time since the space age started we have the ability to follow individual agricultural fields through time and not deal with mixed pixels. This capability will greatly advance food security and famine early warning.

Value to Users

USGS has done a substantial amount of both in-house and extramural analysis of how the Landsat data are used—by both the public and private sector— in many different applications areas (Miller, 2016). Data access, which was historically a problem because of costs, was essentially solved in 2008 by making orders from the Landsat archive free to users. Data usage has skyrocketed since then, and is still increasing, as shown in Figures 4.3 and 4.4.

The utility of Landsat was determined by the U.S. government to be the second-most valuable satellite data source, behind only GPS. Much of this usage is in the public sector, so direct economic estimates of utility are difficult. More than 30 federal agencies and departments use the Landsat data, all 50 states, and a large number of companies. USGS has estimated that the economic value to users exceeds $1.8 billion per year, and there are at least $400 million in savings in 16 government applications.

Finding 4.10: Extension of Landsat capability through synergy with other space-based observations opens new opportunities for Landsat data usage, as has been demonstrated with the ESA through cross-calibration and data sharing for Sentinel-2. These successes serve as a model for future partnerships and further synergies with other space-based observations.

Because of the broad importance and direct economic benefits of the Landsat program, USGS has initiated a process by which it continues to determine the uses, potential uses, and both direct and indirect economic value of the program. This process surveys user communities and government and private programs to determine how the data are used, and supports the federal effort to evaluate how all remote sensing products are used. It is essential for understanding how data should be processed, enhanced, archived, and distributed, and how the observing system should evolve to meet user needs.

Recommendation 4.13: USGS should ensure that its process for understanding user needs is continued and enhanced throughout the life of the Sustainable Land Imaging (SLI) program. The studies and surveys that USGS has done to document the scientific and operational uses of Landsat should be repeated at appropriate intervals, so that progress can be tracked, and these studies should be broadened to incorporate the other components of the SLI program.

Partnerships

The relationship of USGS and NASA is thus of critical importance to the performance and maintenance of the SLI program, of which Landsat is the primary set of measurements. Indications from both agencies are that their partnership is productive, and in fact, plans for the next mission are well under way. There are four challenges that each agency will have to remain alert to, however, to ensure a successful long-term partnership.

Challenge 1—Budgets

Although the operating and science team costs of the Landsat mission are small compared to the capital costs of developing, building, and launching instruments and satellites, they are substantial compared to the base costs of the USGS budget, the vast majority of which are salaries. As such, USGS must argue for their inclusion each year in a much broader Department of Interior budget, and at the same time not allow the operational costs to subsume too large a fraction of its overall agency budget.

Challenge 2—Technological Evolution of the Main Imager(s)

NASA has typically been the agency that sponsors technology demonstrations as the measurement technologies evolve over time. Consistency and continuity have been evaluated because there have been periods of overlap of different instruments orbiting at the same time, which allows intercomparisons. Evolution of the measurement technologies will continue to be necessary, both to satisfy data continuity and to manage costs on the NASA side of the ledger. While this challenge has been met so far, continuing to meet it will require specific steps to be taken to explore new technologies in a way that is cautious enough to satisfy scientific and applications users, but visionary enough that important advances and potential efficiencies are not overlooked.

Finding 4.11: With the establishment of the long-term SLI program, budgetary stability is now a priority while maintaining standards. The major costs will remain the NASA development and launch costs. The USGS component (the ground operations, data archiving and distribution, and support of science team investigations) represents a proportionally large fraction of the total USGS budget.

Recommendation 4.14: NASA should constrain cost growth in the development portion of the Sustainable Land Imaging (SLI) partnership, and ideally reduce cost from one generation to the next. USGS should ensure budget growth is minimal, to avoid strain on the overall USGS budget.

Challenge 3—Technological Evolution and Relationships with the Private Sector

The advent of cloud computing, and the ability of companies like Google or Amazon to ingest the entire Landsat archive and make data quickly available for free, has created valuable new opportunities for the use of large satellite data sets. But this evolution also means that USGS needs to evaluate its relationship with such companies, in analogous fashion to NOAA and NASA in order to continue to provide essential governmental services in cost-effective ways. Similarly, the advent of new imagers with higher spatial resolution than Landsat, but that still retain the capability to do global surveys creates opportunities for USGS and NASA to consider how those capabilities might be incorporated in a broader SLI mission. There are many unanswered questions, especially with respect to calibration of instruments, reliability and cost of data access, and long-term access, but those need to be understood as soon as possible.

Challenge 4—International Interactions

NASA has done excellent work with ESA in comparing and calibrating Landsat and Sentinel data, but this is only the first step. USGS needs to continue to play an important role in this collaboration, as it provides critical guidance regarding the needs of both scientific and applications users.

Recommendation 4.15: Partnerships and user communities associated with Sustainable Land Imaging (SLI) program should be protected and continue to expand. USGS should:

- **Ensure and continue to expand the benefits of SLI for its scientific and operational user communities.**
- **In partnership with NASA, further evaluate ways to more effectively cooperate with or use emerging commercial capabilities for data archiving and dissemination and for imagery acquisition.**
- **Work with NASA and international partners, continue to expand the use of international observation programs that complement and enhance SLI.**

REFERENCES

Adams, R.M., K.J. Bryant, B.A. McCarl, D.M. Legler, J. O'Brien, A. Solow, and R. Weiher. 1995. Value of improved long-range weather information. *Contemporary Economic Policy* 13(3):10-19.

Babcock, B.A. 1990. The value of weather information in market equilibrium. *American Journal of Agricultural Economics* 72(1):63-72.

Balmaseda, M.A., K. Mogensen, and A.T. Weaver. 2013. Evaluation of the ECMWF ocean reanalysis system ORAS4. *Quarterly Journal of the Royal Meteorological Society* 139:1132-1161.

Banzon, V., T.M. Smith, T.M. Chin, C. Liu, and W. Hankins. 2016. A long-term record of blended satellite and in situ sea-surface temperature for climate monitoring, modeling and environmental studies. *Earth System Science Data* 8:165-176.

Bauer, P., A. Thorpe, and G. Brunet. 2015. The quiet revolution of numerical weather prediction. *Nature* 525:47-55.

Benjamin, S.G., S.S. Weygandt, M. Hu, C.A. Alexander, T.G. Smirnova, J.B. Olson, J.M. Brown, et al. 2016. A North American hourly assimilation and model forecast cycle: The Rapid Refresh. *Monthly Weather Review* 144:1669-1694.

Bernknopf, R., and J. Pearlman. 2016. A use case for implementing Earth observation (EO) to avoid regional groundwater contamination in the Midwest US. *AGU Fall Meeting Abstracts*.

Bernknopf, R.L., D.S. Brookshire, M. McKee, and D.R. Soller. 1997. Estimating the social value of geologic map information: A regulatory application. *Journal of Environmental Economics and Management* 32(2):204-218.

Bernknopf, R.L., W.M. Forney, R.P. Raunikar, and S.K. Mishra. 2012. Estimating the benefits of land imagery in environmental applications: a case study in nonpoint source pollution of groundwater. Pp. 257-299 in *The Value of Information*, eds. R. Laxminarayan and M.K. Macauley. Netherlands: Springer.

Bi, L., J.A. Jung, M.C. Morgan, and J.F. LeMarshall. 2011. Assessment of assimilating ASCAT surface wind retrievals in the NCEP global data assimilation system. *Monthly Weather Review* 139(11):3405-3421.

Bikhchandani, S., J. Hirshleifer, and J.G. Riley. 2013. *The Analytics of Uncertainty and Information*. Cambridge: Cambridge University Press.

Bojinski, S., M. Verstraete, T.C. Peterson, C. Richter, A. Simmons, and M. Zemp. 2014. The concept of essential climate variables in support of climate research, applications, and policy. *Bulletin of the American Meteorological Society* 95:1431-1443.

Bonavita, M. 2014. On some aspects of the impact of GPSRO observations in global numerical weather prediction. *Quarterly Journal of the Royal Meteorological Society* 140(685):2546-2562.

Bonavita, M., M. Hamrud, and L. Isaksen. 2015. EnKF and hybrid gain ensemble data assimilation. Part II: EnKF and hybrid gain results. *Monthly Weather Review* 143(12):4865-4882.

Bosilovich, M., S. Akella, L. Coy, R. Cullather, C. Draper, R. Gelaro, R. Kovach, et al. 2015. MERRA-2: Initial evaluation of the climate. *NASA Technical Report Series on Global Modelling and Data Assimilation NASA/TM-2015-104606, Vol. 43*. https://gmao.gsfc.nasa.gov/pubs/docs/Bosilovich803.pdf.

Bosilovich, M.G., J. Kennedy, D. Dee, R. Allan, and A. O'Neill. 2013. On the reprocessing and reanalysis of observations for climate. In *Climate Science for Serving Society: Research, Modelling and Prediction Priorities*, eds. G.R. Asrar and J.W. Hurrell. Dordrecht: Springer SBM.

Bouma, J.A., H.J. Van der Woerd, and O.J. Kuik. 2009. Assessing the value of information for water quality management in the North Sea. *Journal of Environmental Management* 90(2):1280-1288.

Bradford, D.F., and H.H. Kelejian. 1977. The value of information for crop forecasting in a market system: some theoretical issues. *The Review of Economic Studies* 44(3):519-531.

Buckley, M.W., R.M. Ponte, G. Forget, and P. Heimbach. 2014. Low-frequency SST and upper-ocean heat content variability in the North Atlantic. *Climate* 27:4996-5018.

Buehner, M., L. Bertino, A. Caya, P. Heimbach, and G. Smith. 2017. Sea ice data assimilation. In *Sea Ice Analysis and Forecasting*, eds. T. Carrieres, M. Buehner, J.F. Lemieux, and L.T. Pedersen. Cambridge: Cambridge University Press.

Callaghan, T.V., M. Johansson, R.D. Brown, P.Y. Groisman, N. Labba, V. Radionov, R.G. Barry, et al. 2011. The changing face of Arctic snow cover: a synthesis of observed and projected changes. *Ambio* 40:17-31.

Cardinali, C., and F. Prates. 2011. Performance measurement with advanced diagnostic tools of all-sky microwave imager radiances in 4D-Var. *Quarterly Journal of the Royal Meteorological Society* 137:2038-2046.

Carman, J.C., D.P. Eleuterio, T.C. Gallaudet, G.L. Geernaert, P.A. Harr, J.A. Kaye, D.H. McCarren, et al. 2017. The National Earth System Prediction Capability: Coordinating the giant. *Bulletin of the American Meteorological Society* 98(2):239-252.

CCSP (Climate Change Science Program). 2008. *Our Changing Planet: The U.S. Climate Change Science Program for Fiscal Year 2009*. Washington, DC: US Climate Change Science Program.

Clayson, C.A., J.B. Roberts, and A. Bogdanoff. 2013. SeaFlux Version 1: A new satellite-based ocean-atmosphere turbulent flux dataset. http://seaflux.org/seaflux_data/DOCUMENTATION/Seaflux_final.pdf.

Compo, G.P., J.S. Whitaker, P.D. Sardeshmukh, N. Matsui, R.J. Allan, X. Yin, B.E. Gleason, Jr., et al. 2011. The Twentieth Century Reanalysis Project. *Quarterly Journal of the Royal Meteorological Society* 137A:1-28.

Compo, G.P., P.D. Sardeshmukh, J.S. Whitaker, P. Brohan, P.D. Jones, and C. McColl. 2013. Independent confirmation of global land warming without the use of station temperatures. *Geophysical Research Letters* 40:3170-3174.

Considine, T.J., C. Jablonowski, B. Posner, and C.H. Bishop. 2004. The value of hurricane forecasts to oil and gas producers in the Gulf of Mexico. *Journal of Applied Meteorology* 43(9):1270-1281.

Cooke, R., B.A. Wielicki, D.F. Young, and M.G. Mlynczak. 2014. Value of information for climate observing systems. *Journal of Environment, Systems, and Decisions* 34:98-109.

Cooke, R.M., A. Golub, B. Wielicki, M. Mlynczak, D. Young, and R.R. Baize. 2016a. Real option value for new measurements of cloud radiative forcing. *Resources for the Future Discussion Papers* 16-19:1-21.

Cooke, R., A. Golub, B.A. Wielicki, D.F. Young, M.G. Mlynczak, and R.R. Baize. 2016b. Using the social cost of carbon to value Earth observing systems. *Climate Policy* 17(3):330-345.

Dowell, M., P. Lecomte, R. Husband, J. Schulz, T. Mohr, Y. Tahara, R. Eckman, et al. 2013. *Strategy Towards an Architecture for Climate Monitoring from Space.* Joint report of the World Meteorological Organization, Committee on Earth Observation Satellites, and the Coordination Group for Meteorological Satellites.

Dozier, J., and W.B. Gail. 2009. The emerging science of environmental applications. In *The Fourth Paradigm: Data-Intensive Science*, eds. T. Hey, S. Tansley, and K. Tolle. Redmond: Microsoft Research.

ECCO Consortium. 2017a. *A Twenty-Year Dynamical Oceanic Climatology: 1994-2013. Part 1: Active Scalar Fields: Temperature, Salinity, Dynamic Topography, Mixed-Layer Depth, Bottom Pressure.* March 20. http://ocean.mit.edu/~cwunsch/papersonline/climatology_v4_release3_part1.pdf.

ECCO Consortium. 2017b. *A Twenty-Year Dynamical Oceanic Climatology: 1994-2013. Part 2: Velocities, Property Transports, Meteorological Variables, Mixing Coefficients.* June 14. http://hdl.handle.net/1721.1/109847.

Elsaesser, G.S., C.W. O'Dell, M.D. Lebsock, R. Bennartz, and T.J. Greenwald. 2017. The Multi-Sensor Advanced Climatology of Liquid Water Path (MAC-LWP). *Journal of Climate* 30(24):10193-10210.

Fisher, J.B., F. Melton, E. Middleton, Ch. Hain, M. Anderson, R. Allen, M.F. McCabe, et al. 2017. The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources. *Water Resources Research* 53:2618-2626.

Forget, G., J.M. Campin, P. Heimbach, C.N. Hill, R.M. Ponte, and C. Wunsch. 2015. ECCO version 4: an integrated framework for non-linear inverse modeling and global ocean state estimation. *Geoscientific Model Development* 8:3071-3104.

Freeman III, A.M. 2003. Economic valuation: What and why. Pp. 1-25 in *A Primer on Nonmarket Valuation*. (P.A. Champs, K.J. Boyle, and T.C. Brown, eds.) Netherlands: Springer.

Fritz, S., I. McCallum, C. Schill, C. Perger, L. See, D. Schepaschenko, M. Van der Velde, F. Kraxner, and M. Obersteiner. 2012. Geo-Wiki: An online platform for improving global land cover. *Environmental Modelling and Software* 31:110-123.

Geer, A.J. 2016. Significance of changes in medium-range forecast scores. *Tellus: A Dynamic Meteorology and Oceanography* 68(1):30229.

Griffies, S.M., G. Danabasoglu, P.J. Durack, A.J. Adcroft, V. Balaji, C.W. Böning, E.P. Chassignet, et al. 2016. OMIP contribution to CMIP6: experimental and diagnostic protocol for the physical component of the Ocean Model Intercomparison Project. *Geoscientific Model Development* 9:3231-3296.

Hartley, D.M. 2012. Space imaging and prevention of infectious disease: Rift Valley fever. Pp. 231-255 in *The Value of Information*, eds. R. Laxminarayan and M.K. Macauley. Netherlands: Springer.

Haugerud, R.A. 2014. *Preliminary Interpretation of Pre-2014 Landslide Deposits in the Vicinity of Oso, Washington.* Report No. 2014-1065. https://pubs.usgs.gov/of/2014/1065/pdf/ofr2014-1065.pdf.

Hirshleifer, J., and J.G. Riley. 1979. The analytics of uncertainty and information—an expository survey. *Journal of Economic Literature* 17(4):1375-1421.

Hope, C. 2015. The $10 trillion value of better information about the transient climate response. *Philosophical Transactions of the Royal Society A* 373:20140429.

Hoskins, B. 2013. The potential for skill across the range of the seamless weather-climate prediction problem: a stimulus for our science. *Quarterly Journal of the Royal Meteorological Society* 139:573-584.

IRT (Independent Review Team, NOAA NESDIS). 2017. *Final Report.* https://www.nesdis.noaa.gov/sites/default/files/asset/document/nesdis_irt_report_2017_with_notes.pdf. Accessed July 19, 2017.

Iverson, R.M., D.L. George, K. Allstadt, M.E. Reid, B.D. Collins, J.W. Vallance, S.P. Schilling, et al. 2015. Landslide mobility and hazards: implications of the 2014 Oso disaster. *Earth and Planetary Science Letters* 412:197-208.

Janiskova, M. 2015. Assimilation of cloud information from space-borne radar and lidar: experimental study using a 1D+4D-Var technique. *Quarterly Journal of the Royal Meteorological Society* 141(692):2708-2725.

Jones, P.D., D.H. Lister, T.J. Osborn, C. Harpham, M. Salmon, and C.P. Morice. 2012. Hemispheric and large-scale land-surface air temperature variations: An extensive revision and an update to 2010. *Journal of Geophysical Research* 117:D05127.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, et al. 1996. The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society* 77:437-471.

Katz, R.W., and A.H. Murphy, eds. 1997. *Economic Value of Weather and Climate Forecasts*. Cambridge: Cambridge University Press.

Kazumori, M., A.J. Geer, and S.J. English. 2016. Effects of all-sky assimilation of GCOM-W/AMSR2 radiances in the ECMWF numerical weather prediction system. *Quarterly Journal of the Royal Meteorological Society* 142:721-737.

Kousky, C., and R.M. Cooke. 2012. The value of information in a risk management approach to climate change. Pp. 19-43 in *The Value of Information*, eds. R. Laxminarayan and M.K. Macauley. Netherlands: Springer.

Larour, E., H. Seroussi, M. Morlighem, and E. Rignot. 2012. Continental scale, high order, high spatial resolution, ice sheet modeling using the Ice Sheet System Model (ISSM). *Journal of Geophysical Research: Earth Surface* 117(F1).

Lave, L.B. 1963. The value of better weather information to the raisin industry. *Econometrica: Journal of the Econometric Society* 31(1/2):151-164.

Lazo, J.K., and D.M. Waldman. 2011. Valuing improved hurricane forecasts. *Economics Letters* 111(1):43-46.

Leroy, S.S., J.G. Anderson, and G. Ohring. 2008. Climate signal detection times and constraints on climate benchmark accuracy requirements. *Journal of Climate* 21:841-846.

Li, J., and D.P. Roy. 2017. A global analysis of Sentinel-2A, Sentinel-2B and Landsat-8 data revisit intervals and implications for terrestrial monitoring. *Remote Sensing* 9:902-919.

Macauley, M.K. 2009. Earth observations in social science research for management of natural resources and the environment: identifying the Landsat contribution. *Journal of Terrestrial Observation* 1(2):6.

Macauley, M. 2010. Biogenic Carbon Sequestration and Climate Policy: Issues in Using Forests to Offset Greenhouse Gas Emissions.

Macauley, M., and R. Laxminarayan. 2010. The value of information: "Methodological Frontiers and New Applications for Realizing Social Benefits" workshop. *Space Policy* 26(4):249-251.

Macauley, M.K., and N. Richardson. 2011. Seeing the forests and the trees: Technological and regulatory impediments for global carbon monitoring. *Berkeley Technology Law Journal* 26:1387.

Macauley, M.K., and R.A. Sedjo. 2011. Forests in climate policy: technical, institutional and economic issues in measurement and monitoring. *Mitigation and Adaptation Strategies for Global Change* 16(5):499-513.

MacGregor, J.A., M.A. Fahnestock, G.A. Catania, J.D. Paden, G.S. Prasad, S.K. Young, and M. Morlighem. 2015. Radiostratigraphy and age structure of the Greenland Ice Sheet. *Journal of Geophysical Research: Earth Surface* 120(2):212-241.

Maschhoff, K.R., J.J. Polizotti, H.H. Aumann, and J. Susskind. 2016. MISTiC winds, a microsatellite constellation approach to high-resolution observations of the atmosphere using infrared sound and 3D winds measurements. *Proceedings of SPIE 10000, Sensors, Systems, and Next-Generation Satellites* 20:100000L.

McCall, J.J., ed. 1982. *The Economics of Information and Uncertainty*. Chicago: University of Chicago Press.

Miller, H.M. 2016. *Users and uses of Landsat 8 satellite imagery—2014 survey results: U.S. Geological Survey Open-File Report 2016–1032*. http://dx.doi/org/10.3133/ofr20161032.

NASA (National Aeronautics and Space Administration). 2014. *Measuring Socioeconomic Impacts of Earth Observations—A Primer. Applied Sciences Program NASA*. http://appliedsciences.nasa.gov/pdf/SocioeconomicImpactsPrimer.pdf.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2015. *Continuity of NASA Earth Observations from Space: A Value Framework*. Washington, DC: The National Academies Press.

NASEM. 2016a. *Extending Science—NASA's Space Science Mission Extensions and the Senior Review Process.* Washington, DC: The National Academies Press.

NASEM. 2016b. *Achieving Science with CubeSats: Thinking Inside the Box*. Washington, DC: The National Academies Press.

NRC (National Research Council). 2001. *Transforming Remote Sensing Data into Information and Applications.* Washington, DC: The National Academies Press.

NRC. 2002. *Toward New Partnerships in Remote Sensing—Government, the Private Sector, and Earth Science Research.* Washington, DC: The National Academies Press.

NRC. 2003. *Using Remote Sensing in State and Local Government—Information for Management and Decision Making.* Washington, DC: The National Academies Press.

NRC. 2007. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond.* Washington, DC: The National Academies Press.

NRC. 2008. *Earth Observations from Space: The First 50 Years of Scientific Achievements.* Washington, DC: The National Academies Press.

NRC. 2012. *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey*. Washington, DC: The National Academies Press.

NRC. 2013. *Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program.* Washington, DC: The National Academies Press.

Nelson, R.R., and S.G. Winter, Jr. 1964. A case study in the economics of information and coordination: the weather forecasting system. *The Quarterly Journal of Economics* 78(3):420-441.

NOAA (National Oceanic and Atmospheric Administration). 2016. *Strategic Plan: NOAA's National Environmental Satellite, Data, and Information Service.* https://www.nesdis.noaa.gov/sites/default/files/asset/document/the_nesdis_strategic_plan_2016.pdf. Accessed July 19, 2017.

Nordhaus, W.D. 1986. The value of information. Pp. 129-34 in *Policy Aspects of Climate Forecasting*, ed. R. Krasnow. *Resources for the Future Proceedings*.

NSTC (National Science and Technology Council). 2014. *National Plan for Civil Earth Observations*. http://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/national_plan_for_civil_earth_observations_-_july_2014.pdf.

O'Dell, C.W., F.J. Wentz, and R. Bennartz. 2008. Cloud liquid water path from satellite-based passive microwave observations: A new climatology over the global oceans. *Journal of Climate* 1(8):1721-1739.

Osgood, D., and K.E. Shirley. 2012. The value of information in index insurance for farmers in Africa. Pp. 1-18 in *The Value of Information*, eds. R. Laxminarayan and M.K. Macauley. Netherlands: Springer.

Palmer, T.N., F. Doblas-Reyes, A. Weosheimer, and M.J. Rodwell. 2008. Toward seamless prediction: calibration of climate change projections using seasonal forecasts. *Bulletin of the American Meteorological Society* 89:459-470.

Parker, W.S. 2016. Reanalysis and observations: What's the difference? *Bulletin of the American Meteorological Society* 97(9):1565-1572.

Penny, S.G., D. Behringer, J.A. Carton, and E. Kalnay. 2015. A hybrid global ocean data assimilation system at NCEP. *Monthly Weather Review* 143:4660–4677.

Pfaff, A.S.P. 1999. What drives deforestation in the Brazilian Amazon?: Evidence from satellite and socioeconomic data. *Journal of Environmental Economics and Management* 37(1):26-43.

Puri, K., R. Redler, and R. Budich. 2013. *Earth System Modelling I: Recent Developments and Projects. Springer Briefs in Earth System Sciences*. Springer.

Reichle, R., and G. De Lannoy. 2015. Assimilation of SMOS Brightness Temperature Observations in the NASA GEOS-5 Land Data Assimilation System. In *EGU General Assembly Conference Abstracts* 17.

Richardson, N., and M. Macauley. 2012. Forest carbon economics: what we know, what we do not and whether it matters. *Climate Change Economics* 3(4):1250022.

Rocha, C., T.K. Chereskin, S.T. Gille, and D. Menemenlis. 2016. Mesoscale to submesoscale wavenumber spectra in Drake Passage. *Journal of Physical Oceanography* 46:601-620.

Roll, R. 1984. Orange juice and weather. *The American Economic Review* 74(5):861-880.

Santer, B.D., K.E. Taylor, P.J. Gleckler, C. Bonfilsa, T.P. Barnett, D.W. Pierce, C. Wigley, et al. 2009. Incorporating model quality information in climate change detection and attribution studies. *Proceedings of the National Academy of Sciences* 106(35):14778-14783.

Savage, L. 1954. *The Foundation of Statistics*. New York: Wiley.

Schmidt, G. 2011. Reanalyses 'R' us. https://www.realclimate.org/index.php/archives/2011/07/reanalyses-r-us/.

Schröder, M., M. Lockhoff, L. Shi, T. August, R. Bennartz, E. Borbas, H. Brogniez, et al. 2017. GEWEX water vapor assessment (G-VAP). *WCRP Report 16/2017*. Geneva, Switzerland: World Climate Research Programme.

Sedjo, R., and M. Macauley. 2011. Forest carbon offsets: possibilities and limitations. *Journal of Forestry* 109(8):470.

Simmons, A., J.L. Fellous, V. Ramaswamy, K. Trenberth, G. Asrar, M. Balmaseda, J.P. Burrows, et al. 2016. Observation and integrated Earth-system science: A roadmap for 2016-2025. *Advanced Space Research* 57(10):2037-2103.

Skees, J., A. Murphy, B. Collier, M. McCord, and J. Roth. 2007. *Scaling Up Index Insurance: What is needed for the next big step forward*. http://globalagrisk.com/Pubs/2007_Skeesetal_Scaling%20UP%20Index%20Insurance_KfW_dec.pdf.

Sonka, S.T., J.W. Mjelde, P.J. Lamb, S.E. Hollinger, and B.L. Dixon. 1987. Valuing climate forecast information. *Journal of Climate and Applied Meteorology* 26(9):1080-1091.

Stajner, I., C. Benson, H.C. Liu, S. Pawson, N. Brubaker, L.P. Chang, L.P. Riishojgaard, and R. Todling. 2007. Ice polar stratospheric clouds detected from assimilation of Atmospheric Infrared Sounder data. *Geophysical Research Letters* 34(16).

Stammer, D., M. Balmaseda, P. Heimbach, A.Koehl, and A. Weaver. 2016. Ocean data assimilation in support of climate applications: Status and perspectives. *Annual Review of Marine Science* 8:491-518.

Tenkorang, F., and J.Lowenberg-DeBoer. 2008. On-farm profitability of remote sensing in agriculture. *Journal of Terrestrial Observation* 1(1):6.

Trenberth, K.E., A. Belward, O. Brown, E. Haberman, T.R. Karl, S. Running, B. Ryan, M. Tanner, and B.A. Wielicki. 2013. Challenges of a sustained climate observing system. In *Climate Science for Serving Society: Research, Modeling, and Prediction Priorities*, eds. G.R. Asrar and J.W. Hurrell. Springer Press.

Volz, S. 2016. NOAA Satellite and Information Service: NESDIS Program Overview and Decadal Survey Priorities, Presentation to the ESAS2017 Steering Committee and Panels Meeting, June 3. https://www.nesdis.noaa.gov/sites/default/files/asset/document/2016_6_volz_esas2017_jun_3_2016_final.pdf.

Walsh, J.E., F. Fetterer, J.S. Stewart, and W.L. Chapman. 2017. A database for depicting Arctic sea ice variations back to 1850. *Geographical Review* 107(1):89-107.

Wargan, K., S. Pawson, M.A. Olsen, J.C. Witte, A.R. Douglass, J.R. Ziemke, S.E. Strahan, and J.E. Nielsen. 2015. The global structure of upper troposphere-lower stratosphere ozone in GEOS-5: A multiyear assimilation of EOS Aura data. *Geophysical Research* 120(5):2013-2036.

Wartman, J., D.R. Montgomery, S.A. Anderson, J.R. Keaton, J. Benoît, J. dela Chapelle, and R. Gilbert. 2016. The 22 March 2014 Oso landslide, Washington, USA. *Geomorphology* 253:275-288.

Weatherhead, B., B.A. Wielicki, V. Ramaswamy, M. Abbott, T. Ackerman, B. Atlas, G. Brasseur, et al. 2017. Designing the climate observing system of the future. *Earth's Future* 6(1):80-102.

Wentz, F.J., C.L. Gentemann, D.K. Smith, and D.B. Chelton. 2000. Satellite measurements of sea surface temperature through clouds. *Science* 288(5467):847-850.

Wielicki, B.A., D.F. Young, M.G. Mlynczak, K.J. Thome, S. Leroy, J. Corliss, J.G. Anderson, et al. 2013. Climate Absolute Radiance and Refractivity Observatory (CLARREO): Achieving climate change absolute accuracy in orbit. *Bulletin of the American Meteorological Society* 93:1519-1539.

5

Conclusion

At the time of the last Earth Science and Applications from Space (ESAS) decadal survey, the space-based Earth Observing System (EOS) was in a critical state. The Earth observing satellites were past their design lives (well past in many cases) with very few missions in the queue. Given the importance of these space-based observations to our daily lives and our success as a society, the risk to our nation was great.

Since that time, through careful management, strong international partners, the infusion of resources (though still significantly less funding than the period of the EOS in the 1990s), and innovation on the part of the technology, engineering, and scientific communities, the National Aeronautics and Space Administration (NASA) Earth science program has provided opportunity, results, and impact for the nation and the world, in return for the investments made in understanding the planet on which we live. In addition, efforts and investments by the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey (USGS) complement these capabilities and deliver value to the nation in terms of information that directly impacts our daily lives. Investments in the space-based Earth observation enterprise, which supports the quest for knowledge and the conversion of that knowledge value to citizens in this nation and throughout the world, have advanced science, served social interests, and mitigated environmental challenges and enhanced our nation's prosperity.

As we look to the coming decade, it is imperative that this momentum be built upon to realize the maximum value of investments in space-based Earth observation. Doing so effectively requires that we take an integrated approach that (1) fully capitalizes on advancements and opportunities as they emerge, (2) stimulates innovation in the Earth system science community, and (3) boldly seeks to meet the technical, fiscal, and programmatic challenges of the coming decade.

The ESAS 2017 process sought to be inclusive and was built on a foundation of input from across the science and engineering communities to develop recommendations for the coming decade. The priorities and recommendations are expected to stimulate innovation, serve the Earth science and applications community, and deliver value to the citizens that provide the resources that support these pursuits.

The program recommended is an implementable one, with cost estimates for the larger missions validated, and with competition expected to keep costs of the medium-size missions lower and promote innovation. It achieves balance between flight and nonflight elements of the NASA portfolio, paying specific attention to the balance between large and small missions, mission investment and science, continuity of observations and new observations, science and applications, heritage technologies and new technologies.

In addition, recognizing that unforeseen events, external budget pressures, and other various constraints can force difficult choices, the committee has developed a set of decision rules to inform NASA's decision-making process on how to address budgetary challenges. The committee also recognizes the potential for increased investments or additional funds being made available through partnerships and technological innovation, and offers guidance on how to use additional resources.

NASA, NOAA, and USGS have faced a number of challenges in their ability to develop and maintain their portfolio in support of their missions. Given their constraints, they have managed these challenges well, and our nation's space-based observation enterprise is able to provide information and value to its citizens. However, it is continually at risk: some needs go unmet and many opportunities are never realized, as limited resources constrain the programs. Without the infusion of additional resources, there will always be shortfalls in meeting national needs, but to partially mitigate against this, it is imperative that the agencies find ways to implement their programs as cost effectively as possible through partnerships, programmatic innovation, exploitation of new technology, and so on, as doing so will enable them to realize the full potential of their investments.

Finally, a critical element of a successful civilian space-based Earth observation program is coordination among agencies that recognizes the roles and responsibilities of each, maps resources to the fulfillment of those responsibilities, and ensures a healthy interaction among those delivering the science, those developing technologies, and those developing and implementing applications. As each of these elements informs the other, and when executed in concert, with appropriate resource alignment, we will be in the best position possible to deliver an effective and successful Earth Science and Applications from Space Program.

Earth science and applications from space have transformed the way we live. A better understanding of the Earth environment, and the relationship humans have with it, will continue to produce scientific advances, drive economic opportunities, inform sound policy decisions, serve critical humanitarian needs, and much more. The coming decade provides new opportunities for making advances in each of these areas, building on yesterday's achievement and on today's investment, to enable tomorrow's success and ongoing prosperity.

PART II

Panel Inputs

6

Global Hydrological Cycles and Water Resources

INPUT SUMMARY

Water—the medium for life—shapes Earth's surface and controls where and how we live. Chemical, biological, and physical processes alter and are altered by water and its constituents. Water is the most widely used resource on Earth, its mass nearly 300 times that of the atmosphere. On this foundation, humans add engineered and social systems to control, manage, use, and alter our water environment for a variety of uses and through a variety of organizational and individual decisions (Figure 6.1).

Therefore, understanding the hydrologic cycle and monitoring and predicting its vagaries are of critical importance to our societies. Remotely sensed data play a key role in advancing our insight about Earth's water resources. Missions such as the Tropical Rainfall Measurement Mission (TRMM), Global Precipitation Measurement (GPM), Soil Moisture Active-Passive (SMAP), and the Gravity Recovery and Climate Experiment (GRACE)—along with sensors of the Earth Observing System (EOS)—including the Clouds and the Earth's Radiant Energy System (CERES), the Moderate-Resolution Imaging Spectroradiometer (MODIS), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), the Atmospheric Infrared Sounder (AIRS), the Advanced Microwave Scanning Radiometers (AMSR-E and AMSR2), and lidar altimetry (Ice, Cloud, and Land Elevation Satellite, ICESat)—have provided important measurements of shortwave and longwave radiation, snow and glacier extent and change, soil moisture, atmospheric water vapor, clouds, precipitation, terrestrial vegetation and oceanic chlorophyll, and water storage in the subsurface, among many others. Visual, infrared, and lightning imagery from Geostationary Operational Environmental Satellites (GOES), especially GOES-16 and satellites in the GOES series through 2036, provide monitoring capabilities to improve nowcasting and warning for extreme storms and associated responses to hazards. Together, the Landsat 8 Operational Line Imager (OLI) and Thermal Infrared Sensor (TIRS), combined with the European Sentinel-2 satellites and the future launch of Landsat 9, will image Earth's land area at 15-30 m spatial resolution every 3 days.

NOTE: This chapter was written by members of the Panel on Global Hydrological Cycles and Water Resources and is provided for reference only. Any study finding or consensus recommendation will appear in Chapters 1-5, the report from the survey steering committee.

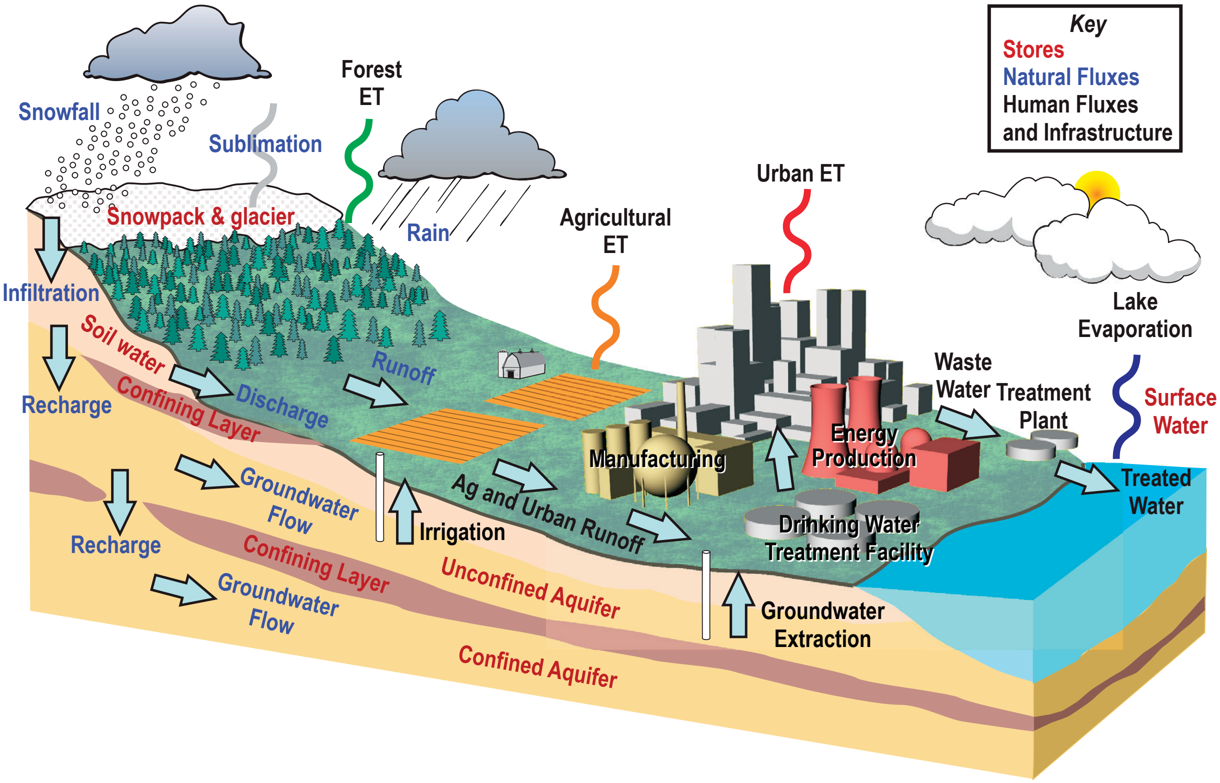

FIGURE 6.1 Earth's freshwater landscape, including stores, transformations, and fluxes, from high mountain seasonal snow and glaciers, through ecosystems that may be managed, into our engineered agricultural, industrial, and urban landscapes. SOURCE: Courtesy of Jerald Schnoor.

Future planned missions like Surface Water and Ocean Topography (SWOT) will measure surface water elevations in lakes, reservoirs, and large rivers, and NASA-ISRO Synthetic Aperture Radar (NISAR) will enable detection of surface disturbance by identifying subtle changes in surface elevation.

As a part of the Decadal Survey for Earth Science and Applications from Space, the Panel on Global Hydrological Cycles and Water Resources (Hydrology, or "H") was tasked with identifying the high-level integrative questions in understanding the movement, distribution, and availability of water and how these are changing over time, and proposing the remote sensing measurements that will enhance and continue developments needed to address these questions and critical associated applications.

The chapter identifies four scientific and societal goals associated with the hydrologic cycle: (1) coupling the water and energy cycles; (2) prediction of changes; (3) availability of freshwater and coupling with biogeochemical cycles; (4) hazards, extremes, and sea-level rise. Scientific advances toward these four goals will support the development of societal mitigation for risks to the hydrologic cycle (e.g., contamination of drinking water supplies) or risks derived from the hydrologic cycle (e.g., floods and droughts).

Within each of the four scientific and societal goals, this chapter identifies key scientific quantifiable objectives that, when addressed, will advance our scientific understanding toward the scientific and societal goals. The quantifiable objectives serve as guideposts for identifying the scientific inquiries necessary to achieve progress toward each of the four goals, and as such they provide the basis for the suggested enabling measurements. Just as phases of the hydrologic cycle are linked, the scientific and societal goals and quantifiable objectives are also linked. For example, simply quantifying the basic fluxes of the hydrologic cycle—precipitation, evaporation, streamflow, and groundwater flow—will enable progress on all four scientific and societal goals and many of the quantifiable objectives. The links between the quantifiable objectives are an important consideration for prioritizing the scientific and societal goals, the associated quantifiable objectives, and the resulting suggestions for enabling measurements.

The priorities of the panel are summarized in two tables. Table 6.1 lists the scientific and societal goals with the associated highest priority measurement objectives. The priorities listed in the following table are classified as Most Important (MI), Very Important (VI), and Important (I). The minimum ranking is Important owing to the criticality of water resources to water and food security, economic prosperity, and the health of the planet.

Methods for monitoring and modeling of the water cycle, and their application to societal goals, cover the wide range of needs for a comprehensive understanding of the hydrologic cycle as they relate to freshwater availability, water quality for human health and ecosystem services, and prediction of extremes and hazards. These extend from the accurate quantification of water and energy fluxes at the river basin scale, to accurate snow water equivalent (SWE) measurements for water supply forecasting, to improved drought monitoring, to flash flooding hazard prediction, to changes in land use and water quality in highly coupled human-natural systems. They also extend from recommendations to extend ongoing measurements, to new endeavors in detecting the phase (rain or snow) of precipitation, to measuring evapotranspiration, to new fields for application of remotely sensed data, such as water quality, groundwater recharge, effects of urbanization, water-modulated biogeochemical cycling, and prediction of hazard chains. Our science and applications have relied heavily on data availability since the beginnings of remote sensing. Improvements sought mainly relate to water and energy fluxes at Earth's surface—evapotranspiration, snow and ice melt, rainfall, snowfall, and recharge and withdrawal of groundwater.

Table 6.2 presents the priority targeted observables for the science and societal targets/objectives the panel ranked as Most Important or Very Important.[1] The information is taken from the subsection titled Enabling Measurements.

Implementing this program will enable the following scientific and applications advances:

- Improve monitoring of precipitation and evapotranspiration, with the goal to measure and model each so that the accuracy of the estimation of their difference is less than the rates of runoff or groundwater recharge:
  - Especially for rates of precipitation of mixed water and ice, so as to estimate snowfall as well as rainfall; and
  - In measurement and modeling of convective and orographic precipitation.
- Improve measurement and modeling of albedo of the components of Earth's land surface—snow, ice, vegetation, and soil—to enable closing of the surface radiation balance to within 10 percent of the magnitude of the absorption:
  - Necessary to model evapotranspiration, snowmelt, and retrospective reconstruction of the snow water equivalent.
- Understand how human modification of the land surface affects evapotranspiration, and the consequences for the hydrologic cycle.
- Understand how hazards in mountainous terrain and along coasts relate to weather extremes.

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[1] Not mapped here are cases where the targeted observables may provide a narrow or an indirect benefit to the objective, although such connections may be cited elsewhere in this report.

TABLE 6.1 Summary of Science and Applications Questions and Their Priorities

	Science and Applications Questions	Science and Applications Objectives (MI = Most Important, VI = Very Important, I = Important)
H-1	**Coupling the Water and Energy Cycles.** How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?	**(MI) H-1a.** Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance from headwater catchments to continental-scale river basins. **(MI) H-1b.** Quantify precipitation rates and phase (rain and snow/ice) worldwide at convective and orographic scales suitable to capture flash floods as well as processes at longer and larger spatial scales. **(MI) H-1c.** Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide at scales driven by topographic variability.
H-2	**Prediction of Changes.** How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally, and globally, and what are the short- and long-term consequences?	**(VI) H-2a.** Quantify how changes in land use, water use, and water storage affect evapotranspiration rates, and how these in turn affect local and regional precipitation systems, groundwater recharge, temperature extremes, and carbon cycling. **(I) H-2b.** Quantify the magnitude of anthropogenic processes that cause changes in radiative forcing, temperature, snowmelt, and ice melt, as they alter downstream water quantity and quality. **(MI) H-2c.** Quantify how changes in land use, land cover, and water use related to agricultural activities, food production, and forest management affect water quality and especially groundwater recharge, threatening sustainability of future water supplies.
H-3	**Availability of Freshwater and Coupling with Biogeochemical Cycles.** How do changes in the water cycle impact local and regional freshwater availability, alter the biotic life of streams, and affect ecosystems and the services these provide?	**(I) H-3a.** Develop methods and systems for monitoring water quality for human health and ecosystem services. **(I) H-3b.** Monitor and understand the coupled natural and anthropogenic processes that change water quality, fluxes, and storages, in and between all reservoirs, and the response to extreme events. **(I) H-3c.** Determine structure, productivity, and health of plants to constrain estimates of evapotranspiration.
H-4	**Hazards, Extremes, and Sea-level Rise.** How does the water cycle interact with other Earth system processes to change the predictability and impacts of hazardous events and hazard chains (e.g., floods, wildfires, landslides, coastal loss, subsidence, droughts, human health, and ecosystem health), and how do we improve preparedness and mitigation of water-related extreme events?	**(VI) H-4a.** Monitor and understand hazard response in rugged terrain and land margins to heavy rainfall, temperature and evaporation extremes, and strong winds at multiple temporal and spatial scales. **(I) H-4b.** Quantify key meteorological, glaciological, and solid Earth dynamical and state variables and processes controlling flash floods and rapid hazard chains to improve detection, prediction, and preparedness. **(I) H-4c.** Improve drought monitoring to forecast short-term impacts more accurately and to assess potential mitigations. **(I) H-4d.** Understand linkages between anthropogenic modification of the land, including fire suppression, land use, and urbanization, on frequency of and response to hazards.

TABLE 6.2 Priority Targeted Observables Mapped to the Science and Applications Objectives That Were Ranked as Most Important (MI) or Very Important (VI)

Priority Targeted Observables	Science and Applications Objectives
Surface Characteristics • Spectral albedo of snow, vegetation, and soil • Surface temperatures of snow, vegetation, and soil, covering diurnal cycle	**H-1a and H-2a.** Estimate rates of evapotranspiration and quantify how land use affects them. **H-1c.** Measure snowmelt, ice melt, and sublimation from snow and ice.
Snow Depth and Snow Water Equivalent (SWE)	**H-1c.** Quantify rates of snow accumulation, and track snowmelt. SWE = depth × density, but depth is the main contributor to spatial variability.
Soil Moisture • Especially in the root zone	**H-1a and H-2a.** Measure rates of evapotranspiration and quantify how land use affects them.
Precipitation and Clouds	**H-1b.** Improve identification of precipitation phase and rates of precipitation, especially when ice is present, and capture rainfall at orographic and convective scales.
Terrestrial Ecosystem Structure	**H-2a.** Improve the estimation of evapotranspiration.
Temperature, Water Vapor, Planetary Boundary Layer (PBL) Height	**H-2a.** Improve the estimation of evapotranspiration and sensible heat exchange.
Aquatic-Coastal Biogeochemistry	**H-3a.** Support emerging efforts to remotely sense water quality.
Surface Deformation and Change	**H-4a.** Monitor hazards and response in rugged terrain and land margins. **H-1a and H-2.** Monitor elastic and inelastic subsidence related to groundwater withdrawals. **H-1c.** Estimate snow density using interferometric Synthetic Aperture Radar (SAR) measurements.
Ice Elevation	**H-1c.** Help quantify rates of ice melt in basins where glaciers contribute significantly to runoff.

NOTE: Summary text is included in the second column to illustrate the types of knowledge needed to achieve the objectives.

With growing populations, the demands on our water resources are increasing. The study of our hydrologic cycle, and how it changes over time, is critical to understanding and quantifying freshwater availability, water quality and ecosystem health, and anticipating and managing risks due to extremes. Remotely sensed data have permitted the scientific community to develop broad new understandings of the water cycle at scales from small basins to continents and the entire Earth, and to advance socially important applications. This chapter's priorities will, if implemented, support and enhance the continuation of that work for the benefit of society and for a safe and prosperous future.

INTRODUCTION AND VISION

Motivation and Context

Water is the most widely used resource on Earth, and unlike other natural resources, water is a ubiquitous solvent and a medium for life itself. Fluxes of water connect the land to the atmosphere and the oceans. Water mediates Earth's energy budget in the form of clouds, and it acts as a universal transport agent moving energy in the form of latent heat and all types of materials from sediments to bacteria across the planet (Evenson and Orndorff, 2013). The hydrologic cycle involves many processes (precipitation as rain or snow, evapotranspiration and evaporation, snowmelt, condensation, sublimation, surface runoff, infiltration, percolation, and groundwater flow) whereby water circulates between the atmosphere, land surface, and the oceans. To understand the physical structure, chemistry, biodiversity, and productivity of the biosphere, it is important to know how water moves and how water is stored in the Earth system (NRC, 2012). Further, the movement of water influences Earth's biogeochemical cycles and Earth's climate (Vitousek et al., 1997). As Figure 6.2 shows, all components of the water cycle are linked at scales ranging from global to small basins, impacting and being impacted by human activities such as water withdrawals for agriculture and infrastructure development such as dams (Dalin et al., 2017).

The management of water resources is crucial for ensuring public health (Seid-Green, 2016) and securing the supply and allocation of water and food production to support human well-being, while sustaining healthy ecosystems. This is a major challenge for the 21st century (Poff et al., 2016). Opportunities exist, however, to integrate ecological health and human water needs in a comprehensive way (Gleick, 2000). In the Anthropocene, it is increasingly important to incorporate the human dimensions of freshwater use, to understand and predict aspects of freshwater resources (Konar et al., 2016).

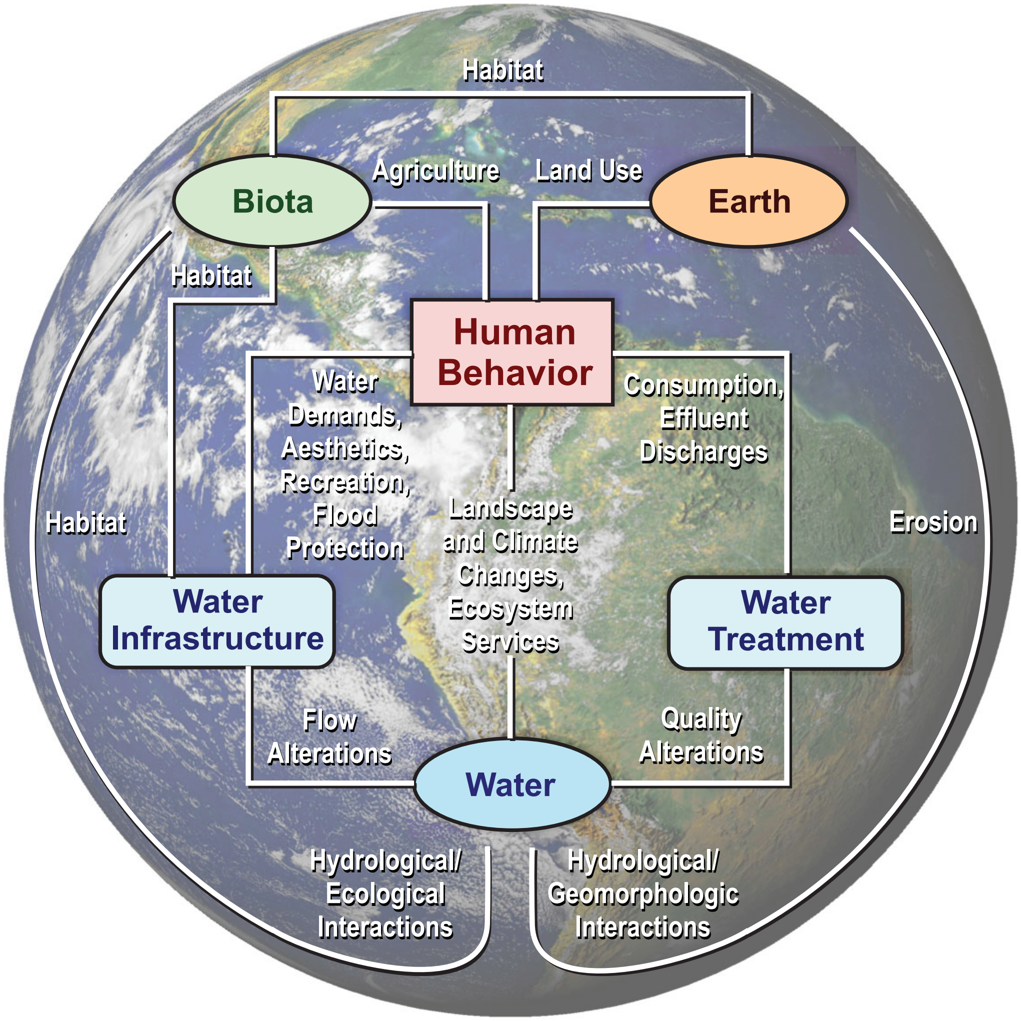

FIGURE 6.2 Interacting water and environmental processes, illustrating some couplings between natural and engineered systems and human processes in the water environment. SOURCE: Courtesy of Jeff Dozier.

Beginning with the launches of *Sputnik* in 1957 and *Explorer 1* in 1958, remote sensing provided an opportunity to observe the Earth system, especially its water cycle, and its changes in space and time from a global perspective (Vince, 2011; Lettenmaier et al., 2015). Measurements from spaceborne and airborne platforms advance understanding of the hydrologic cycle and water resource assessment, which can improve society's ability to manage water in our ever-changing world. To understand the dynamics of Earth's terrestrial water cycle requires detailed in situ and remotely based measurements. Remote sensing has become a common tool in hydrology and water resources research, and because it enables a quantitative assessment of interconnections among multiple physical and biophysical and biogeochemical process across the world's landscapes, it has enabled and catalyzed the advancement of Earth system science research and applications, and the fundamental role of the water cycle therein (McCabe et al., 2017).

The Earth observing systems that produce these sustained observations constitute vital national infrastructure, providing well-established, direct benefits to society and the economy, such as protecting life and property and securing food and water during disasters (Seid-Green, 2016). However, in spite of the importance of water to humanity, ecology, and environment, a comprehensive global hydrological observing system for monitoring the storage and movement of Earth's water does not exist (Rodell et al., 2015).

The motivation for the Global Hydrological Cycles and Water Resources Panel's work is to increase understanding of the hydrologic cycle from an integrated Earth system perspective. The intent is to provide a comprehensive perspective on the hydrologic cycle, including impacts and feedbacks at key coupled human-natural interfaces (water resources, agriculture, urbanization and infrastructure, natural resource use, and stewardship). The panel addresses its important task according to four distinct organizing themes that capture both scientific and societal imperatives: (1) coupling of water and energy processes between land and the lower troposphere; (2) prediction with a focus on variability, biogeochemical cycling, and extreme events; (3) water use and availability of quality water; and (4) hazards such as floods, droughts and related fires, landslides, and others that capture both scientific and societal imperatives.

This section, "Introduction and Vision," provides the motivation and context for why the panel objectives are both scientifically compelling and societally important, and why now is a suitable time for investment into additional efforts to measure hydrologic parameters remotely using Earth observing satellites. The section then provides a review of the improvements in understanding, monitoring, and predicting hydrologic processes and resource assessment by Earth-orbiting satellites since the last decadal survey. The subsection "Challenges and Opportunities" identifies science and applications for which new or sustained measurements of hydrologic parameters are necessary to advance the hydrologic sciences and best serve society. The next section, "Prioritized Science Objectives and Enabling Measurements," identifies and prioritizes 13 science and application objectives, which are categorized into broad societal questions based on coupled cycles, predicting change, water availability, and hazards. The subsection "Enabling Measurements" describes how these measurements can address the quantitative science objectives and questions. The section that follows, "Resulting Societal Benefit," discusses priority measurements in the context of benefiting society, considering measurements that have broad application to water resource challenges such as availability of freshwater and hydrologic hazards.

Benefits of Prior Efforts

The previous decadal survey (NRC, 2007a), emphasized the need for high-quality global estimates of precipitation, soil moisture, and snow-water equivalent. In addition to these variables, the previous survey noted that measures of surface-water storage and transport would improve both modeling and an integrated understanding of the global water cycle. The four missions most relevant to the water cycle were:

- The already approved Global Precipitation Measurement (GPM) mission to provide estimates of precipitation;
- A soil moisture mission to address this crucial part of the land-surface water balance;
- A surface-water and ocean-topography mission to provide observations of water storage and associated variability; and
- A cold land processes mission to provide estimates of the water stored in snowpack.

Since that time, substantial progress has been made. Space-based observations of the hydrologic cycle and water resources have both improved scientific understanding and resulted in a variety of societal benefits. Some key achievements and transformational technologies include the following (Lettenmaier et al., 2015):

- The Global Precipitation Measurement (GPM) mission, which contributed to developing a capability to forecast floods and droughts and understand how precipitation patterns change through time across local to regional and global scales. GPM provides improved measurements to help improve weather and climate models (Skofronick-Jackson et al., 2016).
- The Gravity Recovery and Climate Experiment (GRACE), which contributed to the ability to measure the change in total water storage over large areas and information on global groundwater depletion (Alley and Konikow, 2015; Lakshmi, 2016; Famiglietti and Rodell, 2013; Richey et al., 2015).
- The Soil Moisture Active-Passive (SMAP) mission, which included improvements to water and climate forecasting, flood and drought monitoring, and predictions of agricultural productivity (Entekhabi et al., 2010). SMAP has been providing soil moisture observations that have been calibrated and validated at various locations (Chaney et al., 2016; Burgin et al., 2017; Colliander et al., 2017; Kim et al., 2017).

In addition to pertinent missions that have already launched, scheduled launches also represent substantial achievement to help understand the hydrologic cycle and provide societal benefits. The Surface Water and Ocean Topography (SWOT) mission, scheduled for launch in 2021, will provide both water surface elevations and extent and thereby information about surface-water storage and fluxes globally. The mission is expected to contribute to the understanding of individual lakes and reservoirs a few hundred meters in size and larger, and the information generated will aid the management of transboundary waters and ungauged basins (Biancamaria et al., 2016). The upcoming TROPICS mission—Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats (NASA EOS, 2017), to be launched in 2019—uses passive microwave spectrometry to provide for the first time high-revisit thermodynamic soundings and storm structure down to the boundary layer that can be integrated with high spatial resolution observations and rapid-refresh data assimilation systems to improve hydrological and hazard forecasts in remote regions generally and mid- and large-size ungauged basins (>300 km^2).

Other recommended missions (NRC, 2007a) included the Snow and Cold Land Processes (SCLP) mission and the Hyperspectral Infrared Imager (HyspIRI) mission. SCLP's objective is to measure the snow-water equivalent (SWE), snow depth, and snow wetness over land and ice sheets. As a third phase mission still in formulation, its status is conceptual, with newer approaches to measuring SWE addressed in this report. The HyspIRI mission was recommended as a second-phase mission for launch in the 2012 to 2016 period. Based on hyperspectral instruments designed to globally observe at high spatial and spectral resolution (Devred et al., 2013), such measurements provide an opportunity to assess ecosystem changes and functions, natural hazards such as volcanic eruptions and wildfires, and snow properties (Hook, 2014; Dozier et al., 2009). Since the last decadal survey, the mission concept has been refined to achieve needed measurements more economically, based partly on experience with hyperspectral observations of the lunar surface by the Moon Mineralogy Mapper (Green et al., 2011; Lee et al., 2015). Additionally, the ECOsystem Spaceborne Thermal Radiometer on Space Station (ECOSTRESS), with a planned launch of May 2018, provides NASA the opportunity to collect very high spatial (35 × 75 m) land-surface temperature (LST) at a 4-day temporal resolution. This measurement addresses the Objective H-1a measurement priority ("diurnal cycle of surface temperature [vegetation, soil, snow], at agricultural or topographic scales") and can provide critical measurements that will help better design a spectrometry mission. To fully exploit the ECOSTRESS mission, its measurements plan needs to be expanded to cover all land areas rather than the current plan of selected regions and validation sites.

Challenges and Opportunities

Over the last 30 years, NASA's Earth Observing System (EOS) transformed water cycle science and applications by providing—for the first time—frequent multiscale observations over large spatial domains across the planet. From the privileged vantage point of space orbits, coordinated missions such as the Afternoon Constellation (A-Train) and a developing suite of precipitation sensors rely on measurements from multiple satellites and collaborations with international partners, mainly space agencies and centers in Europe, Japan, and India to measure systematically key geophysical variables including shortwave radiation, atmospheric composition, clouds, precipitation, soil moisture, terrestrial vegetation and oceanic chlorophyll, water storage in the subsurface, and land subsidence, among many others, thus effectively establishing a de facto Earth Observing System. Such integrated observations show interrelatedness and feedbacks among seemingly removed processes and states, such as atmospheric composition and evapotranspiration, linking atmospheric pollution to clouds and surface temperature and water availability, and linking, in turn, public and environmental health to irrigation needs for food production and energy security.

NASA's initiation of the EOS idea was foundational to the advent and growth of Earth system science and applications. Where lead time is paramount (e.g., seasonal climate for food production and water supply, 5-day weather forecasts for the construction industry, flashflood warnings for public safety, next-day snowfall for school closings), the integration of satellite-based observations and models through Data Assimilation Systems (DAS) significantly increased the predictability skill of existing forecast systems with implications for decision making under uncertainty across weather and water socioeconomic sectors (Magnusson and Källén, 2013; Bauer et al., 2015; Pagano et al., 2014; Bolten et al., 2010). An entirely new service industry developed over the last two decades to provide specialized value-added information products and client-based modeling and observing systems (Benson, 2012; Mandel and Noyes, 2012; NRC, 2003; Acclimatise, 2014).

In recent years, even as NASA's original EOS missions surpassed expectations of longevity and utility, continuing to operate beyond their design life, the number of new satellite launches has declined and is split between improved continuation missions (e.g., GPM and GRACE-Follow On) and new missions (e.g., SWOT, NISAR). Benefiting from NASA's early leadership in technological innovation, data access policy, and research and development, and more recently through international collaborations, the Program of Record (POR) of current and planned missions relies on mature (proven) technology to ensure essential data continuity. Yet, prompted by developments in sensor technology, high-performance computing, and scientific advances over the last decade, the current POR is inadequate for current and anticipated modeling capabilities, or to meet the data granularity and specific needs of data-driven decision making in the near future. This report proposes a measurement plan that addresses these needs.

PRIORITIZED SCIENCE OBJECTIVES AND ENABLING MEASUREMENTS

Science and Societal Goals, Questions, and Objectives

The linkages between the water cycle and freshwater availability, food and energy production, and environmental resilience highlighted in this decadal survey emerge from Grand Challenges of opportunity for a wide range of research programs (e.g., Trenberth and Asrar, 2014). Figure 6.3 and Table 6.1 summarize the goals, objectives, and assigned priorities from the details in this section. Quantifiable objectives and measurements (discussed in the next subsection) are intertwined, without a one-to-one mapping between them. Indeed, consistent with the ubiquitous role of the water fluxes connecting reservoirs and interfaces across the Earth system, many of objectives of lower priority would be achieved if specific higher priority objectives (Most Important or Very Important) are achieved.

H-1: Coupling the Water and Energy Cycles

Question H-1. How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?

Satellite-based observations available since 1979 have been used to generate multiple precipitation data sets (Ashouri et al., 2015; Xie et al., 2003; Adler et al., 2003; Xie and Arkin, 1997; Huffman et al., 1997; Xie et al., 2017) suitable for monitoring the water cycle at global scale. The frequency and space-

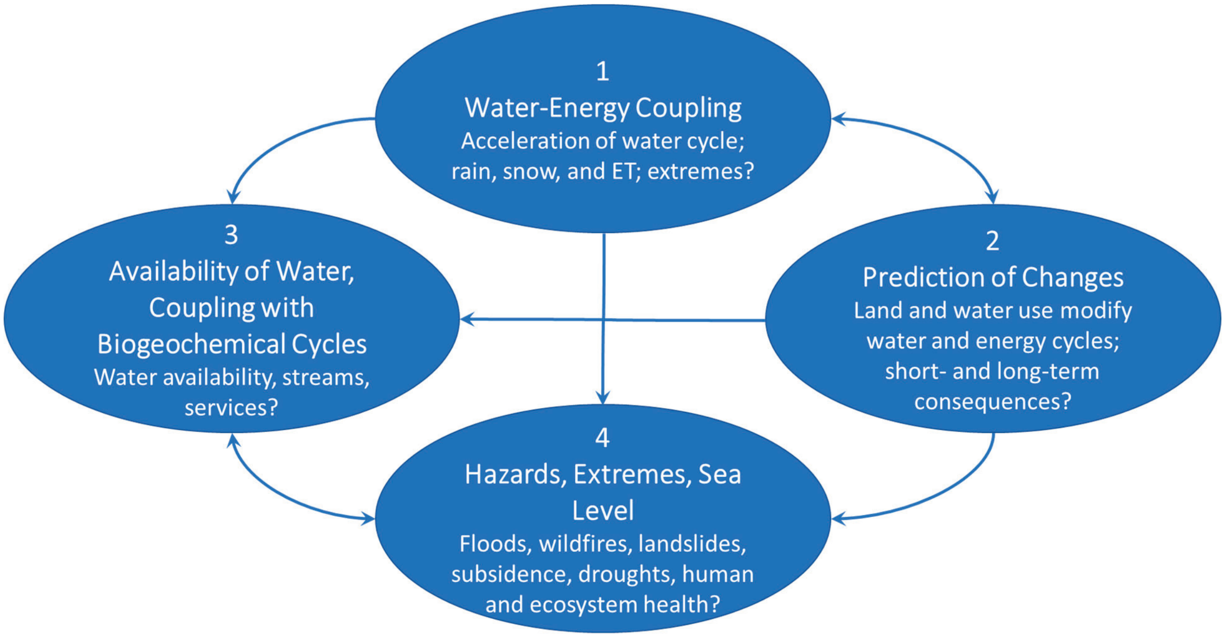

FIGURE 6.3 Schematic view of four science and societal themes and associated questions related to hydrology and water resources, and relevant at all spatial and temporal scales. SOURCE: Efi Foufoula-Georgiou.

time patterns of rainfall, snowfall, snowmelt, soil moisture, and evapotranspiration control the water and energy cycles at basin, regional, and global scales. Changes in these patterns caused by climate change and human modification to the environment, coupled with increasing population and per-capita demand for water, pose significant challenges in the management of water-resources systems; threaten water, food, and energy security; challenge the health of ecosystems; and increase susceptibility to hazards and their socioeconomic consequences (e.g., Trenberth, 2011; Emori and Brown, 2005; Alexander et al., 2006; Min et al., 2011; Wentz et al., 2007). Changes in precipitation extremes, typically understood as the top 95th to 99.9th percentiles of daily accumulations, have been documented in many places (Alexander et al., 2006; Berg et al., 2013; Emori and Brown, 2005; Groisman et al., 2005; Kunkel et al., 2003), as well as in the duration of wet and dry spells (Zolina et al., 2013; Trepanier et al., 2015; Guilbert et al., 2015), and in the seasonality and phase (Barnett et al., 2005; Nayak et al., 2010). At the global scale there is large spatial variability with both negative and positive trends over large regions at multiple spatial scales (Ashouri et al., 2015; CHRS Rainsphere, 2017), with high uncertainty depending on the length of the available precipitation data records, both rain gauge observations and satellite products.

Accurately monitoring the timing, amount, phase (snowfall or rain), and vertical structure (hydrometeor composition) of precipitating systems globally and with sufficiently high spatial and temporal resolution to detect change and to quantify water availability at multiple scales from headwater catchments to continental river basins is an imperative challenge for the next decade. For basin-scale budget studies, estimating precipitation at spatiotemporal scales of 1 km and 1 hour are adequate, with temporal resolutions as fine as 5 minutes needed for urban flood warning and response (Berne et al., 2004; Emmanuel et al., 2012) and long-standing engineering design standards (Brown et al., 2009). Such observations will improve modeling of weather and climate, provide real-time warning for hazards such as floods and landslides, and increase the predictive understanding of teleconnections to attribute, anticipate, and manage environmental change.

Accurate estimation of precipitation amounts and detection of changes is challenging over land, especially over complex terrain (Barros, 2013). For example, High Mountain Asia (HMA) contains the largest deposit of ice and snow outside the polar regions; here, shrinking glaciers provide evidence of climate change in one of the world's iconic regions, and the region plays a critical role in controlling the land-surface energy balance, and downstream irrigation and freshwater availability in several densely populated river basins (Kehrwald et al., 2008). In the past few decades a wide range of climatic changes, accelerated by economic developments and urbanization, has altered HMA's radiation budget by increasing the temperature, depositing soot and dust in the snowpack that reduces its albedo, shifting the precipitation patterns, reducing snowfall, and amplifying the melting rate of glaciers and permafrost (Qui, 2008; Kaspari et al., 2014). HMA's precipitation exhibits strong interannual variability (Barros et al., 2004; Lang and Barros, 2004; Barros and Lang, 2003), and its changes are still only poorly known because of the paucity of in situ observations and thereby the lack of validation of climate models. It is likely that future seasonal melting will shift the river peak flows toward the spring and decrease the water availability during the summer, posing risks to downstream water availability, impacting food and energy production and ecosystems (Immerzeel et al., 2010). This phenomenon and the lack of ground-based observations is not confined to HMA, but is evident in key mountain regions worldwide, leading to their designation as the Third Pole, which includes mountain ranges in North America, South America, and Europe (Stewart, 2009; Yao et al., 2012).

Whereas the linkages between climate variability and hydrological drought at interannual and decadal scales are well established (e.g., Barros et al., 2017), there is large uncertainty in assessing the sensitivity of drought frequency to observed changes in global temperatures (Sheffield et al., 2012; Dai, 2012; Trenberth et al., 2014). However, just as warmer temperatures increase the water holding capacity of the atmosphere, contributing to more extreme precipitation in some regions, higher temperatures—concurrent with regionally lower humidity that leads to greater potential evapotranspiration—can result in increased drought severity due to persistent decreases in soil moisture, increased plant water stress, and degradation of plant productivity (Weiss et al., 2009; Easterling et al., 2000). Drought amplification by the interplay of concurrent and persistent high temperatures and low atmospheric moisture conditions is illustrated by Moran et al. (2014), who compared the Dust Bowl drought in the 1930s to the droughts in the 1950s and the early part of the 21st century in the western United States. They found that the 1950s drought was more severe than the 1930s and the early twenty-first-century droughts, even if the warm season temperature was only 0.68°C above the historic mean. Changes in post-drought ecosystem composition due to invasive species during recovery from recent "hot" droughts (Willis and Bhagwat, 2009) pose further challenges in managing the interplay between water, food, energy, and ecosystem services. Interestingly, drought "busting" events that replenish regional soil moisture and aquifers, including atmospheric rivers in the western United States (Dettinger, 2013) and land-falling hurricanes and tropical cyclones in the South and Southeast (Brun and Barros, 2014; Lowman and Barros, 2016), are also associated with major hazards and destructive damage in complex terrain and in urban areas because of heavy precipitation, extreme winds, flooding, and landslides (Guan et al., 2016; Waliser and Guan, 2017). The complex and nonlinear interconnections between water availability and water use, extreme events, and hazards encompass spatial scales ranging from 100 m to 1,000 km and temporal scales from minutes to years. They are iconic of the challenges presented to water cycle research, and a powerful motivation to monitor Earth at high spatial and temporal resolution, which can only be accomplished systematically from space.

Objective H-1a. Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance from headwater catchments to continental-scale river basins.

Figure 6.4 shows how the water and energy cycles are linked within the Earth climate system in many ways as well as how the various satellite missions have been used to observe these land and atmosphere variables. Objective H-1a underscores the need for a balanced research program combining observations and analysis systems. It also underscores the potential for scientific discovery that results from the integration of different observation types meeting requirements at distinct spatial and temporal resolution to probe interrelationships and feedbacks in the coupled Earth system.

For example, surface evapotranspiration (and its equivalent latent heat) are common fluxes to both water and energy cycles. However, point-scale evapotranspiration is directly measured by lysimeters, which mainly are installed in agricultural research settings, or estimated from measurements of sap flow in individual trees. It cannot be measured remotely. Instead, sensible and latent heat flux modeled from in situ measurements are the components of the surface available energy that are the primary drivers of the surface boundary layer that influences the coupling of the land with the atmosphere (Ek and Mahrt, 1994; Betts, 2004; Betts et al., 1996) and heats the surface air. Thus, the key to estimating evapotranspiration lies in measuring, or modeling, the variables and parameters that determine other terms of the energy balance equation—solar and longwave radiation, albedo, surface temperature, air temperature and atmospheric water vapor pressure in the boundary layer, and wind. Surface soil moisture influences the boundary layer cloud development through the latent heat flux associated with evapotranspiration, which in turn regulates surface temperature and thus the sensible heat flux and emitted longwave radiation, thereby affecting net surface radiation and available energy (Betts, 2004; Ek and Holtslag, 2004; Findell and Eltahir, 2003).

Quantifying the components of the water and energy cycles at Earth's surface through observations and with sufficient accuracy to close water budgets over a wide range of river basin scales is a challenging problem that remains unresolved, but it is central to programs like the NASA Energy and Water System

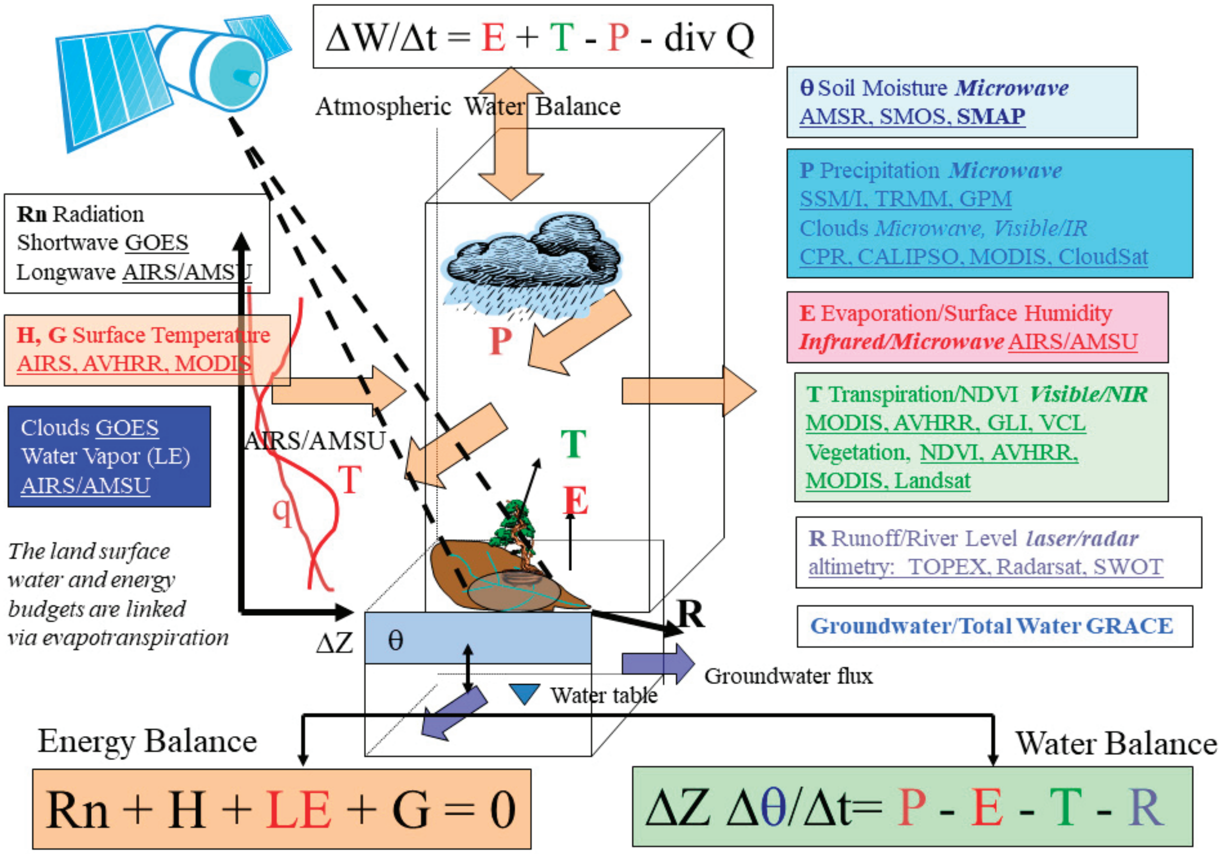

FIGURE 6.4 Closing the terrestrial water balance using remote sensing, showing needed measurements to measure the links between the energy and water cycles. SOURCE: Vankat Lakshmi.

(NEWS) and the World Climate Research Programme (WCRP) Global Energy and Water Exchanges (GEWEX) (Zhang et al., 2016; Rodell et al., 2015). With evidence of increasing climate variability and change (Barnett et al., 2005), and increased utilization of water resources (Oki and Kanae, 2006), understanding the controls on these components from an Earth system science perspective is imperative to assessing change, and to developing effective adaptation strategies.

These processes are explicitly included in climate models, where the surface water and energy cycles are closed (fluxes in balance) by mathematical design at model-resolved scales that are unfortunately much coarser than the governing process scales, which are therefore not appropriately represented (i.e., parameterized). Proper characterization of states and fluxes is complex and requires many parameters, including landscape and vegetation characteristics (e.g., topographic variability, soil properties, land use and land cover, vegetation biophysical parameters, water and land management, to name a few), most of which are poorly measured across the globe and whose effects are poorly understood. This results in high uncertainty and wide variability among predicted water and energy fluxes (Mueller et al., 2011; Rodell et al., 2015; Wild et al., 2015; Zhang et al., 2016) that limits our understanding to changes in water availability, the proper partitioning of evaporation and transpiration and storage, and the effect of the vertical distribution of water vapor and cloud microphysics on precipitation among others that impact extremes like floods, droughts, and heat waves. For example, Chaney et al. (2016) used global FluxNet data to improve the process parameterization in the Noah land surface model. But of the ~650 sites in 30 regional networks covering 5 continents, only 253 eddy covariance stations with a total of 960 site-years of data at the needed 30-minute time resolution have been harmonized, standardized, and gap-filled (ORNL, 2007), with only 154 sites open to the community. Further evaluation and quality control of the data reduced the useable number to 85. Many regions (South America, Africa, Asia, and Australia) have fewer than 3 or 4 sites. The existing observational vacuum handicaps the science and can be addressed effectively only through remote sensing observations in the context of a broader integrated Earth system analysis.

What might comprise this context?

- Improved validation of remote sensing products through a significant increase in core sites (high-quality, multiple-variable measurements sites over ~10 × 10 km grids that can resolve subgrid flux heterogeneity at the 1 km scale or finer) and sparse validation sites measuring fewer locations or variables within a 10 × 10 km grid. This requires the coordination of space agencies and international bodies such as the World Meteorlogical Organization (WMO) and WCRP.
- Development of high-resolution Earth system models at spatial resolutions of 1 to 3 km, which can resolve watershed-scale water and energy states and fluxes with finer spatial heterogeneity and enable improved understanding and landscape management. Approaches could include elements such as the hyper-resolution land-surface modeling based on tiling of complex hydrologic response units, which offers one approach for continental modeling at 30 m (Chaney et al., 2016).
- Coordinated networks of in situ and remote sensing products that can improve the characterization of the land-surface energy fluxes, and resolve surface solar and longwave radiation balances within 10 Wm^{-2} accuracy at 1 km resolution globally, four times daily. Resolving the diurnal cycle is the desirable goal, but progress can be achieved through the integration of models and high-spatial resolution measurements at lower temporal resolution.
- The upcoming ECOSTRESS mission (launch 2018) on the Space Station can provide useful landscape-scale (~70 m spatial and 4-day temporal resolutions) top of the canopy temperatures. Likewise, ongoing efforts to produce 30 m multispectral harmonized surface reflectance products through the fusion of Landsat-8 (and Landsat-9 in 2020) and Sentinel-2a and -2b with high-revisit frequencies (~3-4 days at the Equator, and 1-2 days at midlatitudes) represent significant space-time resolution improvements over the highest resolution MODIS products currently available. Addition of a polar-orbiting imaging spectrometer to this constellation would enable spectroscopic interpretation and validation of the observations from multispectral sensors.
- Development of assimilation techniques and data analytics that can provide the desired integration and synthesis from merging in situ, remote sensing, and hyper-resolution models.

Given these advances, critical science and societal questions can be addressed, such as the following:

1. What are the impacts of increased atmospheric CO_2 and other greenhouse gases on the coupled water-energy-biogeochemical cycles, and do these modify water availability at basin to regional scales?
2. To what extent have the water cycle components and their variability changed, and have these resulted in changes to extreme events (floods and droughts)?
3. How will monitoring and modeling of water and energy balance variables at the basin and field scales lead to improved management practices and resiliency?

Objective H-1b. Quantify precipitation rates and phase (rain and snow/ice) worldwide at convective and orographic scales suitable to capture flash floods and beyond as well as processes at longer and larger spatial scales.

The Global Hydrological Cycles and Water Resources Panel assigned highest priorities to developing an Integrated Earth System analysis, which would integrate models and observations, and to measuring rainfall and snowfall and accumulated snow on the ground, which are key constraints and inputs into that analysis. Precipitation is the most important water flux in terrestrial hydrology, and thus precipitation measurements are key input variables in hydrologic and water resources models. Precipitation is equally important to a vast array of applications from agriculture, to ecosystem management, to climate monitoring and adaptation efforts, including risk-based engineering design of critical infrastructure from highways to water supply systems. For these reasons, precipitation has been at the forefront of NASA's sustained mapping efforts at global scales along with NOAA ground-based radar networks for the continental United States.

NASA, in collaboration with the Japanese Space Exploration Agency, JAXA, launched the Tropical Rainfall Measurement Mission (TRMM) in November of 1997 to quantify tropical rainfall and the associated latent heating structure. The mission success went beyond quantifying mean rainfall over the global tropical oceans, and it spurred the development of innovative algorithms that used the TRMM radars as a way to calibrate existing passive microwave radiometers and sounders as well as infrared observations to increase the spatial and temporal resolution of precipitation (Kummerow et al., 2015; Huffman et al., 2007). Figure 6.5 shows how TRMM detected significant drying trends from 1998 to 2013, especially in the western and central United States, Southern Africa, northeastern Asia, and southern Europe and the Mediterranean. These decreases are concurrent with positive trends elsewhere, resulting in spatial variability at the global scale and large regions of statistically significant negative trends along the midlatitude storm track in the northern Atlantic and positive trends in the maritime subcontinent (Nguyen et al., 2017).

The integration between a radar and sensors that provide wider spatial and temporal coverage was more fully developed in the second collaboration between NASA and JAXA precipitation efforts resulting

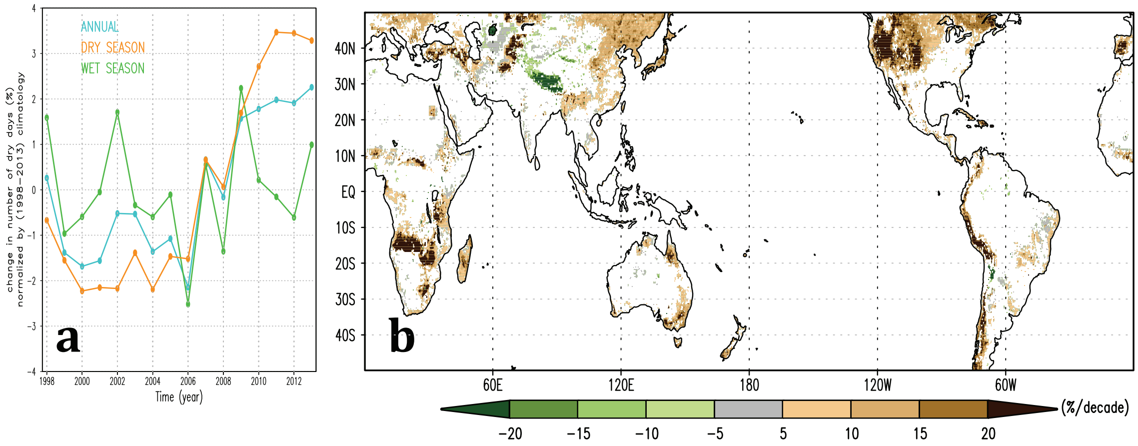

FIGURE 6.5 Percentage changes of dry days over land relative to climatology based on NASA TRMM measurements. Panel A shows the time series (1998-2013) for annual, wet season, and dry season, respectively, and panel B shows the trend pattern for dry season in units of percent change per decade. A significant global drying trend (3.2 percent per decade) over land is evident during the dry season. SOURCE: Wu and Lau (2016).

in the Global Precipitation Measurement (GPM) mission launched in February of 2014 (Hou et al., 2014). GPM not only extends the time series of climate-quality precipitation radar observations from TRMM, but it also extends the core satellite observational domain to high latitudes, and it formalizes the calibration concept developed during TRMM to make a consistent precipitation product from a global constellation of passive microwave and infrared sensors that can include models and both research and operational satellites to produce 5 km, 30-minute precipitation estimates globally. One key improvement in GPM over TRMM is the ability to predict global extreme precipitation. Whereas there is a 50 percent match between TRMM Level 3 precipitation and ground-based rain gauges for determining the extreme precipitation, this number rises to 60 percent for GPM (Huffman et al., 2017), demonstrating increased spatial (0.1 degrees versus 0.25 degrees) and temporal repeat (3 hours versus half hour) monitoring capability. This improvement in estimating extreme rainfall in ungauged regions of the world has important implications for engineering (Libertino et al., 2016; Olsen, 2015). The Integrated Multi-Satellite Retrievals for GPM (IMERG) combines precipitation estimates from all available passive microwave observations, with gaps filled using geosynchronous infrared precipitation estimates (Hong et al., 2004; Joyce et al., 2004; Hsu et al., 1997; Kummerow et al., 2015). These products are being produced today and are expected to continue improving as the community learns to more fully exploit the dual-frequency precipitation radars on GPM, as well as intercalibration procedures to the diverse instruments in the constellation (Berg et al., 2016). Further, by leveraging dual-frequency, dual-polarization radar measurements, improvements are expected in the detection and quantification of light and moderate rainfall that represent a significant fraction of the total precipitation, and in orbital mapping of three-dimensional (3D) storm structures at the mesoscale.

Precipitation is a multiscale process spanning a wide range of scales from the raindrop and raindrop cluster scales (μm to m) to the scale of storm cells (100 m to 10 km) to the scale of organized systems (~100 km; e.g., tropical cyclones, fronts). Continuity of passive microwave instruments, which currently provide the longest records of any geophysical variables derived from space observations, is essential to monitor the variability of global precipitation from decadal to interannual to daily time scales, especially over the world's oceans, and to provide the large-scale context (regional to continental scale) to ongoing measurements of precipitation, soil moisture, sea ice, and other variables sensitive to water fluxes at the land- and ocean-atmosphere interfaces, including at short time scales, as high- revisit passive microwave spectrometry from space becomes available (e.g., TROPICS mission).

Numerous discussions within the precipitation community, reflected in multiple white paper submissions to this decadal survey, indicate the need and desire to continue to advance the quality of spaceborne instantaneous precipitation measurements not adequately covered by GPM, and to refine the spatial and temporal resolutions of precipitation estimates. For the latter, in particular, there is growing consensus that the key to success in this area is better process understanding coupled with assimilation into convection-resolving models that can provide continuous analyses and forecasts of precipitation at 1 km and 5 minutes to 1 hour scales, thus approaching the capabilities of ground-based radars over developed regions of the world today.

Advancing process understanding to properly model precipitation, particularly ice microphysics that can be gleaned from combined Doppler radar and radiometer information (Bryan and Morrison, 2012; Varble et al., 2014), or assimilate precipitation and its latent heating in convection-resolving models to forecast small-scale intense precipitation could possibly revolutionize how we view Earth observing satellites from stand-alone measurement platforms to integral components of coupled observing and modeling systems (Stephens and Kummerow, 2007). In the case of models with parsimonious microphysics, a strong case can be made that observing hydrometeor vertical velocities within the context of large scale environmental conditions, as established from reanalyses such as Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al., 2011), will provide useful constraints on microphysical parameterizations to capture the vertical structure of precipitation in models that currently is lacking (Wilson and Barros, 2014, 2017), and thus to make high-quality, high-resolution, model-based analyses and forecasts of precipitation a reality. Advancing the quality of spaceborne instantaneous precipitation measurements does not require large leaps in technology, but rather innovation with regard to the development of multifrequency instruments and measurement strategies to significantly refine their horizontal and vertical resolutions. This will address continuing issues with orographic precipitation as well as improve the detection and quantification of shallow precipitation in complex terrain, snowfall, and light drizzle (Duan et al., 2015). A swath of 100 km is then needed for the calibration reference to operational microwave imagers, as well as operational sounders and visible and infrared imagers used in geostationary satellites.

Albeit complementary, snowfall (precipitation rate) and snow accumulation (precipitation amount) pose distinct measurement challenges. Snowfall accuracy at short time scales (minutes to hours) is critical for winter weather forecasting, with major implications for transportation and energy security applications, even leading to a snow impact scale for Northeast storms (Kocin and Uccellini, 2004). Currently, quantitative remote sensing of snowfall from satellites is largely limited to X- or W-band radar (Heymsfield et al., 2016; Kulie and Bennartz, 2009) for dry snow. Snow accumulation evolves from pulse contributions from a small number of individual storms with large interannual variability (Lang and Barros, 2004; Lundquist et al., 2013) to form snowpacks that grow in depth and spatial extent through the winter depending on environmental conditions and snowfall history. In the transition from the cold to the warm season, seasonal snow melts over a short period, weeks to several months, to produce runoff that is an essential source of freshwater resources in the foothills of high mountain regions and their adjacent plains such as the western United States (Bales et al., 2006). Not surprisingly, numerous reservoirs have been built to capture snowmelt runoff to further extend water availability.

The global volume of glaciers outside the polar ice sheets is also not accurately known owing to their uncertain thicknesses, but this number does not change as rapidly as SWE. Worldwide, snowmelt and glaciers support about two billion people (Mankin et al., 2015); mountain snowmelt and glaciers support over a billion (Barnett et al., 2005). In the mountains themselves, snowmelt provides essential soil moisture late into the melt season (Harpold and Molotch, 2015), and melting glaciers supply water throughout the melt season, which in some regions is otherwise a dry season. The global inventory of glaciers outside the polar ice sheets comprises 0.35-0.41 m sea-level rise equivalent (Radić and Hock, 2010; Grinsted, 2013), or $1.3\text{-}1.5 \times 10^{17}$ kg. Compared to the global annual river runoff to the seas of $\sim 4.4 \times 10^{16}$ kg (Clark et al., 2015), the nonpolar glacier mass is equivalent to 3-4 years of global river runoff. Regionally and locally, annual glacier melt throughput, and the smaller magnitude net annual mass balance of glaciers, is extremely important for water resources and economies, especially for some arid and semiarid countries.

Albedo, areal extent (snow-covered area, SCA), and snow water equivalent (SWE) are important metrics of seasonal snow accumulation. The extent and albedo of seasonal snow govern the surface energy budget of large regions of the world at high latitudes and at high elevations, and therefore play a critical role in the water cycle of large regions of the world, with implications for the interannual variability of climate at global scales (Fletcher et al., 2009). Passive microwave estimates of SWE can succeed when radiative transfer models are coupled with snow hydrology models via data assimilation, but uncertainty and retrieval error increase significantly in complex terrain, when snow is wet, generally when SWE exceeds ~200 mm (deep snowpacks), and when tree canopy cover exceeds ~20 percent (Lettenmaier et al., 2015; Dozier et al., 2016). Measurements of snowfall, or of accumulated snow on the ground, constitute an important unsolved problem in the hydrology and water resources in most of the world. The next section addresses some approaches to this issue.

Objective H-1c. Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide at scales driven by topographic variability.

As noted in the discussion of Objective H-1b, remote sensing of snowfall rate is difficult because of the huge difference in the dielectric properties between water and ice in the microwave spectrum. Even measuring snowfall at a meteorological station is difficult, because catching falling snow in windy conditions generally misses much of it (Yang et al., 2005). Instead, our historical knowledge of the distribution of snow accumulation comes from measurements of the snow on the ground, either by manual surveys (Armstrong, 2014; Church, 1933) or by snow pillows that sense the weight of the overlying snowpack (Cox et al., 1978). In mountain regions, where much of the snowpack in the middle and lower latitudes lies, topographic heterogeneity along with deep snow causes substantial uncertainty in our assessment of a major component of the hydrologic cycle. Even in regions like the western United States with an extensive snow pillow network, the pillows are on nearly flat terrain and in most basins do not cover the highest elevations, so in some years they poorly represent the spatial distribution of the snow and the total volume of water stored in the basin's snowpack (Bales et al., 2006). In the river basins of California's Sierra Nevada, for example, the interquartile error in the forecast of the April-July runoff is 213 percent to 135 percent, but the error distribution has long tails, both positive and negative (Lettenmaier et al., 2015). In the world's great mountain ranges, where surface data are sparse, precipitation estimates from lowland measurements, numerical weather models, or changes in sizes of glaciers span a large range of uncertainty (Kääb et al., 2012; Kapnick et al., 2014). This is further complicated by the fact that at high elevations, snowfall input is highly intermittent and typically associated with specific types of storms and regional conditions (Lang and Barros, 2004). Therefore, seasonal snow accumulation and snowpack conditions strongly depend on local interstorm hydrometeorology and occasional rain-on-snow events (GuanWaliser et al., 2016), which control snowpack evolution between snowstorms.

At mid- and high latitudes, including the Arctic and sub-Arctic regions, complex topography (and landform) also plays a critical role in the spatial organization of snow accumulation as well as snowmelt dynamics at the transition between the cold and warm seasons, impacting snow cover extent and duration, snow water equivalent, and albedo, which feed back into regional and global climate (Derksen et al., 2012). Although significant progress has been achieved to estimate snow water equivalent from passive microwave observations (Kelly and Chang, 2003; Li et al., 2015; Shi et al., 2016) and also using coupled physical and passive microwave models (Kang and Barros, 2012; Langlois et al., 2012), the spatial resolution generally is too coarse for hydrological and eco-hydrological research and applications. A promising new development addresses the resolution limitation by taking advantage of overlapping footprints, to bring spatial resolution at 36 GHz down to ~3 km at the expense of some reduction in signal-to-noise performance (Long and Brodzik, 2016). Other shortcomings of passive microwave retrievals of snow water equivalent remain, particularly its low saturation threshold of about 200 mm SWE (Dozier et al., 2016; Lettenmaier et al., 2015).

In regions like High Mountain Asia, the sparse measurement network supports neither seasonal runoff forecasts nor validation of precipitation models. In regions like the western United States, where in situ measurements and snow-depth measurements from airborne lidar are available, validation of snowpack resources computed with numerical weather models, such as the Snow Data Assimilation System (SNODAS; NSIDC, 2016), show discouraging results with significant under- and overestimates (Clow et al., 2012; Hedrick et al., 2015; Bair et al., 2016). Figure 6.6 shows the importance of snowmelt in the water supply of the western United States. Three years of drought from 2013 through 2015 brought California's reservoirs and groundwater to historically low levels. The storms in the winter of 2017 replenished the reservoirs, but the groundwater remained depleted because of the extensive pumping during the drought (Margulis et al., 2016). Forecasts of the snowmelt runoff are based on a network of surface measurements, but because the sites seldom cover the highest elevations, as pointed out earlier, considerable snow amounts remain on the ground even after point-scale sensors indicate snow-free conditions (Rittger et al., 2016). The sta-

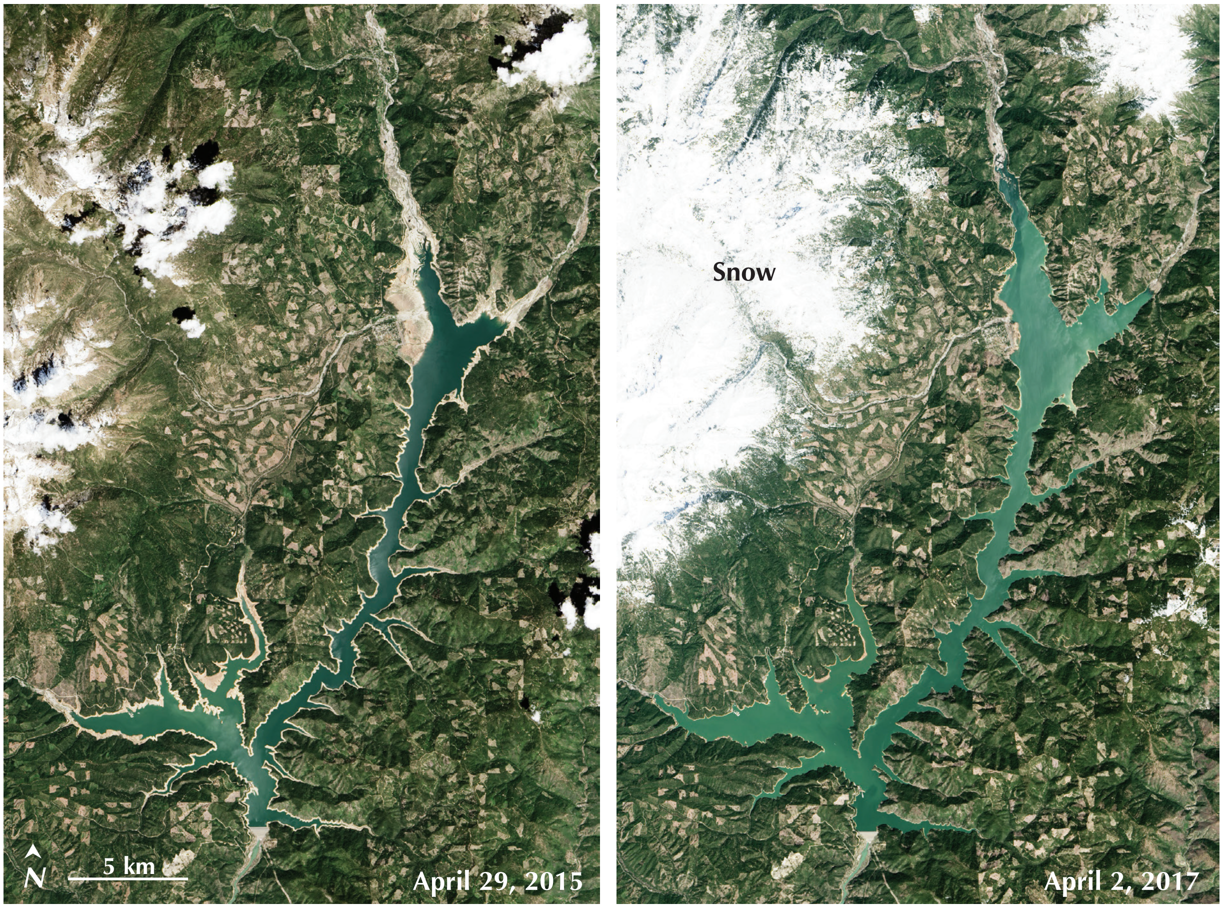

FIGURE 6.6 A 5-year drought in California ended spectacularly in the winter of 2017, with the state emerging from one of its driest periods on record by enduring a wet winter. A steady stream of storms brought 175 percent of the long-term average of rain and snow to California between October 2016 and April 2017. The left image from the Landsat 8 Operational Land Imager (OLI) shows the tan bands around the shoreline of Trinity Lake, California's third largest reservoir, in April 2015, when the reservoir's level was at 59 percent of the historical average; the right image shows the reservoir in April 2017, with the level at 114 percent of the average. SOURCE: NASA, April 21, 2017, https://earthobservatory.nasa.gov/IOTD/view.php?id=90062.

tistically based forecasts on average perform acceptably well, but occasionally generate errors of nearly a factor of two (Dozier, 2011). Therefore, estimating the spatial distribution of SWE in mountainous terrain, characterized by high elevation, steep slopes, and spatially varying topography, is an important unsolved problem in mountain hydrology.

Coupled with the problem of knowing the total quantity and spatial distribution of the snow accumulation are measuring and predicting its rate of melt, relating the rate of melt to environmental drivers, and the consequences of the rate and distribution of melt for water resources, glaciers, and ecosystems. The main drivers, absorption of solar and longwave radiation, vary with the solar geometry, atmospheric scattering and absorption, and illumination variability caused by topography (Marks et al., 1992; Marks and Dozier, 1992). Estimating these surface fluxes is also crucial to Objective H-1a, which requires addressing the components of the surface energy balance. As with any process driven partly by absorbed solar radiation, variability in snow albedo causes variability in the rate of melt.

For surfaces with high albedo (α), an error in the measurement of albedo leads to a greater proportional error in absorption of the solar radiation (absorption = $1 - \alpha$, so for greater values of α closer to 1.0, a small error in α causes a greater proportional error in $1 - \alpha$). Changes in snow albedo are tied to changes in snow microstructure, specifically grain growth that reduces snow albedo at wavelengths beyond about 1 μm, and contamination by absorbing aerosols like dust and soot (Warren, 1982). These issues are included in the discussion of Objective H-2b.

H-2: Prediction of Changes

Question H-2. How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally, and globally, and what are the short- and long-term consequences?

Objective H-2a. Quantify how changes in land use, water use, and water storage affect evapotranspiration rates, and how these in turn affect local and regional precipitation systems, groundwater recharge, temperature extremes, and carbon cycling.

Humans have altered the landscape by changing the vegetation cover over centuries, but with increasing intensity over the latest decades. As a result fluxes in the water cycle have already changed. Specifically, the evapotranspiration flux and the terrestrial surface water budget have changed dramatically over the historical record as a result of human alteration of the landscape. Because sensible and latent heat fluxes are fundamentally coupled by thermodynamics, these changes have already had significant impact on the terrestrial surface energy budget, including surface temperature and outgoing longwave radiation.

The large enthalpy of vaporization (2.5×10^6 J/kg) makes the latent heat flux due to evaporation a major term in the surface energy balance. Only one-fifth of the solar energy available to the Earth system is directly absorbed in the atmosphere. Half of the solar energy is first absorbed by the surface, and then latent heat flux and longwave radiation transfer it to the atmosphere. The latent heat flux is the most efficient dissipation mechanism available to return the surface to thermodynamic equilibrium upon solar forcing, and a major mechanism in zonally redistributing energy from the tropics, including the tropical oceans, to the higher latitudes. Latent heat flux and variations in it due to limiting factors over land such as availability of soil moisture are thus a major factor in the thermal forcing of the atmosphere at its base. It is also a source of moisture for the atmosphere that plays an important role in the formation of clouds, development of convection, and ultimately precipitation from local to regional scales (Aragão, 2012; Sun and Barros, 2014). By its control over buoyancy generation and moisture supply at the base of the atmosphere, evapotranspiration has a large influence on maintaining regional climate and affects the evolution of weather (Betts et al., 1996). In turn, small changes in the magnitude, seasonality and intermittency of precipitation and radiation can be magnified in the evapotranspiration signal. As a result, the future of evapotranspiration under a changing atmospheric composition may be even more uncertain. Because evapotranspiration is also a key conduit for biogeochemical substances, it is also critical to Earth's biogeochemical cycle.

Understanding how evapotranspiration has already changed and what consequences its changes have on ecosystems' health, crop productivity, and climate are priority questions in Earth system science (Bondeau et al., 2007; Canadell et al., 2000; NRC, 1999). Despite the importance of quantitative informa-

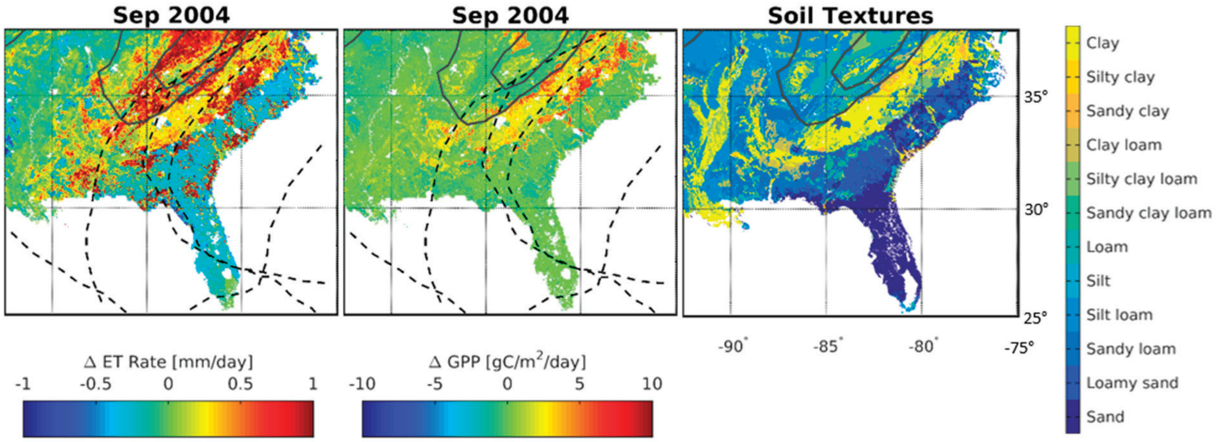

FIGURE 6.7 Differences in ET (right panel) and GPP (midpanel) for model simulations with and without the contribution of precipitation produced along the trajectories (black dashed lines) of land-fallen hurricanes (tropical cyclones, TCs) in the southeastern United States during September 2004. Differences are calculated as monthly averages of (with-without) simulation results. The right-hand panel shows the distribution of dominant soil texture over the region. Spatial resolution is 4 km × 4 km. Notice the significant impact of TC precipitation on GPP and ET in the Piedmont region, where shallow clay-rich soils predominate, and thus soil water storage in the root zone is limited. SOURCE: Lowman and Barros (2016). Reprinted with permission; copyright 2016, American Geophysical Union.

tion on this flux and its historical change, only imperfect measurements—in situ or by remote sensing—provide estimation and mapping of evapotranspiration over regional or global areas.

The water and carbon cycles are tightly linked via complex nonlinear feedbacks (Figure 6.7). Vegetation type and condition determine surface radiative properties (e.g., albedo) and root zone soil moisture uptake, and in turn root zone soil moisture availability modulates stomatal conductance, and consequently evapotranspiration (ET), and photosynthesis, and consequently gross primary productivity (GPP). The photosynthesis process governs the metabolism of plants, and it links the loss of vapor from the plant and the gain of carbon for biomass growth from the atmosphere. ET and GPP exhibit large spatial variability with topography, soil type, and land use, as well as large seasonal and interannual variability with precipitation, especially during the warm season (Lowman and Barros, 2016; Yang et al., 2015).

Quantifying evapotranspiration and understanding its linkages is a grand challenge for Earth system science in the coming decade, given the following principles and observations:

- The central role of evapotranspiration in coupling the global water, energy and biogeochemical cycles;
- The importance of the flux to the health and productivity of natural and agricultural ecosystems;
- The already-realized several-fold changes in evapotranspiration through human alterations of the landscape;
- The potential for amplification of these changes under climate change; and
- The paucity, or total lack, of any direct estimates of evapotranspiration regionally and globally.

The rates and spatial patterns continue to change as humans further modify the physical landscape and alter the vegetation cover. To understand their historical change, current state and future outlook, a more complete understanding of the processes that drive variations in these fluxes is essential.

Basic questions include the following:

1. How do the rates of evapotranspiration respond to human alterations to the physical landscape and vegetation cover and to shifts in climate and its seasonality? These changes remain as gaps in our knowledge of how the Earth system works. Understanding them is essential if we are to become better stewards of the terrestrial biosphere that we have appropriated so pervasively. Evapotranspiration flux can experience changes that amplify shifts in the precipitation and radiation forcing. Knowledge of changes in their magnitude and regional patterns in the future are critical to understanding the impacts of climate change.
2. How does the rate of evapotranspiration respond to changes in precipitation and radiative forcing? These rates are not understood, and they are a source of uncertainty in assessment of climate change impacts (NRC, 2012). Evapotranspiration is a flux at the land-atmosphere interface. Its spatial variations are strongly related to soil type, topography, vegetation, and climate. Their dynamics are affected by the variations in plant growth, weather and seasonal climate. To adequately characterize them, mapping at tens to hundreds of meters and temporal sampling at days to a week are needed at minimum (NRC, 2004). In situ monitoring is not a viable approach for collecting the required data. Observations are needed that span large areas, because installing and maintaining instrumentation at even a single site is costly and challenging (Baldocchi et al., 2001). In this regard, the upcoming ECOSTRESS mission provides a pathway to long-term, spaceborne measurements needed for high-resolution evapotranspiration estimates and to improve the remote sensing algorithms relying on the relationship between land-surface temperature (LST) and evapotranspiration.

Also as a flux, evapotranspiration cannot be directly sensed, as the rates do not uniquely correspond to the thermal or dielectric state of the soil and the vegetation at one level. Rather, they are controlled by vertical and temporal gradients of state variables. Soil moisture is the fundamental state variable that directly controls evapotranspiration (Pollacco and Mohanty, 2012). Vertical gradients in soil moisture drive evapotranspiration and water availability to plant roots. Vertical profiles of soil moisture need to be measured or estimated via integrated models and observations systems (e.g., H-1a) in order to allow estimation of evapotranspiration. SMAP measures soil moisture in the top 5-10 cm and has enabled understanding of links between precipitation, surface soil moisture, and energy fluxes at very coarse spatial scales (10 s km). Information about the top meter of the soil at spatial resolutions that capture the spatial variability in precipitation, energy fluxes, and shallow subsurface flows would enable closing the water budget, including water use by vegetation in the root zone.

Objective H-2b. Quantify the magnitude of anthropogenic processes that cause changes in radiative forcing, temperature, snowmelt, and ice melt, as they alter downstream water quantity and quality.

Snow is the brightest land cover in nature. In the solar spectrum, snow has a distinctive spectral signature—among the brightest natural substances in the visible wavelengths, reduced slightly in the near-infrared beyond 1 μm, and dark beyond about 1.6 μm in the shortwave-infrared—corresponding to the variability in the absorption properties of ice (Warren, 1982; Warren and Brandt, 2008). In the visible wavelengths, both ice and water are transparent to radiation, whereas in the shortwave-infrared both are strongly absorptive. Because snow is so distinctive, mapping of snow-covered areas was one of the first applications of remote sensing in the hydrologic sciences (Lettenmaier et al., 2015), and the combination of visible and shortwave-infrared bands enables discrimination between snow and clouds (Crane and Anderson, 1984).

Characterization of snow and its rate of melt is critical for understanding the Earth system, and its role in regional hydrology for those river basins where people depend on snow- or glacier-melt for water resources. Snow's high but variable albedo and low thermal conductivity together sustain stability of the boundary layer over vast regions (Levis et al., 2007). Our understanding of the strength of the simulated snow albedo feedback, however, varies by a factor of three in global climate models (Lemke et al., 2007), mainly attributed to uncertainties in snow extent and the albedo of snow-covered areas from imprecise remote sensing retrievals (Flanner et al., 2009; Fletcher et al., 2009). Snow cover and its melt also dominate regional hydrology over much of the world. Not only does one-fifth of Earth's population depend on snow- or glacier-melt for water resources, people in these areas generate one-fourth of the global domestic product (Barnett et al., 2005). While long-term observations in many mountain ranges worldwide show a declining snowpack attributable to global warming (Mote et al., 2005; Shekhar et al., 2010), and thus declining glaciers caused by the overlying snow melting earlier in the spring, an equally important anthropogenic contribution lies in the increase in carbonaceous aerosols from combustion and dust from land degradation, darkening the snow and causing its warming due to greater absorption of solar radiation that accelerates melting (Kaspari et al., 2014; Painter et al., 2007; 2013). Earlier snowmelt also warms the climate indirectly by changing terrestrial radiative properties (albedo and emissivity) by earlier exposure of the underlying soil and vegetation. Locally, forest fires yield a source of charcoal that affects snow albedo for many years following the fire (Gleason et al., 2013). Earlier snowmelt affects the seasonal distribution of streamflows, along with the quality of that water, depending on the wet and dry atmospheric deposition of particles and chemicals into the snowpack (Williams and Melack, 1991a, b). Moreover, management of forests implies management of water—for example, in warmer climates, forest thinning retards the rate at which snow disappears (Lundquist et al., 2013).

For these reasons, understanding and managing water from snow- and glacier-dominated basins requires tracking the energy sources that melt the snow and thereby the spatiotemporal distribution of snow and ice properties, especially its albedo as it varies with grain size and presence of absorbing aerosols (Warren, 1982), dust, and rock debris. The same processes govern the health of glaciers that comprise the iconic features of many areas of the world, as they incorporate the history of snowfall during the accumulation season and snow- and ice-melt during the ablation season.

Objective H-2c. Quantify how changes in land use, land cover, and water use related to agricultural activities, food production, and forest management affect water quality and especially groundwater recharge, threatening sustainability of future water supplies.

Agricultural activities involve the conversion of preexisting land uses into pasture or crops, and in many parts of the world, entail managed forest clearing. Most of the heavily irrigated regions were converted from grasslands or from other nonforested systems. Specifically, the impact of conversion of native land to agriculture alters the terrestrial water cycle in both quantity and quality. These changes in the land use and land cover affect infiltration, surface runoff, recharge to the groundwater, water quality, sediment loss, and surface albedo, as well as affecting the temporal dynamics of all of these processes. The water quality variables affected include erosion and sediment loss, total dissolved solids, nitrogen in the forms of nitrate or nitrite, and phosphorus.

Impacts to the hydrologic cycle differ in nonirrigated and irrigated systems. In the nonirrigated, rain-fed case, the water input to the land does not change appreciably except due to weather and climate variability and change. Evapotranspiration, however, may increase or decrease due to changes in the vegetation water demand, as well as rising temperatures and wind forcing due to climate change, thereby affecting groundwater levels, and in turn, streams and other groundwater-dependent ecosystems. The changes can be significant but difficult to determine, making unclear the cause-effect links between land use change and water quantity and quality. A particular challenge in rain-fed systems is the difficulty of resolving the precipitation and evapotranspiration sufficiently accurately to estimate groundwater recharge. As in natural ecosystems, the error in evapotranspiration measurements or estimates often exceeds the magnitude of groundwater recharge, a challenge to coupling surface and subsurface hydrologic processes.

Much of the world's food supply comes from irrigation in dry to moderate climates. Consequently, by far most of the water diverted, impounded, or pumped by humans is for irrigated agriculture (Wada et al., 2013; 2014). Accordingly, irrigated agriculture has created massive dislocations in water stores and disruptions in the hydrologic cycle, as documented by GRACE (Richey et al., 2015), with the record expected to continue with GRACE-Follow On (GRACE-FO). In systems where substantial surface water is available such as California, diversion of surface water for irrigation has caused massive increases in recharge and rising groundwater levels (Faunt et al., 2009; Williamson et al., 1989). In irrigated areas of California where groundwater pumping is not sufficiently high, elevated groundwater levels have caused soil salinity problems akin to those that caused the collapse of agriculture in Mesopotamia by circa 2300 BCE. Conversely, in many other areas of California, excessive, uncontrolled pumping of groundwater has caused groundwater deficits and the attendant undesirable effects, including land subsidence, nonsustainable storage depletion, water quality degradation and increased energy costs (Cannon Leahy, 2016).

The preceding themes, where irrigated agriculture causes either waterlogged soils or nonsustainable groundwater depletion, have been rather common occurrences throughout the world, including the Great Plains and southwestern United States, North China Plain, India, North Africa, South Africa, Australia, and so on. Concomitant with the agricultural water quantity problems are ongoing degradation in groundwater quality owing to salt, nitrate, and other contaminants inherent to agricultural practices. Worldwide, increasing difficulty in sustainably managing water quantity and quality, whether in the subsurface or on the surface, remains a major challenge to soil conservation, food production, and the future of human civilization. This worsening situation calls for combined management of surface water and groundwater that is possible only through advanced, multiscale measurement of all the major water stores and the fluxes between them, with special emphasis on groundwater stores, evapotranspiration, precipitation, recharge, and surface water flows.

While recharge in irrigated regions is reasonably well estimated based on knowledge of crop-water demands, amounts of applied water, and irrigation efficiencies, estimation of recharge in nonirrigated lands is much more challenging. There are several studies on recharge quantification. Scanlon et al. (2006) studied recharge in 140 sites in semiarid and arid regions using the chloride mass balance technique. They found a longer scale variability of recharge rates that depends on El Niño/La Niña and other atmospheric and oceanic variability, and that in relatively warm arid and semiarid regions with thick vadose zones, little or no upland recharge occurs due to native plant adaptation and thermal gradients forcing water vapor upward. Furthermore, regional hydrogeology and the spatial organization of preferential recharge zones and pathways vis-à-vis precipitation patterns play an important role in redistributing groundwater regionally in space and time at multiple scales (Barros et al., 2017). Concentration of runoff in ephemeral channels or areas of high infiltration rates or karstic zones are necessary to overcome thermal gradients and low conductivities and high suctions in unsaturated zone soils (Coes and Pool, 2007; Goodrich et al., 2004; Scott et al., 2000).

Scanlon et al. (2007) carried out a comprehensive study of the impact of agriculture on water resources, both water quality and quantity. In some instances the conversion of native vegetation to croplands could increase the recharge to the aquifers but degrade the water quality. However, the exact nature of this balance depends on the type of vegetation being replaced. In general conversion to agriculture increases the consumption of water and decreases streamflow and raises the water table and in some regions of the world causes waterlogging. However, groundwater-fed irrigation generally lowers the water table in many parts of the world (Northern India, High Plains and Central Valley United States). As observations for estimation of changes in the terrestrial water cycle owing to conversion of land cover from native to agriculture are limited, there has been a use of models such as the Soil Water Assessment Tool (SWAT) to study this issue (Arnold and Fohrer, 2005), and the Variable Infiltration Capacity (VIC) model has been used in the Great Lakes Region to study the impact of the conversion of forests and prairie grasslands to agriculture (Mao and Cherkauer, 2009). One of the earliest and most influential studies (Allan et al., 1997) emphasized the joint management of land and water and the fact that the two were deeply connected, and that the fractional area of agricultural land within a catchment was the best indicator of streamwater quality (higher sediment and nutrient concentrations) based on a study of the River Raisin Basin in southeastern Michigan using a 20-year (1968-1998) study period. Similar land use impacts have been observed in water chemistry (phosphorus P, nitrogen N, and total dissolved solids TDS) in the Saginaw Bay catchment of Central Michigan (Johnson et al., 1997). Phosphate and nitrate in agricultural fertilizer and TDS are mobilized during storms due to the erosive nature of the rainfall impact, which dislodges the soil, and they end up in surface runoff (Hart et al., 2004; Ahearn et al., 2005), thus linking regional weather and climate, precipitation physics, and water quality.

H-3: Availability of Freshwater and Coupling with Biogeochemical Cycles

Question H-3. How do changes in the water cycle impact local and regional freshwater availability, alter the biotic life of streams, and affect ecosystems and the services these provide?

One of the biggest challenges facing human society is the availability of freshwater where it is needed, when it is needed. In fact, at times there is lack of water (droughts) and yet at other times there is too much water (floods). Global climate change, population and economic growth, land use change, water quality degradation, and aging infrastructure are altering water availability and demand equilibrium at every scale (Sun et al., 2008; Padowski and Jawitz, 2009; Ajami et al., 2014; Hering et al., 2013). Coping with these changes and enhancing adaptive capacity of any region relies on informed and sustainable management of our limited water resources. Access to high-resolution (both spatial and temporal) water quantity and quality data is key in enabling integrated water management and enhancing local human and ecosystem health.

Objective H-3a. Develop methods and systems for monitoring water quality for human health and ecosystem services.

While water availability, environmental and ecosystem health, and social and economic well-being are directly affected by water quantity and quality, current Earth observation missions are not fully equipped to measure the quality of inland water bodies such as lakes, rivers, reservoirs, and estuaries, at an appropriate temporal and spatial scale, and enabling technology is still lacking. In addition, there are many water quality indicators that vary independently while having a combined effect on the remote sensing signals (Ampe et al., 2015). This phenomenon makes the sensing process much more complex and in need of methodologies that could invert gathered signals to effectively infer the accurate information (Chang et al., 2015). In recent years there have been some attempts to infer water quality data and map related environmental and biogeophysical processes using the mosaic of available remotely sensed measurements (Usali and Ismail, 2010; Chang et al., 2015; Fichot et al., 2015; Ampe et al., 2015). However, these are limited in size and scope and they still need in situ data to establish and validate the inference methodology.

To advance water quality sensing from space we need to understand (1) the availability and potential utility of various sensing approaches (visible, infrared, and microwave) and how these technologies can be combined to monitor and measure water and ecosystem dynamics; (2) the temporal and spatial scales governing process dynamics and the measurement resolution needed to inform the decision-making process at the local level; (3) the availability of inversion methodologies that have to be developed to leverage satellite data more effectively; and (4) the cost-benefit analysis of remote-sensing strategies (e.g., drones) alternative to space missions.

Objective H-3b. Monitor and understand the coupled natural and anthropogenic processes that change water quality, fluxes, and storages, in and between all reservoirs (atmosphere, rivers, lakes, groundwater, and glaciers), and the response to extreme events.

In many parts of the world, complete transformation of land cover including deforestation, extensive row crop agriculture, and urbanization are affecting the eco-hydrology at local, regional, and continental scales. Change of fluxes and storages, and the transport and residence times of water in the terrestrial part of the landscape, in the streams, and in the subsurface affect bio-geochemical processes and impact water quality and stream biology. A prime example is the midwestern United States, where intensified row crop agriculture—mainly corn and soybeans providing 40 percent of the global supply—along with drainage of wetlands and the extensive subsurface tile drainage system needed to keep the plant roots dry during the growing season, has increased streamflow volumes and peaks (Guanter et al., 2014), which together with increased precipitation over the past decades (Groisman et al., 2012) have accelerated near-bank erosion, and increased nutrient loads contributing to the Gulf of Mexico hypoxia (Blann et al., 2009; Belmont et al., 2011; Novotny and Stefan, 2007; Schilling et al., 2010; Zhang and Schilling, 2006; Foufoula-Georgiou et al., 2015). Similar changes are observed in coastal areas where climatic and human impacts (e.g., sea-level rise and local and upstream basin development that reduce water and sediment to the coast, accelerating subsidence) contribute to increased saltwater intrusion, coastal erosion, degradation of protective vegetation and marshes, and decline of unique biodiversity (Ericson et al., 2006; Syvitski et al., 2009; Tessler et al., 2015).

Remote sensing observations of multiple coupled variables are needed therefore to achieve Objective H-3b (e.g., rainfall, soil moisture, photosynthesis, sediment/water interfaces, river migration rates, water stages, and vegetation composition) at spatial and temporal scales appropriate for detection of trends, local predictive modeling, and mitigation actions on the ground including urban expansion, deforestation, and agricultural practices. Collecting such comprehensive data sets, which is prohibitive on the ground, is necessary to understand and model the coupled human-natural system in an integrated Earth systems modeling perspective. Of special interest is the effect of extremes on the eco-hydrologic trajectories of landscapes at seasonal, annual, and multidecadal time scales and implications for global water cycling, landscape connectivity, and carbon storage.

Objective H-3c. Determine structure, productivity, and health of plants to constrain estimates of evapotranspiration.

The components of evapotranspiration include (1) transpiration from plants; (2) rain or snow intercepted by the plant canopy that subsequently evaporates or sublimates; and (3) evaporation from the soil surface. Plant species, structure (individual and within a complex stand with understory), leaf area, and stomatal density all affect transpiration and interception. Improved knowledge of plant structure and its change over time (productivity and health) will therefore translate directly into improved estimates of evapotranspiration. Spectral remote sensing and associated retrieval methods have proven successful in identifying monoculture or spatially dominant plant species with automatic and supervised classification algorithms. Likewise, numerous vegetation indices have been developed to successfully identify plant chlorophyll, photosynthetically active vegetation, plant vigor, and the phenological cycles of annual and deciduous plant species (Huete et al., 2002).

Spectral methods have had less success in complex multispecies stands where overstory shading, interwoven branches, and understory plants are present. In these instances leaf area index (LAI) and surface roughness affecting canopy conductance are not well estimated (Dingman, 2014). Even within a monoculture stand, the LAI of some species such as cottonwood (*Populus fremontii*) cannot be accurately estimated with spectral remote sensing, and allometric relationships change with tree age (Farid et al., 2006).

Multireturn and waveform lidar can address many of the shortcomings of spectral-based remote sensing noted earlier. Lidar employs a laser system on a platform that transmits laser pulses toward any object of interest at rates up to hundreds of thousands per second. The laser energy interacts with the object (e.g., vegetation, terrain, and structures), and some of the energy is reflected back toward the lidar receiver. If the position and orientation of the moving or stationary lidar instrument platform is known in time and space, the *x*, *y*, and *z* coordinates and return intensity of the reflected portion of the laser pulse can be determined. Airborne, spaceborne, mobile, drone-based, and terrestrial laser scanning systems are advancing rapidly (Jensen, 2006; Lefsky et al., 2002). One National Research Council study concluded (NRC, 2007b) that lidar should be acquired over the entire continental United States based solely on the benefits to improved flood plain mapping for the Federal Emergency Management Agency (FEMA) Map Modernization program.

Lidar has been used extensively for forest inventory and structure (Lim et al., 2003), biomass and carbon stocks (Asner et al., 2012), estimation of LAI (Korhonen et al., 2011), and to constrain and improve evapotranspiration estimates (Farid et al., 2008; Mitchell et al., 2012). More recently, single-photon and Geiger lidar are being employed in nondefense applications. These new systems split a single laser pulse into numerous subpulses, which are then detected with segmented detectors. They offer higher effective pulse rates (~200 million samples per second) over linear-mode lidar (~500,000 samples per second) with lower power needs (1-2 W for single photo and 20-40 W for Geiger) (Jasinski et al., 2016). A single-photon lidar device is being deployed on the upcoming 2017 ICESat-2 mission in the Advanced Topographic Laser Altimeter System (ATLAS) instrument, with the primary goal of polar ice sheet thickness measurements (Abdalati et al., 2010). ATLAS will employ one laser split into six beams at roughly 10,000 pulses per second.

If advances in lidar technology can continue apace so that within 10 to 15 years, spaceborne platforms can provide the 20 to 30 return points per square meter that airborne platforms currently provide, a rich set of attributes on vegetation structure and productivity could be derived to constrain and improve evapotranspiration estimates. The additional benefits of these data to hydrology include improved topography for flow path and drainage derivations, surface water levels, snow depths, and near shore bathometry. Benefits to other disciplines would also be numerous, including landslide characterization, postfire erosion, and postfire recovery for hazards; carbon inventories for ecosystems; and ice volumes and depths for solid Earth.

H-4: Hazards, Extremes, and Sea-Level Rise

Question H-4. How does the water cycle interact with other Earth system processes to change the predictability and impacts of hazardous events and hazard chains (e.g., floods, wildfires, landslides, coastal

loss, subsidence, droughts, human health, and ecosystem health), and how do we improve preparedness and mitigation of water-related extreme events?

Objective H-4a. Monitor and understand hazard response in rugged terrain and land margins to heavy rainfall, temperature and evaporation extremes, and strong winds at multiple temporal and spatial scales.

This socioeconomic priority depends on the success of addressing Objectives H-1b, H-1c, H-2a, and H-2c. Natural disasters pose major threats to the livelihood and security of millions of people worldwide. Increasing trends of natural disaster impacts can be linked to amplification of the hydrologic cycle from climate-related events (Field et al., 2012), dramatic changes in land use and land degradation, and overpopulation in at-risk areas (e.g., coastlines, river margins, estuaries and deltas, mountainous regions) (Oki and Kanae, 2006). Recent estimates indicate that over 88 percent of natural disasters are water related (Adikari and Yoshitani, 2009) and are one of the greatest global threats to socioeconomic development. Depending on the nature and location of the event, the number of people affected by natural hazards can range from hundreds to thousands (e.g., landslides), to several million (e.g., regional flooding and agricultural drought). Lasting impacts of natural hazards include significant damage to infrastructure, land degradation, loss of life, economic loss, disease, and combinations thereof.

Sustainable risk reduction of natural hazards consists of prevention and preparation as well as mitigation and response. Thus, it requires not only proper characterization and understanding of the events themselves, but also sufficient modeling and prediction of the processes that underlie and drive the hazards. Given the nature of water-related disasters, impacts from too much or too little water can result in a wide array of events, including coastal and lake floods, flash floods, hurricanes, landslides and avalanches, subsidence, agricultural droughts, and waterborne epidemics. A key question to understanding these events is: How does the water cycle interact with other Earth system processes to change the probabilities, magnitudes, and frequency of these events? To this end, improved understanding of the quantification of their dynamics and impacts is needed.

Hazard process monitoring and modeling in at-risk areas such as mountainous terrain and land margins such as coastlines, floodplains, deltas and estuaries, and land-water interfaces generally is particularly needed. Some key measurement variables common to these Earth system process and water-related hazards include precipitation, soil moisture, snowmelt, water depth, water flow, and atmospheric water vapor (for monitoring and predicting certain weather conditions). The ability to measure these variables at the temporal and spatial scales consistent with event dynamics is crucial for improved hazard response. For example, severe thunderstorms can be on a local (1-10 km) spatial scale and can evolve in a matter of minutes (Schmidt et al., 2009; Mathew et al., 2014). On the other hand, several slow-onset drought events have occurred in the past decade (AghaKouchak et al., 2014; Long et al., 2013), with magnitudes and intensities leading to regional and long-standing (months to years) impacts.

Several applications of Earth observations exist for improved hazard mitigation. In mountainous regions, frequent measurements of near-surface soil moisture and of snow water equivalent (SWE) coupled with physically based models can improve landslide susceptibility mapping by estimating antecedent soil moisture conditions and snowmelt and isolating the triggers for the onset of spring season landslides. Regular monitoring of streamflow can enable improved management of risk and water strategies in flood-prone areas. Evapotranspiration has been shown to be a critical hydrologic variable for capturing drought magnitude, intensity, and timing (Anderson et al., 2011; Fisher, 2014). At low elevations, along the land margins of the world's major rivers and coastlines, surface water elevation measurements from the Surface Water and Ocean Topography (SWOT) mission can potentially improve inundation mapping as well as serve as boundary conditions for high-resolution models of rivers, storm surges, and coastal circulation.

In addition to providing increased hazard security and forecasting, key questions to be addressed by the implementation of Earth observations needed for monitoring and modeling hazard response include the following:

- How are changes in land use affecting evapotranspiration rates, and how do these in turn affect local and regional precipitation systems, temperature extremes, and carbon cycling?
- How does the water cycle interact with other Earth system processes to change the probabilities and impacts of hazardous events and hazard chains such as floods, wildfires, landslides, coastal loss, subsidence, droughts, and human and ecosystem health?
- How do we improve preparedness and mitigation of water-related extreme events using measurements and integrated observing systems and models?
- Can we improve our understanding of trigger mechanisms to improve predictions for all hazards and flooding and landslides—in particular, in headwater basins and along land margins?
- How do we improve our understanding of post-hazard landscape response using integrated systems and models toward more effective recovery and preparedness?

Objective H-4b. Quantify key meteorological, glaciological, and solid Earth dynamical and state variables and processes controlling flash floods and rapid hazard chains to improve detection, prediction, and preparedness.

This socioeconomic priority depends on the success of addressing Objectives H-1b, H-1c, and H-4a. Floods and other hazards, like landslides, can devastate communities. In 1999, combined flash floods and landslides claimed the lives of 30,000 Venezuelans, displaced an additional 110,000 residents, and destroyed 23,200 homes (IFRC, 2000). In July of 2012, a 7 m wall of water raced through the town of Krymsk in southern Russia, killing 170 people and displacing 13,000 (Russia Today, 2012). Increased risk of persistent and intermittent inundation due to increased runoff in flat terrain is linked to increased storm activity, sea-level rise, and storm surges, within the context of coastal landscapes hardened by built infrastructure; the resulting increased risk of persistent and intermittent inundation poses a significant societal challenge (Tebaldi et al., 2012; Hallegatte et al., 2013).

Figure 6.8 shows how predicted sea-level rise interacts with storms to increase the probability of catastrophic coastal floods in Boston. In the United States, the 2015 damages from flash floods reached $2.1 billion, with 129 deaths (NOAA, 2015). While other flooding hazards have a broad impact on U.S. society, flash floods are the ones that consistently kill more people (Ashley and Ashley, 2008). Figure 6.9 provides a synopsis of reported flashflood occurrences over a 5-year period in the continental United States. Rainfall-induced landslides are equally destructive. The U.S. Geological Survey (USGS) estimates that the annual cost of landslides in the United States is between $2 billion to $4 billion and that 25 to 50 people are killed by them (USGS, 2016). Worldwide, between the years 2004 and 2010, 2620 deadly landslides killed 32,000 people (Petley, 2012); though not all were rainfall induced, the great majority were.

Flash floods and shallow, rainfall-induced landslides are caused by high-intensity, high-volume precipitation events coupled with the proper hydrological scenario, which is defined by current soil moisture; the slope, shape, and soil types of the basin; the impervious region in the basin; and the built drainage structures of the basin. As our climate warms, the hydrologic cycle is shifting toward an overall increase in heavy precipitation events across the United States (2005; Groisman et al., 2004). The risk of and impact of flash floods and landslides increases with the frequency of intense or long-duration precipitation.

Figure 6.10 shows the global distribution of landslide occurrences overlying a global landslide susceptibility map (Kirschbaum et al., 2009). Because both hazards depend on precipitation and the physiographic

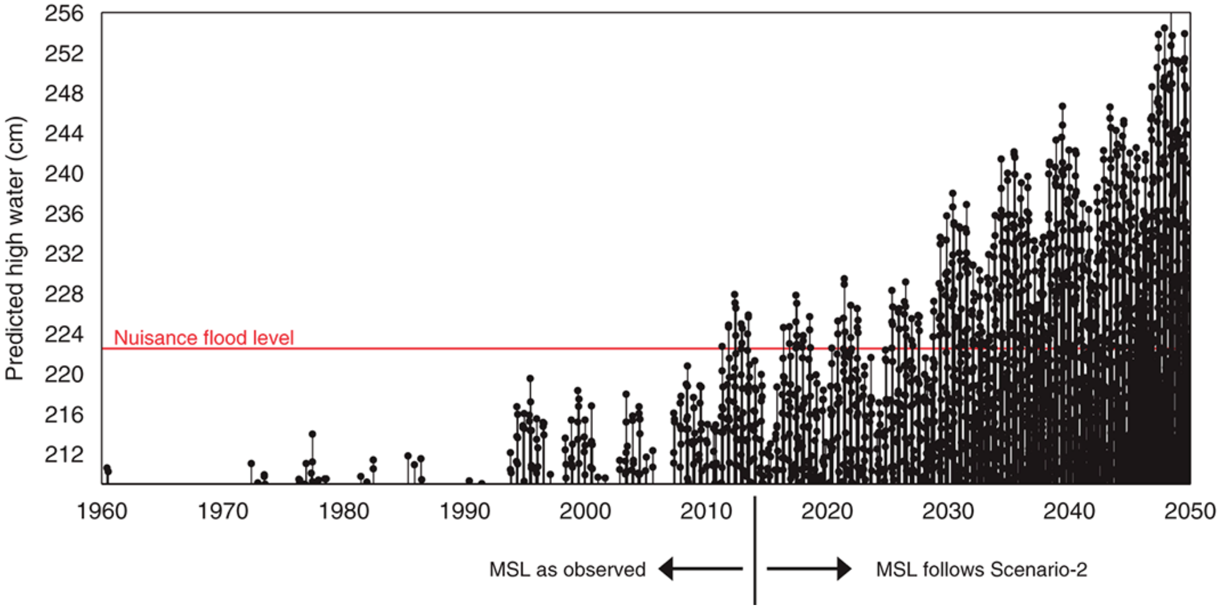

FIGURE 6.8 Predicted high tides at Boston near or exceeding the "nuisance flood" level of 68 cm above mean high water, and their relationship to sea-level rise. Before 2010 the tides alone never exceeded flood levels; from 2011 onward, and likely into a future climate, sea level has risen and will rise sufficiently that tides alone can produce nuisance (i.e., frequent low-impact flooding). Catastrophic flooding that results in system failure can occur if a storm occurs on top of a high tide. SOURCE: Ray and Foster (2016).

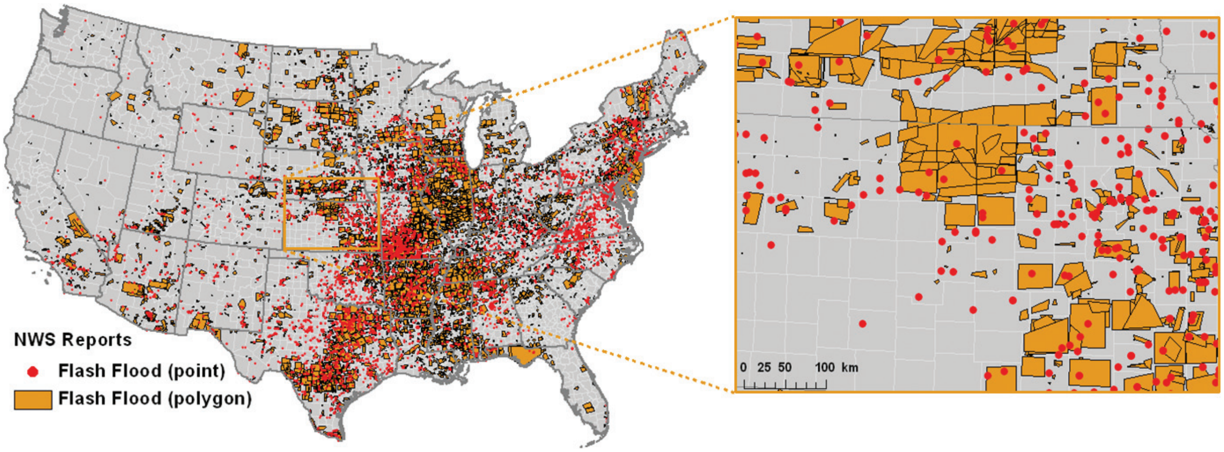

FIGURE 6.9 National Weather Service reports of flash flooding from October 1, 2006, through December 31, 2011. Flash flood points correspond to river gauge locations; polygons represent areas impacted by the flash flood, often coinciding with county boundaries. Note that flash floods are largely underreported, as many occur in ungauged basins, which frequently are not populated. SOURCE: Gourley et al. (2013).

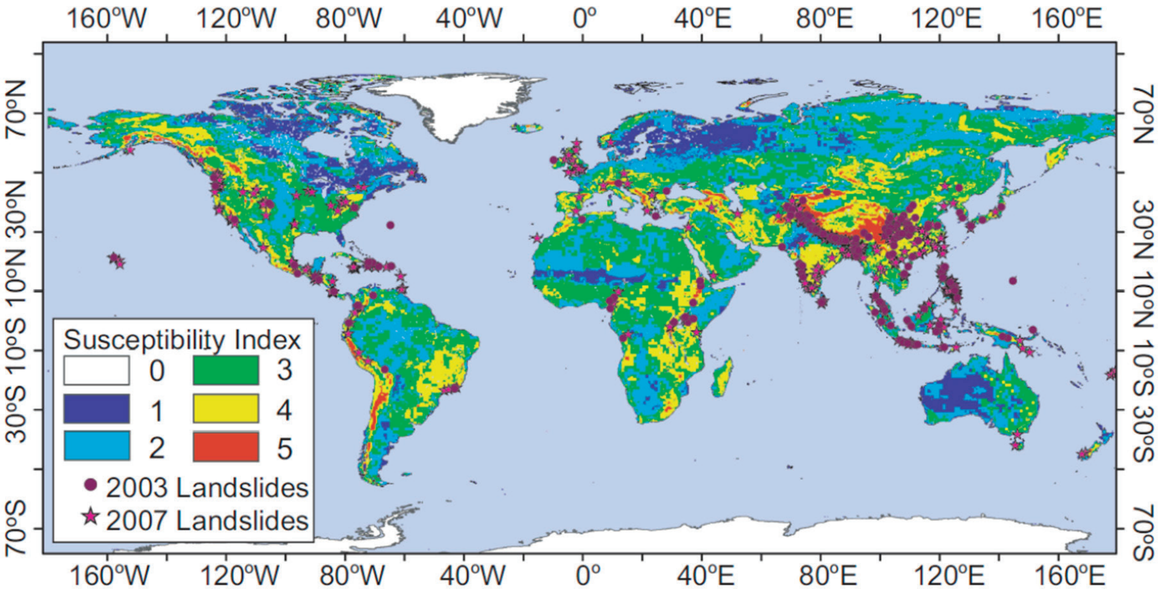

FIGURE 6.10 Global landslide susceptibility index (Hong et al., 2007) plotted with 2003 and 2007 landslide inventory data. The index integrates slope land cover change, geology, and road presence, and operational nowcasts of landslide potential are made by checking whether 1-day, 3-day, and 7-day precipitation intensity thresholds and accumulations are met. Further details and up-to-date forecasts are available at https://pmm.nasa.gov/precip-apps. SOURCE: NASA (2017).

characteristics of a region, both offer the possibility of mitigation through Early Warning Systems based on observed and forecast precipitation intensity coupled with a model of regional topography, geology, and land use and land cover (Gourley et al., 2011; Hong et al., 2007; Hossain, 2006; Sättele et al., 2015). Although uncertainty in estimating precipitation intensity in mountainous regions, as well as ambiguity with regard to the definition of susceptibility index classes, pose challenges to forecast skill, this methodology was used to increase situational awareness to the U.S. Army and its partners during the Peruvian floods and landslides in 2015-2016 linked to a strong El Niño. NASA Global Precipitation Measurement (GPM) satellite precipitation estimates are already being used for flood and landslide nowcasting purposes and to quantify risk (Kirschbaum et al., 2015; Stanley and Kirschbaum, 2017; Wu et al., 2014). Further, these models can be coupled to hyper-resolution physically based models to pinpoint hotspots of slope instability and warnings (Tao and Barros, 2014b).

While an Early Warning System cannot stop a 7 m wall of water from descending upon a city, an Early Warning System can provide the lead time necessary for people to move out of harm's way. As noted by Di Baldassarre et al. (2010), Early Warning Systems were critical in reducing the impacts of floods in India and the Czech Republic. An effective Early Warning System depends on informative input data and a model that uses that data to project into the future. Improving the predictability of the flashy events will depend on improving the measurements of the input data as well as improving our understanding of the processes that control these phenomena and so improve our predictive models. Near-real-time (i.e., latency depends on telecommunications or post-processing) monitoring—such as the WMO Global Telecommunications System (WMO, 2017), the Global Flood Monitoring System (GFMS, 2017), the Dartmouth Flood Observatory (DFO, 2017), and the Global Flood Detection System, part of the Global Disaster Alert and

Coordination System (GDACS, 2017)—can update initial conditions and identify "Early Watch Regions" to which modeling efforts can be directed aiming at improving forecast lead times and situational awareness. Predictions and early warnings in mountainous regions remain the most challenging due to the difficulties of precipitation retrieval in complex terrain and the very rapid rainfall-runoff response in steep terrain. Tao and Barros, (2013) showed that by merging GPM-like observations with Quantitative Precipitation Forecasts (QPFs) from the National Forecast Database (NDFD), significant improvements (up to 50 percent) could be attained in the skill of Quantitative Flood Forecasts (QFFs) using physically based models, as long as revisit time is less than the response time of specific watersheds. Further, significant inroads toward longer warning lead times can be expected through coupled prediction frameworks and data assimilation systems to integrate forecasts and observations (Tao et al., 2016). Indeed, systems such as NOAA's Rapid Refresh (Benjamin et al., 2015) with assimilation of ground-based radar data every 15 minutes at present can be envisioned only for operations outside the continental United States by assimilating remote-sensing observations (e.g., satellite-based radar, as discussed in the section on Objective H-1b). Analysis of large observational data sets provides unique opportunities for developing targeted location-specific flood and debris flow forecasts with lead times of hours to days (Akhtar et al., 2009; Campolo et al., 2003; Kim and Barros, 2001; Sättele et al., 2015).

In many glacierized mountains, and Arctic lowland countries with glaciers, glacier thinning and retreat are causing the growth of glacial lakes. Glacier lake outburst floods are an important natural hazard in many of these places, such as Alaska, Greenland, Iceland, Peru, and Nepal (Bajracharya et al., 2007). Debris flows, ice and snow avalanches, landslides, and—on ice-capped volcanoes—lahars are frequent and sometimes deadly consequences of heavy precipitation and snow and ice accumulation on steep slopes. The interactions between the solid Earth and land cover and surface dynamics—for example, earthquake triggering of ice avalanches and landslides, landslide blocking of rivers, and consequent landslide-dammed lake outburst floods—can be strongly influenced by the preceding history of the thermal state and retreat of glaciers, or by the seasonal state of shallow groundwater saturation of soils and snow melting (Kargel et al., 2016).

Economically vital minerals and petroleum and gas extraction and transport from and through mountains and over lowland areas of permafrost and beside or across rivers, the routing pipelines, roads, and bridges, and the security of mountain villages and cities must consider the multitude of hazards due to rainfall runoff floods, snowmelt floods, glacier lake outburst floods, thawing permafrost, as well as glacier surges, landslides, snow and ice avalanches, and other physical elements and processes of the hydrogeological environment. The mountain hazard environment is changing around the world due to climate change as glaciers thin and retreat, snowpack and monsoonal precipitation patterns change, patterns and intensity of freeze-thaw processes shift, and vegetation communities are altered. Likewise, coastal hydrology in relation to rivers and lake and seacoasts is manifestly altered by the effects of climate change, floods, and land subsidence and uplift and general sea-level rise. The tracking of hydrologic and hydrogeological natural hazards requires optical and radar methods of monitoring changes to glaciers and glacier lakes, snowpack, rivers, lakes, and vegetation; thermal monitoring of volcanoes; and high-resolution topographic mapping. The large data sets produced by satellite monitoring argue in favor of reliable semiautomated and autonomous hazard detection and monitoring, hazard susceptibility mapping, and hazard forecasting and real-time warnings (Kirschbaum et al., 2016), along with development of reliable human networks to support uniform, standardized data analysis.

Because much of the world is not well instrumented, including many areas that are vulnerable to these high-impact episodic hazards, spaceborne, remotely sensed data are needed to provide the precipitation and antecedent conditions. As with other Hydrology Panel priorities, the measurement of worldwide precipitation, Objective H-1b, will be essential to enhancing our ability to predict flash floods and landslides.

The characterization of the antecedent conditions, both the fixed topographic variables and the dynamic variables like soil moisture, plant growth, and current river stage, will also be required, as is the case with Objectives H-3a, H-3b, H-4a, and H-4b. Good measurements need to be integrated into models to forecast the likely future precipitation and then the resulting surface processes that may (or may not) result in a flash flood or landslide.

Objective H-4c. Improve drought monitoring to forecast short-term impacts more accurately and to assess potential mitigations.

This socioeconomic priority depends on the success of addressing Objectives H-1b, H-1c, and H-2c. Droughts have significant economic and societal impacts. Unlike other extremes, their onset tends to be slow, their persistence long, and their recovery poorly predicted. Wilhite, (2000) estimated the average annual drought impact in the United States at $6 billion to $8 billion, while the 2015 severe drought in California was estimated to have $2.7 billion in damages in the agricultural sector alone (Howitt et al., 2015).

Compared to other natural disasters, a greater proportion of the population can be affected by droughts. Although droughts can have larger impacts on gross national products in the more developed countries, the magnitude of impacts on people's health and overall well-being is especially severe in less-developed regions. In Africa, droughts account for less than 20 percent of natural disasters but account for over 80 percent of the affected population (UNISDR, 2009). It is estimated that 300,000 people died in Ethiopia alone during the height of the Sahel drought in the early 1980s (EM-DAT, 2017) due to crop failure, lack of drinking water, and disease. Half a million people are estimated to have died because of drought-related impacts in Africa during the 1980s (Kallis, 2008). The impacts of drought are intimately linked to the vulnerability of a population to adverse conditions and how society responds within the constraints of changing economies. In general, loss of life is greater in developing regions, and the economic impacts are greater in the developed world. Timely determination from a drought early warning system and monitoring drought will aid the decision-making process in order to reduce drought impacts (Wilhite et al., 2007).

Drought is defined as a deficit (relative to an appropriately defined normal) of water in one or a combination of water stores (river, lake, reservoir, snowpack, soil water, or groundwater) or water fluxes (precipitation, evapotranspiration, or runoff). Depending on the water deficit, drought is usually classified as (1) meteorological (a negative departure from mean precipitation); (2) hydrological (a deficit in the supply of surface and subsurface water); or (3) agricultural (a deficit in soil moisture driven by a combination of meteorological and hydrological drought resulting in reduced supply of moisture for plants and crops). A variety of drought indices have been developed to reflect the various types of drought (Sheffield and Wood, 2011).

Observations of hydrologic variables needed to estimate drought indices are scarce over large spatial regions that are of interest for drought monitoring and management, especially in the developing world. Precipitation is one of the best observed variables although near-real-time gauge observations are limited in most regions outside the United States, and gauge networks are also sparse over much of the developing world (e.g., Africa). In situ soil moisture is one of the least observed aspects of the hydrologic cycle in terms of long-term, large-scale measurements. Thus, to overcome the deficiencies in in situ observation systems, remote sensing of precipitation (both liquid and solid) as well as soil moisture is necessary for early warning drought monitoring.

For meteorological drought, progress must be made on addressing Objective H-1b—namely, the improved monitoring of precipitation—and gaining knowledge on the predictability of rainfall at seasonal time scales. For many regions of the globe, winter snow provides the needed water supplies in the summer seasons. Thus, advances in the monitoring of mountain snowpacks, as quantified in Objective

H-1c, is required to make progress on predicting drought in snow-dominated water supply systems. Better monitoring of snowpacks and precipitation, when used with appropriate land-surface models, can help improve river flow predictions, and therefore hydrological drought. Improved predictions of inflows into water supply reservoirs are a key requirement for early warning and planning of such hydrological droughts.

For agricultural drought, soil moisture is the monitoring variable. There are currently four systems that provide soil moisture products at various spatial and temporal resolutions: MetOp with the advanced scatterometer (ASCAT) (Brocca et al., 2011; Wagner et al., 2013); JAXA's Advanced Microwave Scanning Radiometer 2 (AMSR2) with the C- and X-band passive radiometers on the GCOM-W1 satellite; ESA's Soil Moisture and Ocean Salinity (SMOS) L-band radiometer (Kerr et al., 2016); and NASA's Soil Moisture Active-Passive (SMAP) L-band radiometer and radar (Entekhabi et al., 2010). The preferred system is based on low-frequency microwave active and passive remote sensing where the radiometer provides measurements with high sensitivity but at low resolution and the radar provides high-resolution complementary capability. Airborne experiments have demonstrated that P-band measurements can provide potentially the basis for subsurface sensing of soil moisture in the root zone.

Objective H-4d. Understand linkages between anthropogenic modification of the land, including fire suppression, land use, and urbanization on frequency of and response to hazards.

This objective is linked to Objectives H-2a, H-2b, H-4a, H-4b, and H-4c. Humans have altered landscapes for centuries through development of the built environment, conversion of woodlands to agricultural lands, and more recently, through extensive forest management policies. Conversion of Earth's surfaces to alternative or highly structured land cover significantly alters land-atmosphere processes, and ultimately, can increase the risk of hazards to human populations. Fire suppression has been a significant goal of forest management policies since the 1920s, facilitating an increase in large wildfires across the western United States (Westerling et al., 2006). Warmer spring and summer temperatures, coupled with lower than average precipitation, have also produced longer wildfire seasons with more frequent and larger fires (Morgan et al., 2008; Westerling et al., 2011). Climate change is also expected to increase fire risk and may lead to changes in vegetation types and increased fuel loads (Spracklen et al., 2009; McKenzie and Littell, 2017). Wildfires impact water resources that are in high demand in the arid West. The acute loss of vegetation reduces infiltration and enhances soil water repellency and decreases soil cohesion and organic matter (Robichaud, 2000; DeBano, 2000), ultimately increasing runoff and the risk of flooding, excessive erosion, and debris flows (Rulli and Rosso, 2007; Ebel et al., 2012). Kinoshita and Hogue, (2011) documented elevated streamflow for 7 years after fire in southern California, while dry season flow increased for over a decade (Kinoshita and Hogue, 2015). Wildfires also impact water quality and threaten drinking water supplies (Smith et al., 2011; Stein et al., 2012; Burke et al., 2013). Nutrients associated with sediments (i.e., total phosphorous) increase in streams impacted by fire (Mast and Clow, 2008; Emelko et al., 2015). Studies on forest fires throughout the western United States and Canadian Rockies also show increases in nitrate concentrations in receiving waters after forest fire (Riggan et al., 1994; Earl and Blinn, 2003; Rhoades et al., 2011; Bladon et al., 2008).

Fire suppression policies, in conjunction with ongoing drought, have also caused extensive insect invasions in North America (Adams et al., 2012; Anderegg et al., 2013; Williams et al., 2010). The mountain pine beetle epidemic has affected conifer forests at historic levels (Raffa et al., 2008), with over 6 million hectares of forests in the United States and British Columbia impacted by bark beetles and more than 5 million ha affected by the mountain pine beetle (Meddens et al., 2012). This includes headwater catchments to the Colorado, Arkansas, Rio Grande, and Missouri Rivers. The progressive reduction in forest canopy due to bark beetle outbreaks does not completely remove the understory vegetation and canopy, making it challenging to predict the impact of bark beetle infestation on watersheds (Mikkelson et al., 2013; Adams et al., 2012). Recent work (Slinski et al., 2016) for 33 western U.S. watersheds noted no significant change in peak flows or average daily streamflow following bark beetle infestations, and that climate is a stronger driver of streamflow patterns and snowmelt timing than insect forest disturbance for the studied systems.

Biederman et al. (2015) also found a muted hydrologic response in eight infested catchments in the Colorado River headwater to beetle-induced tree die-off. Expectations of increased streamflow were not supported by observations. They attribute the findings to "increased transpiration by surviving vegetation and the growing body of literature documenting increased snow sublimation and evaporation from the subcanopy following die-off in water-limited, snow-dominated forests."

Urbanization, or the addition of impervious land cover and related infrastructure, has some of the most significant impacts on land-surface processes: increased runoff, decreased lag time between precipitation and runoff (Guan et al., 2016), and larger peak flows (Sheng and Wilson, 2009). This leads to an increase in the risk of flooding in highly urbanized areas and therefore nonstationarity in flood statistics (Cuo et al., 2009; Meierdiercks et al., 2010; Barros et al., 2014), increase in the heat island effect (Rizwan et al., 2008), decreased recharge of groundwater (Harbor, 1994; Rose and Peters, 2001), but increased groundwater recharge in the southwestern United States due to the increases of flow and its concentration in ephemeral channels noted under Objective H-2c (Kennedy et al., 2013), and development of extensive regional infrastructure to transport needed water to urban centers (Mitchell et al., 2001, 2003; White and Greer, 2006). Climate change is also altering regional precipitation and temperature patterns, increasing the risk of extreme events and urban flooding (Ekström et al., 2005; Berggren et al., 2012).

Key needs in space-based estimates for land cover/land use change include higher resolution soil moisture, including at scales for better estimates of plant water availability for evapotranspiration (i.e., less than 1 km and at a daily scale); estimates of plant biomass and density from microwave and visible/near-infrared sensors, including identification of plant type or species for which an imaging spectrometer would benefit; improved estimates of photosynthesis activity (infrared bands to determine plant activity and dynamics); and finer spatial resolution radiation terms, including skin and air temperature, both under clear sky and cloudy conditions. Other critical needs include precipitation at high spatial and temporal resolutions, and lidar for urban and plant structure and form.

Enabling Measurements

This section explains how the objectives described in the previous section translate into measurements. Some measurements are already available from sensors in the Program of Record (Appendix A; already employed or those in the queue). Some require new approaches to the interpretation of existing sensors. Last, this section identifies new measurements that are needed to achieve the objective and describes technologies that might enable them.

In general, the science and applications objectives and the measurements are interrelated, without a one-to-one mapping between them. Many of the lower-priority objectives would be achieved simply as a result of achieving specific higher priority objectives.

To illustrate these relationships, consider Objective H-1a, designated Most Important in Table 6.1 and described as follows: "Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance from headwater catchments to continental-scale river basins." Fulfilling this objective requires success with Objectives H-1b and H-1c, and it also requires that we estimate evapotranspiration, which in turn requires that we estimate the surface energy balance, especially the surface radiative fluxes, so surface albedo and temperature are needed. To estimate water availability, we need to know about the soil moisture in the root zone, as well as the vapor pressure deficit between the leaves and the atmosphere. Last, we gain additional information from knowing the species of the vegetation involved, and the vegetation structure. Table 6.3 maps the Most Important and Very Important objectives from Table 6.1 to measurements and potential technologies for achieving them, including use of sensors already in the Program of Record as well as potential new sensors. Notably, adding the Very Important objectives adds just one set of measurements, related to groundwater, beyond the set of measurements needed to achieve the Most Important objectives. Table 6.4 provides the same information for the Important objectives, in less detail but illustrating that most of those objectives could be achieved if the Most Important and Very Important objectives were addressed.

Details on the measurements, their role in achieving the objectives, and prospects for those measurements are given in the following sections. Some information about current capabilities is extracted from a recent review (Lettenmaier et al., 2015).

Energy and Water Fluxes in the Surface Layer

Radiative Flux at Surface, Downscaled to Topography

Estimating the net solar and net longwave radiation at the surface, corrected for atmospheric attenuation, is crucial for calculating energy-driven water fluxes such as evapotranspiration or snowmelt. While the net radiative fluxes depend on the surface albedo and temperature, they are also driven by the incoming values of solar and longwave radiation, which are affected by the atmosphere and topography. A probing scientific question about Earth's climate is the net radiation balance of the Earth system. For the hydrologic cycle, the concern mainly addresses the disposition of net radiation at the surface.

At spatial scales of 100 km or so, and especially when averaged over time and space, the surface and top-of-atmosphere estimates of solar and longwave radiation from the Cloud-Earth Radiant Energy System (CERES) instruments on three satellites—Terra, Aqua, and TRMM—are generally viewed as satisfactory (Kato et al., 2011). For hydrologic analyses, however, the same values at temporal intervals for models and at spatial resolutions that reflect topographic variability are needed. In this case the estimates of solar radiation at the surface match station observations on average (Hinkelman et al., 2015), but in the mountains the average atmospheric properties of a CERES grid cell (~1 degree) are often different than at specific locations, especially higher elevations where errors of several hundred W/m^2 can occur when clouds are present but not recognized by the sensor (Bair et al., 2016). Longwave radiation estimates are not as easily validated because in situ measurements are less available. Given estimates of incoming direct and diffuse solar radiation, longwave radiation, surface albedo, vegetation structure, and surface temperature, the net values at the surface can be estimated (Rittger et al., 2016).

Probably, atmospheric properties can be downscaled from the CERES resolution using observations from the Program of Record, but this remains a problem to solve. Information about topography is available worldwide from the Shuttle Radar Topography Mission (Farr et al., 2007). Information derived from Landsat imagery for the United States is available via the LANDFIRE product (Rollins, 2009), which could be processed worldwide in the future.

Albedo of Vegetation, Soil, and Snow

Estimation of energy fluxes such as evapotranspiration or snowmelt at the surface requires that we consider the radiative properties of the vegetation, soil, and snow including emissivity and albedo. Albedo is especially critical because it determines the magnitude of the net solar radiation term in the energy budget equations, and because it exhibits spatial, seasonal, and diurnal variability because of changes in local environmental conditions, and with illumination angle (Tao and Barros, 2014a; Bair et al., 2017).

TABLE 6.3 Mapping Most Important and Very Important Objectives in Table 6.1 to Fluxes and State Variables, and Potential Implementations

Objective	Knowledge Needed	Flux or State Variable (Priority Order)	Potential Technologies
H-1a (MI)	Energy and water fluxes in the surface layer, specifically *evapotranspiration*, which is not directly measured but instead inferred from the energy fluxes to get the latent heat flux	Radiative flux at surface, downscaled to topography	improved algorithms with existing sensors in the Program of Record: CERES, MODIS, VIIRS, GOES-16, Himawari, MSG
		Albedo (vegetation and soil, separately)	Imaging spectrometer
		Soil moisture in root zone	L-band and P-band radiometer and radar
		Diurnal cycle of surface temperature (vegetation, soil, snow), at agricultural or topographic scales	Thermal infrared, in 4 µm and 11 µm spectral regions, multiple platforms to get diurnal cycle
		Vapor pressure deficit in boundary layer	Microwave and IR sounders
		Winds in boundary layer	Active sounders, radar or lidar
		Vegetation species	Imaging spectrometer
		Vegetation structure	Landsat (e.g., LandFire extended globally), *lidar*
H-1b (MI)	Rainfall	Rain rate at both high and low intensities	Passive and active microwave observations at finer spatial resolutions Geostationary IR/VIS observations to support operational applications (GOES series)
	Snowfall	Intensity of snowfall and mixed-phase precipitation	Higher frequency radar and radiometer
H-1c (MI)	Snow water equivalent (SWE)	Snow depth, weekly, at topographic scale	Ka-band or lidar altimeter
		Snow density (less heterogeneous than depth)	Interferometric L-band or S-band SAR or model
	Snowmelt rate	Radiative flux, albedo of snow separately from vegetation and soil, and surface temperature of the snow, at topographic scale	Imaging spectrometer
	Sublimation from snow		Thermal infrared, in 4 µm and 11 µm spectral regions, multiple platforms to get diurnal cycle
H-2a (VI)	Evapotranspiration (ET)	Same as for H-1a, earlier	
	Land use and land cover	Land use and land cover categories	Landsat and Sentinel-2, in Program of Record
	Rainfall	Same as for H-1b, earlier	
H-2c (MI)	Groundwater storage and recharge	Groundwater storage, at basin scale (50 km or better)	Gravimetric measurements if possible to achieve 50 km resolution
			Interferometric SAR or GPS to measure elastic changes
		Rate of recharge (precipitation-evapotranspiration to accuracy finer than rate of recharge)	See H-1a and H-1b, earlier
		Rate of subsidence (to diagnose overdrafting)	Interferometric L-band or S-band SAR
H-4a (VI)	Hazard response to extremes	Same as H-1b, H-1c, H-2a, H-2c, earlier	

NOTE: New measurements are indicated in italics.

TABLE 6.4 Mapping Important Objectives in Table 6.1, in Less Detail than in Table 6.3, to Fluxes and State Variables, and Potential Implementations

Objective	Knowledge Needed	Flux or State Variable (Priority Order)	Potential Technologies
H-2b	Snowmelt	Same as H-1c in Table 6.3	
	Water quality	See H-3a, later	
H-3a H-3b	Water quality	Important biological, chemical, and physical variables (biggest connection between environment and human health)	Something like Pre-Aerosol, Clouds, and Ocean Ecosystem (PACE) at scale of rivers is too expensive, but *imaging spectrometer* would address many problems
H-3c	Structure of vegetation	Leaf and woody variables (need to address which properties are essential to constrain evapotranspiration)	Landsat, imaging spectrometer, lidar
H-4b	Flash floods	Same as H-1b, H-1c, H-4a	
H-4c	Drought monitoring	Same as H-1b, H-1c, H-2c	
H-4d	Linkage between land modification and hazards	Same as H-2a, H-2b, H-4a, H-4b, H-4c	

NOTE: New measurements are indicated in italics.

Broadband albedo of a surface is the convolution of the spectral albedo with the spectral distribution of solar radiation at the surface. The albedo of an arbitrary land cover cannot be directly measured with a multispectral sensor. Even if the atmospheric attenuation of the signal is corrected, estimating the albedo requires interpolating between the wavelengths where the reflected radiance is measured. Moreover, calculation of evapotranspiration or snowmelt might require the albedo of the surface of interest in a mixed pixel. To calculate the albedo of an arbitrary surface, or the albedo of individual constituents in a pixel, requires the spectral richness of an imaging spectrometer. Such a sensor can determine the broadband albedo without having to assume the shape of the spectral curve between separated bands, and it can provide enough information for a spectral mixing model to derive the fractional coverage of each surface in a mixed pixel, along with the reflective properties of each as well as viewing and illumination geometry. Such capability has been demonstrated with airborne sensors over both chaparral and snow environments (Roberts et al., 1998; Dozier et al., 2009). For global coverage at biweekly or monthly intervals, a spaceborne imaging spectrometer would be needed.

The HyspIRI mission was recommended as a second-phase mission in the previous decadal survey (NRC, 2007a). That proposed sensor included spectrometer coverage in the solar reflected part of the spectrum (0.38 to 2.5 μm) and multispectral coverage in the thermal infrared (3 to 12 μm). HyspIRI remains in its design (“contemplation”) phase (Lee et al., 2015), possibly because its multitude of capabilities drive size and cost. The thermal infrared sensor can estimate atmospherically corrected surface temperature but also distinguish among the spectral emissivities of the silicate minerals (which lack features in the solar spectrum). However, the temporal resolution for spectral information about the surface—to determine various characteristics of vegetation, minerals in soil, and snow—requires less frequent observations than the temporal resolution for vegetation and soil temperatures to estimate evapotranspiration. Thus, there is an argument to separate these two capabilities; hence, the recommendation of the National Academies’ Committee on the Future of Land Imaging to consider free flyers to acquire the thermal data (NRC, 2013). The ECOSTRESS mission, with 5 thermal bands and a spatial-temporal resolution of 70 m and 4-day repeat with a diurnally progressive orbit, offers a critical measurement platform to advance the science using thermal imaging.

Experience with the Moon Mineralogy Mapper (Green et al., 2011), and prototype designs for an imaging spectrometer with Landsat-like coverage and spatial resolution (Mouroulis et al., 2016), show that an economical imaging spectrometer is feasible. Such an instrument would also address the Most Important objectives described in Chapter 8.

Soil Moisture in Root Zone

Spatial variations of groundwater recharge and evaporation are strongly related to soil type, topography, vegetation, and climate. Their dynamics are affected by the variations in plant growth, weather, and seasonal climate. To adequately characterize them, mapping at spatial scales of tens to hundreds of meters and temporal sampling at days to a week are needed. The required spatial resolution is dictated by the spatial scales of factors that affect the variations in soil moisture (topography, soil texture heterogeneity, and vegetation distribution). The temporal requirement is dictated by the rate of change in soil moisture due to intermittent rainstorms and drying rates.

Fluxes such as recharge and evaporation cannot be directly sensed, as they do not uniquely correspond to any thermal or dielectric state. Rather they depend on spatial, vertical, and temporal gradients of state variables. The need to measure profiles of water vapor in the atmosphere and water in soils, to thereby allow estimation of these fluxes, sets the need for observations at multiple wavelengths to probe multiple depths. A second need is to sense the properties of the interface across which these fluxes are occurring. The atmosphere and the vegetation canopy that stand between the spaceborne sensor and the flux interface need to be as transparent as possible. This consideration leads to the selection of low-frequency microwave (less than 2 GHz) for the observations. Final requirements address sensitivity and resolution. Sensitivity is required if gradients in states and not the states themselves are the basis for estimation. Spatial resolution is required, since variations in soil type, topography, solar illumination, and vegetation that drive recharge and evaporation vary across spatial scales. The sensitivity and resolution requirements lead to the selection of active and passive low-frequency microwave sensors.

Put together, the space-based sensors should be (1) multichannel; (2) low-frequency microwave; and (3) active (radar) and passive (radiometer). A sensor package that combines all of these attributes is L- and P-band (around 1.5 and 0.5 GHz) active/passive. Capabilities for sensing the relevant surface and root zone states have been tested (Entekhabi and Moghaddam, 2007; Akbar et al., 2016; Chaney et al., 2016; Tabatabaeenejad et al., 2015; Entekhabi et al., 2010).

Several space programs—including JAXA's PALSAR-2 (L-band active), NASA's SMAP (L-band active-passive), NASA/ISRO's NISAR (L-/S-band active), ESA's Biomass (P-band active), and CONAE's SAOCOM (L-band active)—are operational or in the development phase. They provide individual observation capabilities, but not the combined multifrequency (L-/P-band) active-passive observation requirements. The ESA Biomass mission P-band radar revisit rates are only seasonal. They are appropriate for biomass mapping but not for capturing surface water balance dynamics. The L-band SAR missions also have revisit rates that could be tens of days. Future combined L-/P-band systems will require an operations concept that covers a wide swath for frequent revisit. A system study is required to determine the architecture of a space-based sensing system for the multifrequency active-passive observation requirement and to identify required technology development.

An active-passive L-/P-band system would also support continuity of surface soil moisture estimation using the NASA SMAP and ESA SMOS missions. Soil moisture, a state variable of the land branch of the water cycle, has temporal variations ranging from daily to interannual. Long climate records are needed to characterize the variability of the water, energy, and carbon cycles as affected by the soil moisture state. L-band radiometry of the Earth system has been continuous since 2009. The active-passive L-/P-band system will not only support the needed climate record but also enhance the capability for deeper sensing of the soil column. The system will also support finer spatial resolution to capture the heterogeneities induced by variations in topography, vegetation type, soil texture, and precipitation intermittency.

Diurnal Cycle of Surface Temperature

Estimation of energy fluxes such as evapotranspiration or snowmelt requires that we consider the individual surface temperatures of the vegetation, soil, and snow. Remote-sensing methods to do this have been derived from thermal imagery in the 4 μm and 11 μm regions, for the purpose of detecting fires when they occupy only a small part of a pixel, as small as 0.01 percent (Dozier, 1981; Matson and Dozier, 1981; Giglio and Kendall, 2001). The same principle, based on the slope of the Planck equation versus temperature at different wavelengths, also enables the separation of temperatures of vegetation, soil, and snow, as long as the differences exceed about 10 K. Putting thermal sensors on a satellite constellation capable of spatial resolutions at the size of an agricultural field, as recommended by the National Research Council report on the *Future of Land Imaging* (NRC, 2013), would enable measurement of the diurnal cycle of surface temperatures, and thereby improve the modeling of surface fluxes.

One of the most important aspects of land-surface dynamics is the continuous variability of land-surface temperature. In the continental United States, spatially discontinuous networks of point measurements of surface skin and boundary layer temperature—NOAA's U.S. Climate Reference Network (NOAA USCRN, 2017) and others with the National Centers for Environmental Information (NOAA NCEI, 2017), USDA's Soil Climate Analysis Network (NRCS, 2017), and the Ameriflux tower network (AmeriFlux, 2017)—can be used for validation and verification of remotely sensing estimates. Outside Europe and North America, however, in situ measurements of surface temperature are limited. From space, land-surface temperature has been measured using various infrared and thermal sensors—HIRS2/MSU (Lakshmi et al., 1998); AIRS (Susskind et al., 2003); AVHRR (Price, 1984); MODIS (Wan and Li, 1997)—but all of these are at most twice a day (polar orbit), and only MODIS (on two platforms, Terra and Aqua) comes close to mapping a diurnal variability of surface at four different times of day. Recently launched geostationary satellites—U.S. GOES-16, Japan's Himawari 8/9, China's Fengyun-4, and Europe's MTG —have the thermal band coverage needed to deconvolve skin temperatures from a variety of surfaces, and the value they provide of observing the diurnal variability of surface temperature can translate into better estimation of the outgoing longwave radiation and fluxes of sensible heat, latent heat, and conduction into or out from the soil. Clouds are another complicating factor, masking the land surface from visible, near infrared, and thermal bands.

Most land-surface parameterization schemes in land simulation systems such as the North American Land Data Assimilation System and Global Land Data Assimilation Systems (NLDAS and GLDAS; Rodell et al., 2004; Mitchell et al., 2004) and the Land Information System (LIS; Kumar et al., 2006) have a temporal resolution of half-hourly to hourly time steps and can readily use more frequent observations. While geostationary satellites provide fine temporal frequency, polar orbiting satellites provide spatial resolution at the scale of individual fields. Simulation studies will have to be undertaken to study the efficacy of surface temperature observations and the fusion of spatial and temporal resolutions. Surface temperature and vegetation observations are available at a finer spatial resolution than soil moisture, and this along with the relation between soil moisture and diurnal change in surface temperature can be used to downscale the coarser spatial resolution soil moisture (Fang et al., 2013). Clouds obscure the surface from visible, near-infrared, and thermal infrared sensors, so the temperatures sensed during clear conditions must be used to model energy transfers within canopy and canopy-soil interactions (Jin and Dickinson, 2010).

Vapor Pressure Deficit in Boundary Layer

In understanding the energy and water fluxes in the surface layer, knowing the vapor pressure deficit (VPD) in the planetary boundary layer (PBL) is critical (Betts, 2004). No sensor in the Program of Record addresses temperature and humidity within the PBL with sufficient fidelity to directly estimate sensible and latent heat transfer from space.

Currently, the highest resolution operational instrument is the Infrared Atmospheric Sounding Interferometer (IASI) sensor on ESA's MetOp-A (Level 2 retrievals). IASI takes 8461 spectral samples between 3.62 and 15.5 μm with a resolution of 0.5/cm after tapering, and has an instantaneous field of view that ranges from 12 to 39 km. In addition to the humidity data at meteorological stations and flux towers in the context of surface temperature, globally distributed weather balloon profiles (radiosondes) of quality-controlled air temperature, humidity and wind observations starting at 3 m above the surface launched twice or four times daily are also available from NCEI among other repositories. Assessment of the IASI instrument (August et al., 2012) found that comparisons with European Centre for Medium-Range Weather Forecasts (ECMWF) analysis fields for the temperature fields below 800 hPa had errors between 2.5 and 3.5 K on average. For humidity, the root mean square (RMS) differences are about 20 percent of the relative humidity, and with a smaller dynamic range than estimated by ECMWF. Similar results were found in comparisons with radiosonde data.

August et al. (2012) caution against using IASI for the boundary layer at this time. It is believed that the relatively large errors can be reduced by improved retrieval algorithms (better channel selection, improved land emissivity inputs; Masiello et al., 2012) as well as joint use of information from the Advanced Microwave Sounding Unit (AMSU) and Microwave Humidity Sounder (MHS)/MetOp. Whether sharpening the channel selection or advancing the algorithm development will lead to the needed improvements is yet undetermined, but is a potential path forward before investing in new hardware.

Precipitation and Its Phase

Rainfall

Precipitation is the longest measured parameter, with in situ observations dating back to 2000 BCE. Precipitation is critical from both a climate perspective, as a key marker of the speed of the water and energy cycle, and a weather perspective, affecting nearly all human activities. NASA and JAXA have led the global community in the global assessment of precipitation using passive and active microwave observations through their successful TRMM and GPM missions, while NOAA has led the way in ground-based radar and geostationary infrared/visible (IR/VIS) measurements. Geostationary measurements at fine temporal and spatial resolution are useful for nowcasting and hazard-warning applications, albeit with lower accuracy than microwave measurements. Synergies are currently being exploited (Huffman et al., 2017).

Precipitation exhibits variability over a wide range of spatial and temporal scales (from a few meters to hundreds of kilometers in space, and from a few minutes to storm and seasonal scales in time. Ground radars can bridge these scales but are available only in industrialized countries and designed for civil defense purposes rather than routine monitoring or understanding. Rain gauges are more common but do not capture spatial variability and are sparse over much of Earth's surface. Accurate estimation of precipitation from space is thus of paramount importance for improving weather and climate prediction models, for closing water budgets at the catchment scale, for providing global coverage of this most critical component of the water cycle, and for early prediction of severe storms.

The Tropical Rainfall Measuring Mission (TRMM) satellite, launched in 1997, was the first of its kind to successfully carry a single polarization Ku-band (13.8 GHz) weather radar, along with a multichannel radiometer TRMM Microwave Imager (TMI; frequencies 10.65, 19.35, 21.3, 37.0, and 85.5 GHz; horizontal and vertical polarization except for the vertical-only water vapor channel of 21.3 GHz). TRMM considerably improved our understanding and estimation of rainfall over the tropics (Kummerow et al., 1998). The GPM mission followed in 2014, with a constellation of satellites covering the globe (Hou et al., 2014). The GPM core satellite includes a Dual-Frequency Precipitation Radar (DPR) (Ku- and Ka-band frequencies) and a passive microwave radiometer with 13 channels (10.7 to 183 GHz). GPM aspires to provide global estimates of precipitation at resolution of 5 km every 3 hours, and even finer resolutions (down to 2 km and 15 minutes) when combined with the constellation of geostationary IR/VIS imagers.

Passive retrieval of rainfall from observed upwelling spectral radiance is challenging (Ebtehaj et al., 2016; e.g., Gopalan et al., 2010), mainly because of the background surface and atmospheric signal contamination. In microwave frequencies (6-200 GHz), the hydrometeor vertical profile is radiometrically active and alters the upwelling radiation largely through absorption-emission (over ocean) and scattering (over land).

Whereas space-based radar measurements such as the DPR on GPM are the most promising with regard to spatial and temporal resolution of precipitation, retrieval quality is strongly tied to the algorithm's ability to produce realistic descriptions of the vertical and spatial distribution of hydrometeors needed to quantify Path Integrated Attenuation (PIA) and scattering effects that modify the radar signal as it travels through a storm system (e.g., Iguchi et al., 2016). Radar-based quantitative precipitation estimates (QPE) underestimate heavy rainfall due to strong attenuation effects when significant ice and large-size water hydrometeors are present, and light rainfall is often missed due to the lack of significant scattering when hydrometeors are small. In complex terrain and mountainous regions generally, ground-clutter artifacts (excessive reflectivity when the radar signal is intercepted by the terrain) add ambiguity to the interpretation of reflectivity measurements from lower levels in the atmosphere, resulting in QPE errors as large as 100 percent (Duan et al., 2015). Because orographic precipitation accounts for more than half of the world's renewable freshwater resources and most hydropower production, decreasing retrieval error and systematic uncertainty is critical to closing the basin water balance from headwaters to continental-scale basins.

The challenge of providing accurate precipitation estimates everywhere and at spatial and temporal resolutions needed for accurate and timely prediction of extreme weather and floods remains a critical issue in global water and food security and in global health. From GPM this challenge will be met in the coming decade by combining products from several sensors, and learning from the coincidental active and passive sensors to improve physics-based and data-learning retrieval algorithms.

Snowfall and Mixed-phase Precipitation

A significant portion of precipitation at middle and high latitudes falls as snow (Liu, 2008). Snowfall and mixed precipitation retrievals from space, unfortunately, encounter all the difficulties discussed for rainfall, plus additional complications due to unknown surface characteristics as well as the details of the snow size, shape, and density. Because ice is much more transparent than water in the microwave frequencies, mixed-phase precipitation comprising snowflakes and supercooled water droplets is particularly difficult to measure.

Over snow-covered areas, where it is hard to disentangle the weak rain-scattering signal at high frequencies from the snow-cover emission, satellite-based estimates of snowfall are unreliable. Yet, such retrievals are critically important for improving assessment of water storage and for constraining climate models. For example, outside Greenland and Antarctica, High Mountain Asia (HMA) contains the largest deposit of ice and snow, roughly 8,600-13,600 GT, with a decreasing mass of 26±15 GT per year, largely due to reduced snow albedo caused by deposition of soot and dust (Kaspari et al., 2014), temperature increase, and decline of high-altitude snowfall (Pfeffer et al., 2014; Radić et al., 2014). Warmer temperatures over the past decade (IPCC, 2014) have not only increased evaporation and melting but have also shifted precipitation patterns to a more rain-dominant regime (Bhutiyani et al., 2010) and reduced the number of snowfall days (Shekhar et al., 2010). While there is a growing evidence of improved skills of climate models, studies confirm that their capability is severely limited in simulating precipitation and especially snowfall over HMA's complex terrain (Turner and Annamalai, 2012). Reliable estimates from GPM might narrow this gap, but the problem of remotely sensing snowfall remains.

Snow and mixed-phase precipitation measurements are challenging no matter the vantage point. Rain gauges that catch liquid precipitation do not effectively catch snowfall, especially in windy environments (Doesken and Judson, 1996; Yang et al., 2005). Manual measurements from snow boards are accurate, but too sparse for practical monitoring (Greene et al., 2016). Ground-based radars suffer from the same issues related to snow size, shape, and densities as the spaceborne sensors (Wen et al., 2017). The main shortcoming is that while we understand particle scattering from well-defined particle shapes such as needles, plates, or rosettes, the more amorphous aggregates that often make up snow near the freezing level (where most snow falls) have been difficult to model, particularly in the 0°C to –10°C range. New advances using triple-frequency radars have made strides in this area (Kulie et al., 2014). Specifically, differences between Ku and Ka, as well as Ka- and W-band frequencies appear to contain much of the ice habit information, and in particular, offer a distinct signature of snowflakes and aggregates. Their results, confirmed by in situ aircraft observations during the AMSR-E validation campaign in Wakasa Bay (Lobl et al., 2007) are encouraging. The GPM satellite flies Ku and Ka radars, while CloudSat uses a W-band radar. In this respect, the needed technology is not new. It is flying today, albeit not on the same platform, and not with the needed sensitivity for snowfall detection. (GPM minimum sensitivity at Ku- and Ka-bands limits detection to moderate and heavy rain and strongest snowfall events, thereby missing significant precipitation in middle and high latitudes.)

While the Wakasa Bay data and other work done with triple-frequency radars appears very promising, the current studies deal largely with stratiform precipitation that contains relatively little supercooled water and no mixed-phase precipitation. The phase of the precipitation is rather easily distinguished using Doppler measurements to observe particle fall velocities. With terminal velocities around 1 m/s for snow, 2-3 m/s for graupel, and approximately 6 m/s for liquid rain, the phase is easily discriminated with 0.5 m/s resolution. This capability will be demonstrated by EarthCare, a joint ESA/JAXA mission scheduled to launch in 2019 (Illingworth et al., 2015), albeit not quite at the pixel level needed for many hydrologic applications. The supercooled water is more problematic, as the water makes radar-only observations difficult to interpret. For this problem the solution is seen in a combination of active and passive microwave sensors, also discussed in the preceding subsection on rainfall. The microwave signature is quite sensitive to the liquid water emission. Grecu and Olson (2008) were able to simultaneously retrieve cloud liquid water and ice contents for a lake-effect snowstorm using a W-band radar and a high-frequency radiometer covering the GPM radiometer channels from 89 to 183 GHZ. A single-frequency radar was sufficient in this study, as the retrievals were for clouds over the water, so the background contribution to the signal was known.

Specific Improvements Needed

Falling snow can be detected by observing scattering signals in high-frequency passive microwave sounders such as Advanced Technology Microwave Sounder (ATMS; Kongoli et al., 2015) and W-band radars like CloudSat (Stephens et al., 2002) also detect the backscatter of snow and ice hydrometeors. Nevertheless, quantitative snowfall retrievals remain elusive (Levizzani et al., 2011), but the work described in the previous section provides the basis for a triple-frequency radar for snowfall detection and quantification. Frequencies currently flying on GPM (14 and 35 GHz) coupled with CloudSat (95 GHz) would constitute the basis of such a measurement. One of the radars should be equipped with Doppler capabilities to aid in the mixed-phase classification. Beyond that it is postulated that the spatial resolution should be at least that of GPM and ideally better (perhaps 1-4 km) in order to minimize issues related to inhomogeneous radar fields of view (FOVs). The radar system should further be coupled with a high-frequency radiometer, not unlike the current ATMS sensor, but with increased spatial resolutions to match the radar FOVs. As with GPM, this radiometer would also serve as a transfer standard to operational sounders that could achieve the necessary sampling to address the myriad of applications related to snowfall accumulations and water availability.

Beyond better precipitation observations, however, the next generation of improvements in weather and climate models critically relies on better understanding of precipitation physics. The rapid development and increasing use of global CRMs means that an understanding of atmospheric processes and feedbacks is rapidly becoming critical for the accurate prediction of not only weather but global cloud regimes and climate as well. Improving our observations of dynamical and microphysical cloud processes with multifrequency radars and Doppler velocities as proposed for new precipitation measurements would immediately contribute to addressing the following important unresolved problems through process evaluation or model constraints:

- *Improvement in the manner in which the large ice species are parameterized.* This will shrink inaccuracies in surface precipitation rates, convective-stratiform precipitation, and precipitation probability density functions (Adams-Selin et al., 2013; Bryan and Morrison, 2012; TaoWuLang et al., 2016).
- *Improvement in the connection between vertical velocities and resulting ice hydrometeor species.* Properly representing vertical velocity reduces inaccuracies in the nucleation rates, numbers and sizes of cloud droplets and ice crystals, and hence the hydrometeor size distributions (Saleeby and Cotton, 2005; Saleeby and van den Heever, 2013; Varble et al., 2014).
- *Improvement in the understanding of the partitioning between water and ice particles.* Accurately representing cloud microphysical processes reduces significant inaccuracies in the partitioning between the liquid and ice water species, the depth of the mixed-phase cloud region, the vertical redistribution and location of ice and liquid water, and upper-level detrainment of water vapor.
- *Improvement in the understanding and quantitative description of the vertical structure of microphysical properties of precipitation in regions of complex terrain.* Accurately representing the vertical heterogeneity of hydrometeors at lower levels will significantly reduce systematic errors and uncertainty in orographic precipitation, including layered stratiform systems with and without embedded convection.

Together, these insights into cloud and hydrometeor behavior, coupled with corresponding aircraft campaigns that provide more in-depth views of the identified regimes, could revolutionize our understanding of clouds and our ability to predict their development.

Snow and Glaciers

The difficulties in measuring snowfall and mixed-phase precipitation are partly compensated by the fact that snow lies on the ground for a while before it melts or sublimates. Therefore, a complementary strategy is to measure snow depth and density and thereby snow water equivalent (SWE = snow depth × snow density). In February 2017, NASA ran the first campaign of a multiyear plan (SnowEx, https://snow.nasa.gov/snowex) to test and validate a variety of airborne and ground-based instruments to measure snow properties. Some of the proposed technology developments for measurement of snow properties will be examined during SnowEx.

Snow Water Equivalent (SWE)

In many regions of the world where snowfall dominates precipitation, the snowpack comprises a larger seasonal cycle in water storage than the surface water reservoirs or groundwater (Zhou et al., 2016). Therefore, measurement of snow water equivalent on the ground has been a century-long component of hydrologic practice, especially for seasonal forecasts of streamflow (Church, 1914). The in situ data now comprise manual measurements at designated snow courses (Armstrong, 2014), typically monthly, and automatic measurements from snow pillows that continuously sense the weight of the overlying snowpack (Cox et al., 1978). For logistical reasons, snow pillows and other remote meteorological sites in the mountains all lie on nearly flat terrain, so they may poorly represent snow accumulation and melt rates on nearby slopes (Meromy et al., 2013). Even in mountain ranges with an extensive surface network like California's Sierra Nevada, the in situ measurements do not accurately represent the spatial distribution or basin-wide volume of the snow water equivalent (Dozier et al., 2016; Rice and Bales, 2010). For example, Landsat images often show snow remaining even after all snow has melted from the surface stations (Rittger et al., 2016), so local reservoir managers lack necessary information to choose between maintaining storage or generating hydropower. For regions having more sparsely measured sites, or where data sharing is prohibited, such as much of High Mountain Asia, we rely almost entirely on remote-sensing approaches to SWE determination.

Passive microwave measurement of SWE is now a staple of remote sensing. Because ice is transparent in the microwave spectrum, whereas water is absorptive, the snowpack scatters and attenuates microwave radiation emitted from the soil. Moreover, the attenuation is greater at higher frequencies (shorter wavelengths), so the difference between brightness temperatures at different frequencies provides an index to the snow water equivalent (Chang et al., 1987). This approach works reasonably well in the prairies and tundra of North America and Eurasia, but the signal saturates when SWE values exceed about 20 cm (Kelly et al., 2003). Moreover, emission at microwave frequencies is on the tail of the Planck equation, so the tiny amount of radiation and implications of antenna design require that the pixels be large, 10 to 25 km. The heterogeneity of the surface in that large pixel (Vander Jagt et al., 2013), along with the deep snow often found in mountain ranges, causes substantial uncertainty in our ability to assess a major component of the water cycle. Lettenmaier et al. (2015) argue that, "Among all areas of hydrologic remote sensing, snow (SWE in particular) is the one that is most in need of new strategic thinking from the hydrologic community."

Potential avenues for improving the current inadequacies in assessing snow depth and water equivalent in the world's mountains need further exploration with airborne missions and a resolve to implement a technology that shows acceptably accurate results in a variety of mountain snow settings. Because of the effect of topographic variability on snow accumulation and melt, spatial resolution needs to be no coarser than ~100 m, and the SWE values that need to be assessed range from ~10 cm to several meters. Because snow changes more rapidly than other surface covers, temporal frequency should be about weekly.

Figure 6.11 shows a promising approach; the NASA Airborne Snow Observatory (Painter et al., 2016) uses lidar to measure snow depth by comparing elevations measured weekly or biweekly throughout the snow season with the same topographic data acquired when free of snow in the summer. Snow water equivalent is estimated by multiplying the depths (at spatial resolution of ~3 m) by snow density derived from field measurements and a snowmelt model (Marks et al., 1999). The main source of uncertainty in SWE is thus reduced to only snow density, which varies 3 times less than depth spatially (López-Moreno et al., 2013).

A scanning lidar's narrow swath and the need for frequent altimetry over large areas perhaps makes the Airborne Snow Observatory's approach difficult to implement from satellites. Alternatively, a high-frequency (W- or Ka-band) radar altimeter or interferometer provides an alternative to measuring the snow depth. A Ka-band interferometer has been flown as an airborne sensor as GLISTIN, the Glacier and Land Ice Surface Topography Interferometer (2017; Moller et al., 2011). The advantage of measuring snow depth and inferring SWE through density is not only a cheaper, more feasible implementation, but also the snow depth measurement is insensitive to liquid water in the snowpack. Alternative methods to directly measure SWE at fine spatial resolution through backscattering from synthetic aperture radar (Shi and Dozier, 2000b, a) showed promising results, but only in dry snow and only with a multifrequency, multipolarization radar.

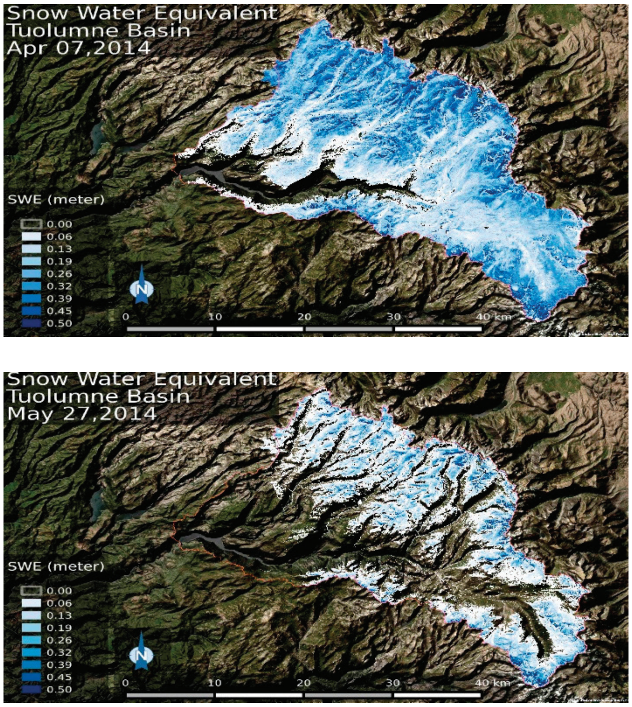

FIGURE 6.11 Snow water equivalent estimated by NASA's Airborne Snow Observatory in California's Tuolumne River Basin in April 2014, by combining lidar measurements of depth with measured and modeled snow density. SOURCE: T.H. Painter, NASA/JPL.

But density can also be measured either by polarimetric (Li et al., 2001) or interferometric L-band (1.4 GHz) SAR; hence, such measurements from the Program of Record (e.g., NISAR) could complement the measurement of snow depth, because density does vary in systematic ways that may affect the calculation of SWE. Generally, densities are lower at higher elevations and on slopes that receive less radiation (Wetlaufer et al., 2016).

Snow and Ice Melt

Energy used to melt seasonal snow and glaciers depends on other enabling measurements described earlier in the subsection "Energy and Water Fluxes in the Surface Layer." Their estimation from satellite data depends on downscaling the coarse satellite estimates from instruments like CERES, along with accurate measurements of snow and ice albedo. Because many regions where snow and ice are important in the hydrologic cycle are in the mountains, many of the pixels are mixed—that is, containing some combination of snow, ice, vegetation, and soil. Spectrally unmixing these pixels and determining the albedo of the snow and ice component would be improved by measurements from a spaceborne spectrometer, which would also support information needs identified by other Decadal Survey panels—particularly ecosystems, discussed in Chapter 8.

Sublimation from Snow

Snow disappears from the land and from glaciers by two mechanisms other than snowmelt—wind transport and sublimation (the direct transition from ice to water vapor). Wind transport can be identified by measurements of snow water equivalent. Estimation of sublimation depends on many of the measurements needed to estimate evapotranspiration, with the problem being somewhat easier because the surface vapor pressure can be reliably estimated from measurement of the surface temperature.

Groundwater Storage and Recharge

Groundwater Storage and Depth to Water Table

Approximately 98 percent of all circulating freshwater (excluding glaciers and ice caps) on Earth is groundwater—that is, below the water table (Federal Council for Science and Technology, 1962). In the context of water resources, whether worldwide or in a local watershed, the groundwater stores of freshwater are vast, which is also one reason why much of the fresh groundwater is fairly old, typically a century to a millennium. That is, the larger the water volume, the longer the water residence time. In most groundwater systems, both the old and the relatively young (a few decades to a century) water is usable and replenishable, although the geology and confinement strongly affect the rate of replenishment of deeper groundwater. Aquifer replenishment occurs through recharge at the top of the groundwater system, the water table. Importantly, the recharge benefits deeper groundwater by bolstering fluid pressure, the changes in which can propagate regionally through the groundwater system much faster than the water itself.

Despite the vast volume of groundwater, only a limited quantity of it can be pumped without causing detrimental effects, which include chronic groundwater depletion, land subsidence, depletion of groundwater-dependent surface water and ecosystems, and groundwater quality degradation (e.g., seawater intrusion in coastal zones). Because of the vastness of groundwater reserves, the consequences of exploiting them, and the way that groundwater is replenished, the essential metric is the *change* in groundwater storage rather than the total quantity. In developed aquifer systems, changes in elevation of the water levels in wells can be measured and changes in storage calculated. Remotely sensing depth to water table with ground-penetrating radar suffers from interference from water in the soil above the groundwater.

In many parts of the world, however, measurements of depth to water table are seldom made, which is one reason why local and global awareness of major groundwater depletion in places like India, China, and North Africa did not come to light until the emergence of GRACE data (Richey et al., 2015). Moreover, even in many monitored groundwater basins and especially in the sedimentary basins that contain most of the major aquifer systems, the groundwater occurs under semiconfined conditions in which the calculation of storage change based on groundwater level data is difficult and typically infeasible without the use of well-calibrated groundwater models.

Accordingly, the capability of GRACE (Tapley et al., 2004) for detecting real-time changes in groundwater storage is in concept a highly relevant and positive development. The main limitation of GRACE is that the scale of its measurements is much larger than the scale of most groundwater systems or of typical water resources management regions. The current GRACE scale of measurement is approximately 400-500 km (Famiglietti and Rodell, 2013), while the scale of most water management basins or problems is on the order of 10-50 km (Alley and Konikow, 2015; Lakshmi, 2016). This disparity in scales of the GRACE measurements and the hydrologic system or problem means that measurements from GRACE in even large groundwater basins such as California's Central Valley include not only the changes in groundwater storage in the major sedimentary aquifers, but also the changes in snow in the adjacent mountain range, soil moisture, and fractured-rock groundwater, which all must be measured and modeled sufficiently to separate them from the important major aquifer storage changes.

NASA announced the end of the GRACE mission in late October 2017; one of the pair of satellites has run out of fuel. The overall objectives of the GRACE-FO (to be launched in 2018) for measuring groundwater change in storage are highly relevant for both water management and understanding of global water balances. It is critically important, however, that the technology be advanced sufficiently to get the resolution down to scales relevant to water resources management (e.g., ~50 km). This scale of measurement is also most appropriate for better understanding of the almost entirely unmonitored changes in subsurface water storage in mountainous regions.

Recharge

In undeveloped groundwater systems, recharge is typically balanced by groundwater discharge (e.g., spring flow, stream baseflow, subsea discharge), driving regional and local groundwater flow system dynamics and to a large extent also keeping the groundwater systems fresh. Furthermore, in most undeveloped groundwater basins that do not discharge groundwater to oceans (e.g., Post et al., 2013), the recharge is balanced by discharge such that the net, regional recharge (i.e., recharge minus discharge) is essentially nil. Although local recharge can be substantial, net recharge does in fact depend on scale, often approaching zero at larger scales in undeveloped systems.

In developed groundwater systems, groundwater pumping can be sustainable or unsustainable, depending on whether the pumping magnitudes exceed the recharge and the reductions in natural discharge that pumping commonly induces. Accordingly, the net recharge can increase as the pumping increases and strongly influences whether the groundwater pumping will lead to unsustainable overdraft of the groundwater system.

A major unknown in both developed and undeveloped groundwater systems is the recharge. There are many ways to estimate recharge. At the landscape scale a water budget approach that accounts for precipitation, evapotranspiration, and runoff can in theory be used to calculate recharge as the residual. A major limitation of this approach is that the errors in measuring or estimating precipitation and evapotranspiration often exceed the magnitude of recharge. As the accuracy of satellite-based evapotranspiration measurements improves, direct estimation of associated recharge rates will become more feasible.

One very important case where a water balance approach has worked well for estimating recharge is in irrigated croplands, which consume more groundwater worldwide than any other use (Döll et al., 2012; Scanlon et al., 2016). Irrigation has not only caused massive, often uncontrolled increases in groundwater pumping in many parts of the world, it has also resulted in significant increases in recharge because typically only about 50 to 80 percent of the water applied to the crop is consumed (evaporated and transpired) by the crop, with most of the remainder typically recharging the groundwater. In such agricultural systems, because the evaporative water demand of the crop is easier to estimate and because the recharge tends to be greater than in nonagricultural watersheds, water budget calculations of recharge can be fairly reliable. Nevertheless, as water scarcity increases and irrigation efficiency improves, the recharge from irrigation will decrease. In turn, the need for continual, more accurate monitoring of crop evapotranspiration will only increase.

Besides irrigation water management, the other forcing that will affect recharge is climate change. Warming will tend to increase potential evapotranspiration, decreasing recharge; but on the other hand, climate-induced changes in vegetation due to reduced soil moisture and deeper groundwater levels may result in less actual evapotranspiration. Here again, our ability to monitor spatial and temporal changes in evapotranspiration, and in turn groundwater recharge and runoff, will hinge on future improvements in satellite-based methods to measure evapotranspiration.

Subsidence and Elastic Groundwater Storage Changes

Earth's surface fluctuates both up and down due to groundwater storage changes that are referred to as either elastic or inelastic. All aquifer systems undergo elastic changes in storage wherein decreases in fluid pressure cause modest amounts of aquifer system compaction that release groundwater from storage, and increases in fluid pressure cause modest amounts of aquifer system expansion, taking groundwater into storage (Galloway et al., 2000; Amelung et al., 1999). In unconsolidated to semiconsolidated sedimentary basins that contain most of the world's major aquifers, the aquifers are confined or semiconfined, and hence a key mechanism by which groundwater comes into or out of storage on the daily to monthly time scales is through these elastic processes, rather than solely through fluctuations of the water table itself. In the confined and semiconfined aquifer systems, water levels in the wells are not the same as the water table, and fluctuate more than the water table by orders of magnitude, and on shorter time scales.

Whether in fresh groundwater systems, oil and gas reservoirs, or geothermal fields, the elastic changes in storage are not easily monitored. Moreover, since in most of the world including parts of the United States, groundwater levels are not sufficiently monitored, measurements of land-surface deflections caused by elastic groundwater storage changes are valuable for discerning quantities and mechanisms of groundwater storage changes (e.g., Amelung et al., 1999). Elastic changes in storage can manifest in land surface deflections on the order of 10 mm, which is within the capability of Interferometric Synthetic Aperture Radar (InSAR), which has resolution of 5-10 mm. Any future improvements in this resolution would obviously benefit real-time monitoring of groundwater storage changes, especially when complemented with information from GRACE and sparse groundwater level measurements. The finer spatial resolution of NISAR (Rosen et al., 2016) will further benefit monitoring of groundwater withdrawal consequences, as well as the subsurface geologic structures that affect it.

Subsidence, also referred to as "inelastic compaction," occurs when declines in fluid pressure are sufficient to increase effective stress (sediment grain-to-grain stresses) to an extent not previously experienced in the geologic burial history of the sedimentary package of coarse and fine sediments (Galloway et al., 2000). This important form of groundwater overdraft is increasingly symptomatic of increasing overexploitation of groundwater resources. Prior to availability of InSAR, real-time knowledge of subsidence and its associated, permanent losses in groundwater storage capacity and damage to surface structures did not come to light until the damage was already done. InSAR revolutionized our ability to monitor subsidence in real time and led to unanticipated discoveries about use of land-surface data for determining previously unrecognized subsurface complexities. Again, NISAR and future missions will significantly enhance this capability.

High-resolution GPS monitoring of the land surface has also recently been used to detect cm-scale deflections in Earth's crust in response to crustal loading and unloading caused by total change in subsurface water content (Borsa et al., 2014). Future improvements in tracking not only subsidence but also groundwater storage will lie in the joint use of GRACE, InSAR, NISAR, and GPS. Collectively, this approach will become increasingly essential for local and regional groundwater management.

Water Quality

One of the essential but overlooked elements of regional water availability and sustainable water resources management is water quality. Water quality issues are local and need to be observed at a finer temporal and spatial resolution in order to be used and incorporated into local decision making. Some progress has been made utilizing satellite-based observations for monitoring and assessing eutrophication impacts in coastal waters (Schaeffer et al., 2012, 2013). However, the current technologies embedded in our Earth observing satellite systems are not adequate to gather the kind of signals that could be used to infer various biological, chemical, or physical variables at a finer scale to map regional or local water quality. The pixel resolution of platforms such as MODIS and Landsat or the forthcoming Sentinel-3 mission is too coarse for this purpose (Lee et al., 2014).

In order to evaluate and manage water quality for inland waters, we need to measure turbidity, salinity, colored dissolved organic matter (CDOM), temperature, sediment load, and chlorophyll-a. Spatial resolution of 30-60 m is required in order to have observations that are interpretable and detectable to evaluate the state of inland water bodies such as rivers and lakes at various geographical scales (Hestir et al., 2015; Turpie et al., 2015). The desired temporal resolution is daily to weekly observations.

Advancement in spectrometer imaging technologies, at spatial scales of rivers, inland water bodies, and coastal regions, can ultimately address some of these problems. More focus is also needed on developing algorithms to infer water quality variables based on receiving signals while addressing land adjacency and atmospheric effects (Lee et al., 2014). In addition, considering the advancement of drones and other imaging technologies, there are possibilities for regions with extensive water quality challenges to rely on these technologies to collect water quality data at a finer temporal and spatial scale.

In January 2017, NASA Earth Sciences Division (ESD) issued solicitation *A.30 Remote Sensing of Water Quality*, to identify investigations that could improve the measurement of water quality from spaceborne and airborne sensors. Selections for the funded investigations were announced in July 2017. Findings from them could affect future recommendations and prospects for remotely sensing water quality from space.

Land Use and Land Cover

Vegetation Species

There has been a long and successful history of obtaining vegetation classifications at the community level with existing sensors such as Landsat, SPOT, and MODIS (Xie et al., 2008). Classification and mapping at the species level requires finer spatial resolution, generally less than 5 m (IKONOS, Quickbird). Classification at the community or species level does not generally provide the condition of the vegetation—for example, whether a grassland's grass is 50 cm or 2 cm tall, owing to grazing or different stages in growth phenology. Finer spatial resolution multispectral sensors will be required for more reliable identification of plant species.

The relative vigor or level of plant stress is another important attribute to constrain evapotranspiration estimates that is not measured by community- or species-level classifications. Thermal remotely sensed measurements have been used as a measure of plant moisture stress to improve evapotranspiration retrievals (Anderson et al., 2004, 2007) also the subsection "Diurnal Cycle of Surface Temperature," earlier). Another relatively recent technique to measure plant vigor is through solar-induced chlorophyll fluorescence (SIF; Joiner et al., 2011). SIF is an indicator of photosynthetic activity and efficiency at the molecular scale (Meroni et al., 2009). When plants are water or temperature limited, photosynthesis is reduced but light absorption continues. To compensate, plants decrease the release of fluorescent photons at wavelengths of 690 to 800 nm. Imaging spectrometers with ultra-fine spectral resolution (ć0.02-0.05 nm full-width half-maximum) in the range centered around 760 nm now enable accurate and global fluorescence retrieval (Frankenberg et al., 2013). The Greenhouse Gases Observing Satellite (GOSAT) and the Orbiting Carbon Observatory-2 (OCO-2) have spectrometers that enable retrieval of chlorophyll fluorescence (Frankenberg et al., 2012). The ESA Fluorescence Explorer (FLEX) is designed specifically to monitor global terrestrial vegetation for steady-state chlorophyll fluorescence and is scheduled to be launched in 2022.

Vegetation Structure

As noted earlier, spectral remote-sensing methods have had less success in complex multispecies stands where overstory shading, interwoven branches, and understory plants are present. Light detection and ranging (lidar) can address many of the shortcomings of spectrum-based remote sensing. With high pulse rates exceeding 500,000 pulses per second, airborne systems can achieve ~10 to 30 multireturn points per square meter. Even in dense foliage, lidar point returns (*x*, *y*, *z*, and returned intensity) typically sample not only the top of the canopy and ground but also numerous points within the canopy. Resulting point clouds can be analyzed for a variety of vegetation structural attributes. If the plant species is also known, greater inferences can be made regarding plant structure using species-specific allometric relationships such as LAI, biomass, and aboveground carbon. Multisensor airborne lidar systems with co-registered multispectral sensors are available to simultaneously tackle the vegetation species identification and vegetation structure estimation.

Single-photon counting lidar systems are advancing rapidly, and a 10-kHz system is being deployed on the upcoming 2018 IceSAT-2 mission in the Advanced Topographic Laser Altimeter System (ATLAS) instrument. This system will provide point returns along six tracks at a spacing of roughly 70 cm. Ideally, a future system could provide ground point densities of approximately 8 points per square meters on biweekly or monthly time scales to provide growth phenology. Growth phenology of major commodity crops, coupled with plant growth models, would provide a powerful tool for improved crop market projections and early warning of famine. Synchronized lidar and traditional multispectral and narrow-band spectrometer measurements coupled with multidata fusion techniques would further address multiple research objectives recommended by several other Decadal Survey panels.

RESULTING SOCIETAL BENEFIT

The crucial question for our interactions with water is: How can we protect ecosystems and better manage and predict water availability and quality for future generations, given changes to the water cycle caused by human activities and climate trends? The problem of sustainable water resources management is itself a grand research challenge not only because prediction of future forcings is challenging but also because real-time measurements of the state of the hydrologic systems, including the essential stores and fluxes of surface water and groundwater, are commonly lacking (NRC, 2012, 1991). The recommended enhancements to remote sensing of the water cycle focus on critical research questions and provide insights that enable us to address societal needs for understanding of water systems. Water will become even more critical and difficult to manage in a highly variable future that involves new and growing stressors on the global water resource, all of which contribute to changes in quality, quantity, and availability of water (Zimmerman et al., 2008). These stressors—changing climate, evolving land use and urbanization, shifting water demands for food, energy and fiber, growing and migrating populations, and individual and societal decisions—complicate efforts to ensure clean water to support humans and ecosystems. Balancing the needs of water for people and water for critical and sensitive ecosystems presents a significant challenge for natural, social, and engineering science. There is widespread agreement with regard to the need to develop methods and application-oriented frameworks for using satellite data in water and ecosystems resources management, to monitor and protect public health and agriculture, and to manage disaster preparedness and response (Hossain et al., 2016).

Use of Remotely Sensed Data to Manage Water

NASA's Applied Earth Sciences Program has developed over the last decade a portfolio of demonstration activities focused on transferring research to operations, toward bringing NASA's observations and models to national and international partners through regional centers (e.g., the SERVIR network), training programs, and capacity building. A track record of successful collaborations with the Federal Emergency Management Agency (FEMA) and state agencies already exists, including reconnaissance of the 2016 Mississippi and Louisiana flooding to support FEMA disaster response. Increasing the use of satellite-based observations by the public in the future requires a comprehensive understanding of how observations and models are integrated in sector-specific decision making toward providing products with information content tailored to meet stakeholder needs. For example, reservoir operations for flood control, water supply, and power generation benefit from river forecasts (Boucher et al., 2012), and more accurate forecasts permit more effective reservoir operations, either through improved seasonal forecasts via improved initial conditions or via more accurate interannual meteorological forecasts (Anghileri et al., 2016). Enhancements to both the initial conditions and the interannual forecasts will be enabled by the goals, objectives, and measurements proposed here. Estimates of snow water equivalent drive many of the water supply forecasts, especially in the western United States. The measurements and the modeling that will result are specifically designed to improve basin snow water equivalent estimates that can be used to update forecast model states. Objective H-1a includes measuring evaporation more accurately, thereby leading to improved formulations of the evaporative fluxes in both meteorological and hydrologic models, which can lead to improvements in the interannual forecasts. Availability of reliable information about water at scales from small basins to Earth itself can improve decisions. Recognizing that decisions about managing water and adapting to its scarcities and abundance will be made regardless of the availability of information, we can examine instances where better information has led to decisions that benefit society, by increasing revenues, decreasing costs, or providing humanitarian benefits that are harder to measure but at least as valuable. In addition, understanding how information is used by various decision makers or planners is key toward developing more effective use of models and tools in water management (Meyer et al., 2013; Matte et al., 2017; Thiboult et al., 2017).

Groundwater at the Scale of Management Decisions

A major challenge in hydrology and water resources management is the lack of integration of groundwater and surface water. This challenge is directly linked to the considerable difficulty of measuring groundwater recharge, which is largely the residual of precipitation and evapotranspiration. Unfortunately, the errors inherent to measurements of precipitation and evapotranspiration often exceed the magnitudes of recharge, rendering this key coupling between surface water and groundwater poorly defined in the past, present, and future. The ongoing improvements in remote sensing of precipitation and evapotranspiration will significantly improve our ability to better couple the surface and subsurface parts of the hydrologic cycle. With current knowledge, directly remotely sensing groundwater storage is feasible only at very coarse scales using GRACE (Richey et al., 2015) or possibly by examining hysteresis in elastic subsidence and rebound, for which there is some intriguing evidence (Chaussard et al., 2014). Inelastic subsidence, whereby groundwater withdrawals have permanently lowered the land surface, has been measured with InSAR (Amelung et al., 1999), but at that point the nonsustainable withdrawal of groundwater has already occurred. Sustainably managing all the major stores of circulating freshwater, most of which are in the subsurface, would benefit from a technology to measure changes in groundwater storage at a scale at which basins are managed, ~50 km. As of the date of publication of this Decadal Survey, such a technology with sufficient evidence of its usefulness does not exist. A GRACE-like instrument would be useful at 50 km resolution, but the GRACE-FO does not achieve that. InSAR has applications in other areas of Earth science, and if such a technology is selected for launch in the 2024-2034 time frame, then exploring its use in estimating groundwater balance through measurement of elastic subsidence is a fruitful research area for NASA and its partners.

Remote Sensing of Snow Water Equivalent

Figure 6.12 shows an example of how remotely sensed information increased confidence in water management. The Tuolumne River in California's Sierra Nevada flows into Hetch Hetchy Reservoir, which supplies water for San Francisco, protects against downstream floods, and generates hydropower. Managing the quantity of water stored in the reservoir thus addresses competing interests: keeping the reservoir as full as possible increases the supply of water, maintaining a buffer below its capacity protects against floods, and releasing water to generate hydropower produces income. Operating the reservoir uses estimates about the snow water equivalent remaining in the basin above the reservoir. Historically, this information comes from

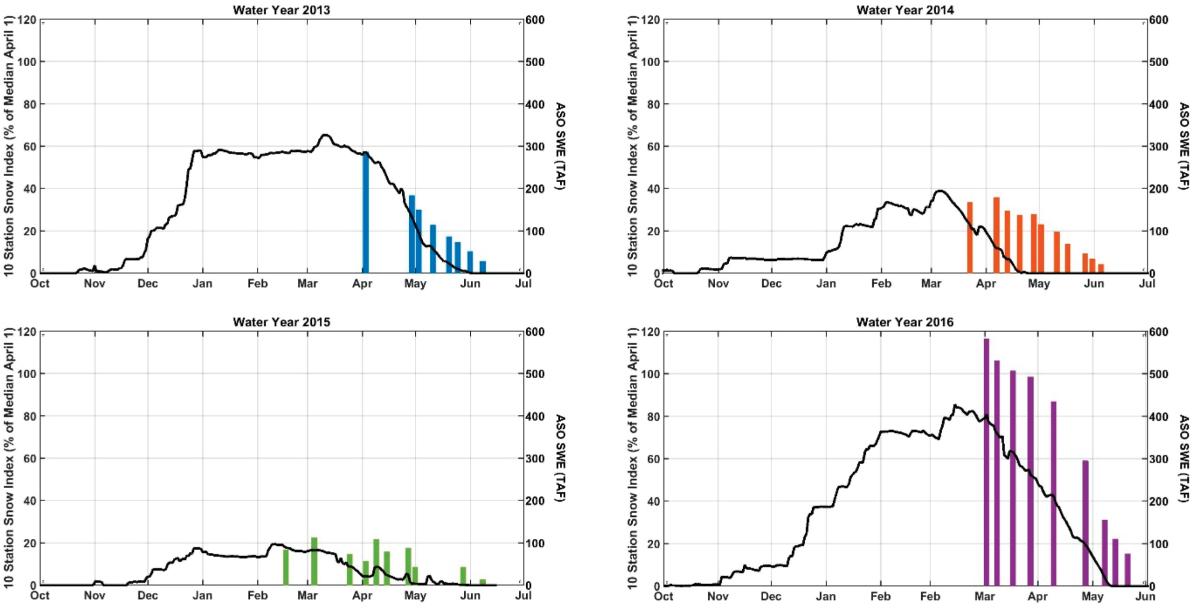

FIGURE 6.12 Information about the snowpack in California's Tuolumne River Basin from the traditional method based on a network of snow sensors (black lines in the figures) and from NASA's Airborne Snow Observatory (colored bars in the figures) for the years 2013 through 2016. The primary (left side) y-axes show the basin-wide snow water equivalent as a percentage of the median value on April 1, while the secondary (right) y-axes show snow water equivalent measured from the Airborne Snow Observatory. In 2013, the surface network provided an adequate picture of the snow resource, but in 2014 and 2016, the surface network underestimated the snow. SOURCE: C. Graham, Hetch Hetchy Water and Power System, and T.H. Painter, NASA/JPL.

a network of snow sensors, but since 2013 NASA's Airborne Snow Observatory (Painter et al., 2016) has measured spatially distributed snow depth weekly in the springtime from near-peak accumulation through the end of the snowmelt season with a scanning lidar. Snow water equivalent is estimated by multiplying these values with snow density, which is determined from measurements at snow sensors in the basin and interpolated in combination with a snowmelt model. ASO's imaging spectrometer measure snows albedo.

In the first year of operation, 2013, the surface network showed the same picture about the remaining snow as the ASO. From 2013 to 2016 Hetch Hetchy Water and Power (HHWP, part of San Francisco's Public Utilities Commission) found that accumulated inflow to the reservoir from dates of ASO acquisition through the end of July in each year strongly correlated ($R^2 > 0.99$) with a linear combination of ASO's measurement of the total basin snowpack and local rainfall during the melt season. These years spanned a historically severe drought from 2013 to 2015 and a near average year of 2016.

In 2013 reservoir managers were happy to see that the remotely sensed observations confirmed what they already knew. Then in 2014, and again in 2016, ASO showed more snow remaining in the basin than the surface network showed (see Figure 6.12), because in those years a different pattern of snow accumulation produced more snow at the higher elevations that are not sampled well by the surface network. HHWP has long used a composite of snow sensors in and surrounding the Tuolumne River Basin to estimate the accumulation and melt of snow in the basin. ASO's measurement of the distribution of snow water equivalent (see Figure 6.11) showed that in 2014, when snow at all the sensors had melted, ASO showed that 85 percent of peak water equivalent remained in the basin.

The robustness of the relationship between runoff and ASO gave HHWP far greater confidence in water management decisions in these critical drought years.

Management of Agricultural Lands

Other examples exist of operational implementation of satellite-based Earth observations and modeling for improved water resources management. The NASA Applied Sciences Water Resources Program (https://appliedsciences.nasa.gov/programs/water-resources-program) supports several efforts including mapping of fallowed area for regional agricultural drought impact assessment, water supply forecasting, regional drought monitoring, optimization of reservoir operations for hydropower, and improved global crop production decision support.

One example includes a joint project with the California Department of Water Resources (CDWR); U.S. Department of Agriculture (USDA); U.S. Geological Survey (USGS); NASA Ames Research Center; and California State University, Monterey Bay (CSUMB). Landsat data are being used to track the extent of fallowed land in the Central Valley of California using satellite imagery including Landsat 5, 7, and 8 (Figure 6.13). Project partners are now working to establish an operational fallowed land monitoring service as part of a California drought early warning information system, a pilot of the National Integrated Drought Information System (NIDIS) led by NOAA. This effort is helping estimate the economic impacts of drought events—for example, the system helped confirm model-based estimates of 1.91 million acres of fallowed land during the 2015 drought in California Central Valley—an increase of 540,000 acres relative to recent years with similar average precipitation across the state.

Few rigorous studies have thoroughly demonstrated the socioeconomic benefits of satellite data applications for improve water resources management. One example included an econometric analysis to characterize the contribution of assimilating GRACE data into the U.S. Drought Monitor (Svoboda et al., 2002) to capture the effects of drought on the agricultural sector. The study employed a multimethod approach to constrain prior and posterior decision-maker beliefs based on GRACE-enhanced observations to estimate economic value of information (Bernknopf and Shapiro, 2015). In this way the method illustrates the risk and potential impact of management decisions from drought events captured (and missed) by the USDM from 2002 to 2013. Results indicate that the sum of errors from the addition of GRACE data assimilation is reduced by roughly $1.1 billion per year (Long et al., 2013; Richey et al., 2015). In addition, the study illustrates how careful integration of satellite-based observations in an operational system such as the USDM can lead to meaningful changes in a policy-making setting.

Another study used a conceptual framework and multiple environmental models to assess the socioeconomic impact of Landsat-based agricultural mapping and groundwater quality (Forney et al., 2012). Effects of dynamic nitrogen loading and transport were considered based on specified distances from specific wells and at landscape scales. Mapped land for corn and soybean production in northeastern Iowa was used to assess the risk of groundwater contamination if corn and soybean production were moved to lands identified to be less prone to leach nitrate (Figure 6.14). The marginal benefit of the Moderate-Resolution Land Imagery (MRLI) value of information (VOI) in 2010 dollars is $858 million ± $197 million annualized.

Floods and Droughts

Globally, floods have accounted for 47 percent of all weather-related disasters, affecting 2.3 billion people. The number of floods per year rose to an average of 171 in the period 2005-2014, up from an annual average of 127 in the previous decade (UNISDR, 2015). Flood events amount to several-billion-dollar costs, up to $4 billion in the United States alone.

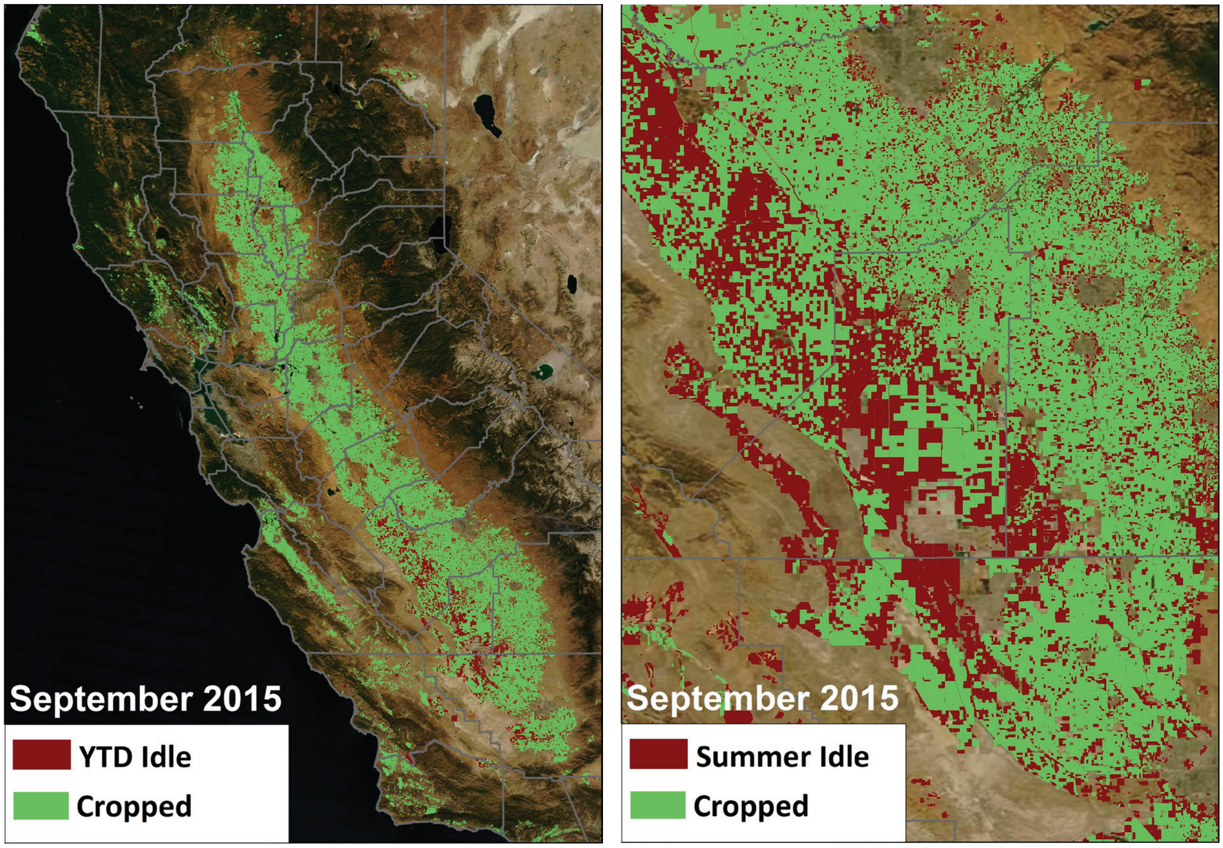

FIGURE 6.13 The images show changes in crop cultivation and idle agricultural lands in California during the summer of 2016. In the left image, brown pixels depict farms and orchards that have been left fallow or "idled" since June 1. Green pixels are lands still being farmed during the summer growing season. Light brown pixels in the map of California (left) show fields that were fallow in both 2011 and 2016. The right-hand image provides a detailed view of land fallowing in the San Joaquin Valley during the summer of 2016. Compared to 2011, an additional 542,000 acres were fallowed. SOURCE: F. Melton, NASA.

Drought prediction and mitigation offers another example of direct societal benefit from the remote sensing measurements listed in this report. Over the last two decades, over 1 billion people have been affected by drought (1995-2015) due to food insecurity, which compounded with water shortages and water quality results in long-term impacts on public health and ecosystems (UNISDR, 2015). In 2016, droughts were estimated to have cost the United States $3.5 billion; in 2015, that same drought cost the United States $4.5 billion, and wildfires, whose likelihood are increased in drought conditions, cost an additional $1 billion in the western United States and Alaska. The 2012 drought cost is estimated at $30 billion and 123 deaths, with an additional $10 billion and 53 deaths in 2013 (NOAA NCDC, 2017). Predicting drought onset and end depends on currently uncertain long-range precipitation predictions and good soil moisture measurements (Wood et al., 2015). In snow-dominated watersheds, seasonal drought is predictable if the snow accumulation can be assessed near the beginning of the melt season. Snow-covered area can be derived from remotely sensed data, but in the mountainous areas where the winter snowpack is deep, passive microwave sensors are ineffective; hence the high priority for Objective H-1c.

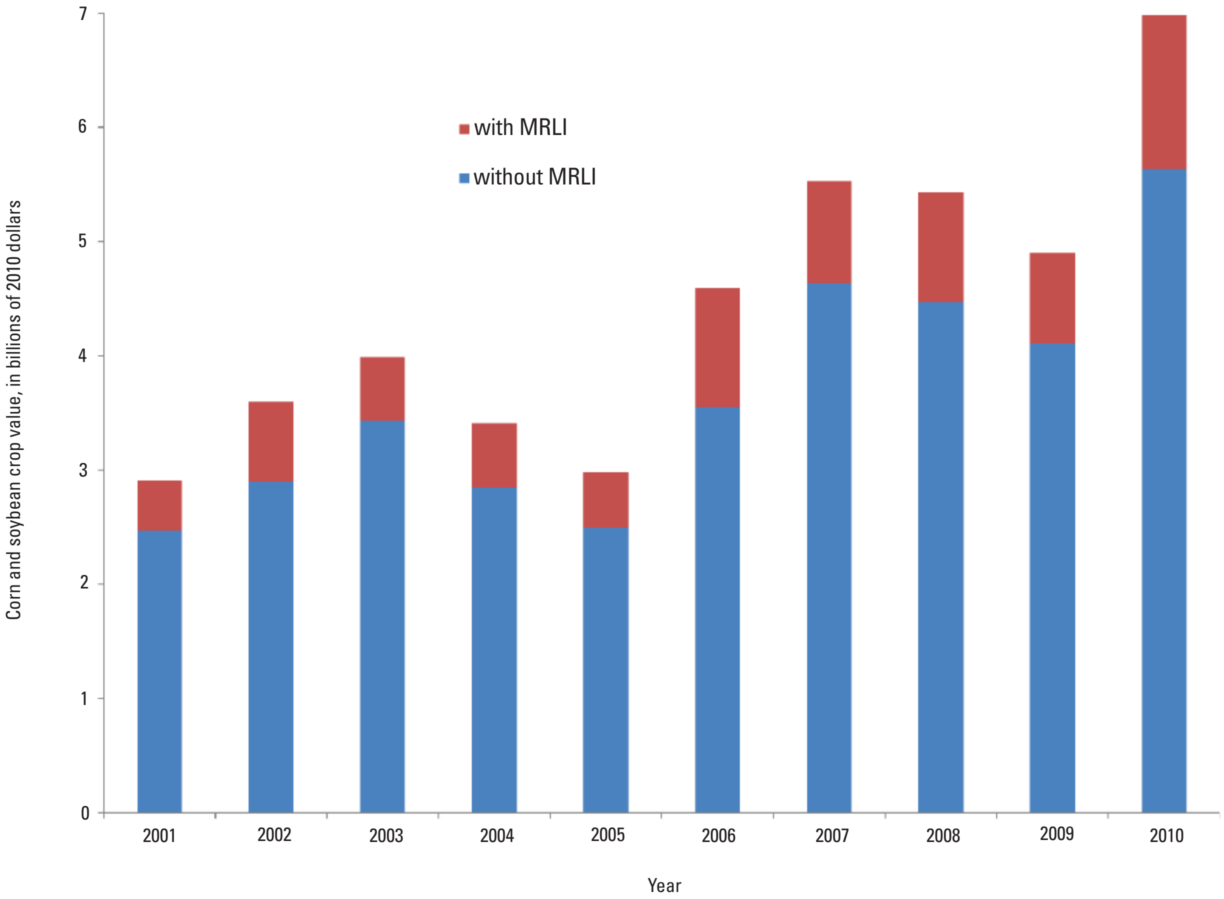

FIGURE 6.14 Annual benefits with and without Landsat imagery (MRLI) for the 35-county northeastern Iowa study region. The value of corn and soybean production using the observed land use pattern is shown by the blue bars. The higher value illustrated by the red bars would be possible without increasing the risk of groundwater contamination if corn production were moved to lands identified to be less prone to leached nitrate and additionally to lands with fate and transport properties that render aquifers less vulnerable to leached nitrate. SOURCES: U.S. Geological Survey; Forney et al. (2012).

Objectives H-1a, H-1b, and H-1c, along with H-2a, combine to quantify the major fluxes of the water cycle, and will be essential contributors to the improvement of the precipitation forecasts. In this case the societal benefit will result from the combination of existing measurement programs (SMAP) with new measurements. Even slight improvements in our ability to manage our water resources to mitigate drought impacts can potentially save many millions of dollars. Conceptually, we understand the water cycle, but our quantitative understanding of its components is limited to some fluxes—streamflow and precipitation, for example—and surface water stores (NRC, 1991, 2002, 2008). Climate change, however, causes changes in vegetation, human extraction of water, the rain-snow transition, and the timing and severity of storms. These changes in turn alter soil properties, channel networks, and other landscape features. Current surface monitoring networks were never designed to examine these factors together, yet remote sensing technologies enable this type of integrated data collection.

Integration with Climate Models

We could list many examples here where recommended advances in remote sensing address gaps in measurements, which in turn inhibit understanding. Choosing one, models of future climate agree better with each other about future temperatures than about future precipitation and evapotranspiration (Coquard et al., 2004). An impediment to progress is that the measurements of precipitation that include both rain and snow are not sufficient to validate numerical weather predictions—for example, sites where precipitation or snow accumulation is measured are generally on flat ground, even on mountain summits, and in most mountain ranges do not extend to the highest elevations where precipitation occurs. Remote sensing can help with this validation through strategies to integrate measured values over the scales of models' grid cells.

Design and operation of water infrastructure have traditionally relied on empirical relationships and engineering experience. Unfortunately, because of our need for ongoing operation of our distributed water infrastructure under dynamic and locally distinct conditions, there are significant gaps in our understanding that are critical for improved operation, maintenance, and future design. Because we cannot turn off our systems or test them to failure, we make small changes to adapt to new conditions, but we cannot evaluate changes at the scale of operational systems or with consideration of the complete engineered water cycle. The small changes we can make enable incremental improvements, but they do not necessarily advance our understanding to a state where we could operate or optimize under different conditions, including energy management.

REFERENCES

Abdalati, W., H.J. Zwally, R. Bindschadler, B. Csatho, S.L. Farrell, H.A. Fricker, D. Harding, et al. 2010. The ICESat-2 laser altimetry mission. *Proceedings of the IEEE* 98(5):735-751.

Acclimatise. 2014. "Climate change resilience in Europe: A snapshot of the private sector." http://www.acclimatise.uk.com/login/uploaded/resources/CDP_Document.pdf.

Adams, H.D., C.H. Luce, D.D. Breshears, C.D. Allen, M. Weiler, V.C. Hale, A.M.S. Smith, and T.E. Huxman. 2012. Ecohydrological consequences of drought- and infestation-triggered tree die-off: Insights and hypotheses. *Ecohydrology* 5(2):145-159.

Adams-Selin, R.D., S.C. van den Heever, and R.H. Johnson. 2013. Impact of graupel parameterization schemes on idealized bow echo simulations. *Monthly Weather Review* 141(4):1241-1262.

Adikari, Y., and J. Yoshitani. 2009. *Global Trends in Water-Related Disasters: An Insight for Policymakers*. Paris: UNESCO.

Adler, R.F., G.J. Huffman, A. Chang, R. Ferraro, P.P. Xie, J. Janowiak, B. Rudolf, et al. 2003. The Version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979-present). *Journal of Hydrometeorology* 4(6):1147-1167.

AghaKouchak, A., L. Cheng, O. Mazdiyasni, and A. Farahmand. 2014. Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought. *Geophysical Research Letters* 41(24):8847-8852.

Ahearn, D.S., R.W. Sheibley, R.A. Dahlgren, M. Anderson, J. Johnson, and K.W. Tate. 2005. Land use and land cover influence on water quality in the last free-flowing river draining the Western Sierra Nevada, California. *Journal of Hydrology* 313(3-4):234-247.

Ajami, N.K., B.H. Thompson Jr., and D.G. Victor. 2014. *The Path to Water Innovation*. Washington, DC: Brookings Institution.

Akbar, R., N. Das, D. Entekhabi, and M. Moghaddam. 2016. Active and passive microwave remote sensing synergy for soil moisture estimation. Pp. 187-208 in *Satellite Soil Moisture Retrieval: Techniques and Applications* (P.K. Srivastava, G.P. Petropoulos, and Y.H. Kerr, eds.). Amsterdam: Elsevier.

Akhtar, M.K., G.A. Corzo, S.J. van Andel, and A. Jonoski. 2009. River flow forecasting with artificial neural networks using satellite observed precipitation pre-processed with flow length and travel time information: Case study of the Ganges river basin. *Hydrology and Earth System Sciences* 13(9):1607-1618.

Alexander, L.V., X. Zhang, T.C. Peterson, J. Caesar, B. Gleason, A.M.G. Klein Tank, M. Haylock, et al. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres* 111(D5):D05109.

Allan, D., D. Erickson, and J. Fay. 1997. The influence of catchment land use on stream integrity across multiple spatial scales. *Freshwater Biology* 37(1):149-161.

Alley, W.M., and L.F. Konikow. 2015. Bringing GRACE down to earth. *Groundwater* 53(6):826-829.

Amelung, F., D.L. Galloway, J.W. Bell, H.A. Zebker, and R.J. Laczniak. 1999. Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer-system deformation. *Geology* 27(6):483-486.

AmeriFlux. 2017. "AmeriFlux Network." http://ameriflux.lbl.gov/. Accessed April 5, 2018.

Ampe, E.M., D. Raymaekers, E.L. Hestir, M. Jansen, E. Knaeps, and O. Batelaan. 2015. A wavelet-enhanced inversion method for water quality retrieval from high spectral resolution data for complex waters. *IEEE Transactions on Geoscience and Remote Sensing* 53(2):869-882.

Anderegg, W.R.L., J.M. Kane, and L.D.L. Anderegg. 2013. Consequences of widespread tree mortality triggered by drought and temperature stress. *Nature Climate Change* 3(1):30-36.

Anderson, M.C., C. Hain, B. Wardlow, A. Pimstein, J.R. Mecikalski, and W.P. Kustas. 2011. Evaluation of drought indices based on thermal remote sensing of evapotranspiration over the Continental United States. *Journal of Climate* 24(8):2025-2044.

Anderson, M.C., J.M. Norman, J.R. Mecikalski, J.A. Otkin, and W.P. Kustas. 2007. A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 1. Model formulation. *Journal of Geophysical Research: Atmospheres* 112(D10).

Anderson, M.C., J.M. Norman, J.R. Mecikalski, R.D. Torn, W.P. Kustas, and J.B. Basara. 2004. A multiscale remote sensing model for disaggregating regional fluxes to micrometeorological scales. *Journal of Hydrometeorology* 5(2):343-363.

Anghileri, D., N. Voisin, A. Castelletti, F. Pianosi, B. Nijssen, and D.P. Lettenmaier. 2016. Value of long-term streamflow forecasts to reservoir operations for water supply in snow-dominated river catchments. *Water Resources Research* 52(6):4209-4225.

Aragão, L.E.O.C. 2012. The rainforest's water pump. *Nature* 489(7415):217-218.

Armstrong, P. 2014. *The Log of a Snow Survey: Skiing and Working in a Mountain Winter World.* Bloomington, Ind.: Abbott Press.

Arnold, J.G., and N. Fohrer. 2005. SWAT2000: Current capabilities and research opportunities in applied watershed modelling. *Hydrological Processes* 19(3):563-572.

Ashley, S.T., and W.S. Ashley. 2008. Flood fatalities in the United States. *Journal of Applied Meteorology and Climatology* 47(3):805-818.

Ashouri, H., K.L. Hsu, S. Sorooshian, D.K. Braithwaite, K.R. Knapp, L.D. Cecil, B.R. Nelson, and O.P. Prat. 2015. PERSIANN-CDR: Daily precipitation climate data record from multisatellite observations for hydrological and climate studies. *Bulletin of the American Meteorological Society* 96(1):69-83.

Asner, G.P., J. Mascaro, H.C. Muller-Landau, G. Vieilledent, R. Vaudry, M. Rasamoelina, J.S. Hall, and M. Van Breugel. 2012. A universal airborne lidar approach for tropical forest carbon mapping. *Oecologia* 168(4):1147-1160.

August, T., D. Klaes, P. Schlüssel, T. Hultberg, M. Crapeau, A. Arriaga, A. O'Carroll, D. Coppens, R. Munro, and X. Calbet. 2012. IASI on Metop-A: Operational level 2 retrievals after five years in orbit. *Journal of Quantitative Spectroscopy and Radiative Transfer* 113(11):1340-1371.

Bair, E.H., R.E. Davis, and J. Dozier. 2017. Hourly mass and snow energy balance measurements from Mammoth Mountain, CA USA, 2011-2017. *Earth System Science Data Discussion* 2017:1-15.

Bair, E.H., K. Rittger, R.E. Davis, T.H. Painter, and J. Dozier. 2016. Validating reconstruction of snow water equivalent in California's Sierra Nevada using measurements from the NASA Airborne Snow Observatory. *Water Resources Research* 52:8437-8460.

Bajracharya, B., A.B. Shrestha, and L. Rajbhandari. 2007. Glacial lake outburst floods in the Sagarmatha region. *Mountain Research and Development* 27(4):336-344.

Baldocchi, D., E. Falge, L. Gu, R. Olson, D. Hollinger, S. Running, P. Anthoni, et al. 2001. FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. *Bulletin of the American Meteorological Society* 82(11):2415-2434.

Bales, R.C., N.P. Molotch, T.H. Painter, M.D. Dettinger, R. Rice, and J. Dozier. 2006. Mountain hydrology of the Western United States. *Water Resources Research* 42:W08432.

Barnett, T.P., J.C. Adam, and D.P. Lettenmaier. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438:303-309.

Barros, A.P. 2013. Orographic precipitation, freshwater resources, and climate vulnerabilities in mountainous regions. Pp. 57-58 in *Climate Vulnerability: Understanding and Addressing Threats to Essential Resources* (R. Pielke, ed.). Oxford: Academic Press.

Barros, A.P., Y. Duan, J. Brun, and M.A. Medina. 2014. Flood nonstationarity in the Southeast and Mid-Atlantic regions of the United States. *Journal of Hydrologic Engineering* 19(10):05014014.

Barros, A.P., J.L. Hodes, and M. Arulraj. 2017. Decadal climate variability and the spatial organization of deep hydrological drought. *Environmental Research Letters* 12(10):104005.

Barros, A.P., G. Kim, E. Williams, and S.W. Nesbitt. 2004. Probing orographic controls in the Himalayas during the monsoon using satellite imagery. *Natural Hazards and Earth System Sciences* 4(1):29-51.

Barros, A.P., and T.J. Lang. 2003. Monitoring the monsoon in the Himalayas: Observations in Central Nepal, June 2001. *Monthly Weather Review* 131(7):1408-1427.

Bauer, P., A. Thorpe, and G. Brunet. 2015. The quiet revolution of numerical weather prediction. *Nature* 525(7567):47-55.

Belmont, P., K.B. Gran, S.P. Schottler, P.R. Wilcock, S.S. Day, C. Jennings, J.W. Lauer, E. Viparelli, J.K. Willenbring, D.R. Engstrom, and G. Parker. 2011. Large shift in source of fine sediment in the Upper Mississippi River. *Environmental Science & Technology* 45(20):8804-8810.

Benjamin, S.G., S.S. Weygandt, J.M. Brown, M. Hu, C.R. Alexander, T.G. Smirnova, J.B. Olson, et al. 2015. A North American hourly assimilation and model forecast cycle: The rapid refresh. *Monthly Weather Review* 144(4):1669-1694.

Benson, E. 2012. One infrastructure, many global visions: The commercialization and diversification of Argos, a satellite-based environmental surveillance system. *Social Studies of Science* 42(6):843-868.

Berg, P., C. Moseley, and J.O. Haerter. 2013. Strong increase in convective precipitation in response to higher temperatures. *Nature Geoscience* 6(3):181-185.

Berg, W., S. Bilanow, R. Chen, S. Datta, D. Draper, H. Ebrahimi, S. Farrar, et al. 2016. Intercalibration of the GPM microwave radiometer constellation. *Journal of Atmospheric and Oceanic Technology* 33(12):2639-2654.

Berggren, K., M. Olofsson, M. Viklander, G. Svensson, and A.M. Gustafsson. 2012. Hydraulic Impacts on urban drainage systems due to changes in rainfall caused by climatic change. *Journal of Hydrologic Engineering* 17(1):92-98.

Berne, A., G. Delrieu, J.D. Creutin, and C. Obled. 2004. Temporal and spatial resolution of rainfall measurements required for urban hydrology. *Journal of Hydrology* 299(3):166-179.

Bernknopf, R., and C. Shapiro. 2015. Economic assessment of the use value of geospatial information. *ISPRS International Journal of Geo-Information* 4(3):1142-1165.

Betts, A.K. 2004. Understanding hydrometeorology using global models. *Bulletin of the American Meteorological Society* 85(11):1673-1688.

Betts, A.K., J.H. Ball, A.C.M. Beljaars, M.J. Miller, and P.A. Viterbo. 1996. The land surface-atmosphere interaction: A review based on observational and global modeling perspectives. *Journal of Geophysical Research: Atmospheres* 101(D3):7209-7225.

Bhutiyani, M.R., V.S. Kale, and N.J. Pawar. 2010. Climate change and the precipitation variations in the northwestern Himalaya: 1866-2006. *International Journal of Climatology* 30(4):535-548.

Biancamaria, S., D.P. Lettenmaier, and T.M. Pavelsky. 2016. The SWOT mission and its capabilities for land hydrology. *Surveys in Geophysics* 37(2):307-337.

Biederman, J.A., A.J. Somor, A.A. Harpold, E.D. Gutmann, D.D. Breshears, P.A. Troch, D.J. Gochis, R.L. Scott, A.J.H. Meddens, and P.D. Brooks. 2015. Recent tree die-off has little effect on streamflow in contrast to expected increases from historical studies. *Water Resources Research* 51(12):9775-9789.

Bladon, K.D., U. Silins, M.J. Wagner, M. Stone, M.B. Emelko, C.A. Mendoza, K.J. Devito, and S. Boon. 2008. Wildfire impacts on nitrogen concentration and production from headwater streams in southern Alberta's Rocky Mountains. *Canadian Journal of Forest Research* 38(9):2359-2371.

Blann, K.L., J.L. Anderson, G.R. Sands, and B. Vondracek. 2009. Effects of agricultural drainage on aquatic ecosystems: A review. *Critical Reviews in Environmental Science and Technology* 39(11):909-1001.

Bolten, J.D., W.T. Crow, X. Zhan, T.J. Jackson, and C.A. Reynolds. 2010. Evaluating the utility of remotely sensed soil moisture retrievals for operational agricultural drought monitoring. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 3(1):57-66.

Bondeau, A., P.C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller, M. Reichstein, and B. Smith. 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology* 13(3):679-706.

Borsa, A.A., D.C. Agnew, and D.R. Cayan. 2014. Ongoing drought-induced uplift in the western United States. *Science* 345(6204):1587-1590.

Boucher, M.A., D. Tremblay, L. Delorme, L. Perreault, and F. Anctil. 2012. Hydro-economic assessment of hydrological forecasting systems. *Journal of Hydrology* 416:133-144.

Brocca, L., S. Hasenauer, T. Lacava, F. Melone, T. Moramarco, W. Wagner, W. Dorigo, et al. 2011. Soil moisture estimation through ASCAT and AMSR-E sensors: An intercomparison and validation study across Europe. *Remote Sensing of Environment* 115(12):3390-3408.

Brown, S.A., J.D. Schall, J.L. Morris, C.L. Doherty, S.M. Stein, and J.C. Warner. 2009. *Urban Drainage Design Manual*. Washington, DC: Federal Highway Administration.

Brun, J., and A.P. Barros. 2014. Mapping the role of tropical cyclones on the hydroclimate of the southeast United States: 2002-2011. *International Journal of Climatology* 34(2):494-517.

Bryan, G.H., and H. Morrison. 2012. Sensitivity of a simulated squall line to horizontal resolution and parameterization of microphysics. *Monthly Weather Review* 140(1):202-225.

Burgin, M.S., A. Colliander, E.G. Njoku, S.K. Chan, F. Cabot, Y.H. Kerr, R. Bindlish, T.J. Jackson, D. Entekhabi, and S.H. Yueh. 2017. A comparative study of the SMAP passive soil moisture product with existing satellite-based soil moisture products. *IEEE Transactions on Geoscience and Remote Sensing* 55(5):2959-2971.

Burke, M.P., T.S. Hogue, A.M. Kinoshita, J. Barco, C. Wessel, and E.D. Stein. 2013. Pre-and post-fire pollutant loads in an urban fringe watershed in Southern California. *Environmental Monitoring and Assessment* 185(12):10131-10145.

Campolo, M., A. Soldati, and P. Andreussi. 2003. Artificial neural network approach to flood forecasting in the River Arno. *Hydrological Sciences Journal* 48(3):381-398.

Canadell, J.G., H.A. Mooney, D.D. Baldocchi, J.A. Berry, J.R. Ehleringer, C.B. Field, S.T. Gower, et al. 2000. Carbon metabolism of the terrestrial biosphere: A multitechnique approach for improved understanding. *Ecosystems* 3(2):115-130.

Cannon Leahy, T. 2016. Desperate times call for sensible measures: The making of the California Sustainable Groundwater Management Act. *Golden Gate University Environmental Law Journal* 9(1):5-40.

Chaney, N.W., P. Metcalfe, and E.F. Wood. 2016. HydroBlocks: A field-scale resolving land surface model for application over continental extents. *Hydrological Processes* 30(20):3543-3559.

Chang, A.T.C., J.L. Foster, and D.K. Hall. 1987. Nimbus-7 SMMR derived global snow cover parameters. *Annals of Glaciology* 9:39-44.

Chang, N.B., S. Imen, and B. Vannah. 2015. Remote sensing for monitoring surface water quality status and ecosystem state in relation to the nutrient cycle: A 40-year perspective. *Critical Reviews in Environmental Science and Technology* 45(2):101-166.

Chaussard, E., R. Bürgmann, M. Shirzaei, E.J. Fielding, and B. Baker. 2014. Predictability of hydraulic head changes and characterization of aquifer-system and fault properties from InSAR-derived ground deformation. *Journal of Geophysical Research: Solid Earth* 119(8):6572-6590.

CHRS (Center for Hydrometeorlogy and Remote Sensing) Rainsphere. 2017. "An integrated system for global satellite precipitation data and information using PERSIANN-CDR." http://rainsphere.eng.uci.edu/. Accessed April 5, 2018.

Church, J.E. 1914. Recent studies of snow in the United States. *Quarterly Journal of the Royal Meteorological Society* 40(169):43-52.

Church, J.E. 1933. Snow surveying: Its principles and possibilities. *Geographical Review* 23(4):529-563.

Clark, E.A., J. Sheffield, M.T.H. van Vliet, B. Nijssen, and D.P. Lettenmaier. 2015. Continental runoff into the oceans (1950-2008). *Journal of Hydrometeorology* 16(4):1502-1520.

Clow, D.W., L. Nanus, K.L. Verdin, and J. Schmidt. 2012. Evaluation of SNODAS snow depth and snow water equivalent estimates for the Colorado Rocky Mountains, USA. *Hydrological Processes* 26(17):2583-2591.

Coes, A.L., and D.R. Pool. 2007. Ephemeral-stream channel and basin-floor infiltration and recharge in the Sierra Vista subwatershed of the Upper San Pedro Basin, southeastern Arizona. Pp. 253-311 in *Ground-Water Recharge in the Arid and Semiarid Southwestern United States* (D.A. Stonestrom, J. Constantz, T.P.A. Ferre, and S.A. Leake, eds.). USGS Professional Paper 1703-J. http://pubs.usgs.gov/pp/pp1703/j/.

Colliander, A., T.J. Jackson, R. Bindlish, S. Chan, N. Das, S.B. Kim, M.H. Cosh, et al. 2017. Validation of SMAP surface soil moisture products with core validation sites. *Remote Sensing of Environment* 191:215-231.

Coquard, J., P.B. Duffy, K.E. Taylor, and J.P. Iorio. 2004. Present and future surface climate in the western USA as simulated by 15 global climate models. *Climate Dynamics* 23(5):455-472.

Cox, L.M., D. Bartee, A. Crook, P.E. Farnes, and J.L. Smith. 1978. The care and feeding of snow pillows. In *Proceedings, 46th Western Snow Conference*. https://westernsnowconference.org/node/1109.

Crane, R.G., and M.R. Anderson. 1984. Satellite discrimination of snow/cloud surfaces. *International Journal of Remote Sensing* 5(1):213-223.

Cuo, L., D.P. Lettenmaier, M. Alberti, and J.E. Richey. 2009. Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin. *Hydrological Processes* 23(6):907-933.

Dai, A. 2012. Increasing drought under global warming in observations and models. *Nature Climate Change* 3:52-58.

Dalin, C., Y. Wada, T. Kastner, and M.J. Puma. 2017. Groundwater depletion embedded in international food trade. *Nature* 543(7647):700-704.

DeBano, L.F. 2000. The role of fire and soil heating on water repellency in wildland environments: A review. *Journal of Hydrology* 231:195-206.

Derksen, C., P. Toose, J. Lemmetyinen, J. Pulliainen, A. Langlois, N. Rutter, and M.C. Fuller. 2012. Evaluation of passive microwave brightness temperature simulations and snow water equivalent retrievals through a winter season. *Remote Sensing of Environment* 117:236-248.

Dettinger, M.D. 2013. Atmospheric rivers as drought busters on the U.S. West Coast. *Journal of Hydrometeorology* 14(6):1721-1732.

Devred, E., K. Turpie, W. Moses, V. Klemas, T. Moisan, M. Babin, G. Toro-Farmer, M.H. Forget, and Y.H. Jo. 2013. Future retrievals of water column bio-optical properties using the Hyperspectral Infrared Imager (HyspIRI). *Remote Sensing* 5(12):6812.

DFO (Dartmouth Flood Observatory). 2017. "Dartmouth Flood Observatory." http://floodobservatory.colorado.edu/. Accessed April 5, 2018.

Di Baldassarre, G., A. Montanari, H. Lins, D. Koutsoyiannis, L. Brandimarte, and G. Blöschl. 2010. Flood fatalities in Africa: From diagnosis to mitigation. *Geophysical Research Letters* 37(22):L22402.

Dingman, S.L. 2014. *Physical Hydrology*. 3rd ed. Long Grove, IL: Waveland Press.

Doesken, N.J., and A. Judson. 1996. *The Snow Booklet: A Guide to the Science, Climatology, and Measurement of Snow in the United States.* Fort Collins, CO: Colorado Climate Center.

Döll, P., H. Hoffmann-Dobrev, F.T. Portmann, S. Siebert, A. Eicker, M. Rodell, G. Strassberg, and B.R. Scanlon. 2012. Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics* 59-60:143-156.

Dozier, J. 1981. A method for satellite identification of surface temperature fields of subpixel resolution. *Remote Sensing of Environment* 11(3):221-229.

Dozier, J. 2011. Mountain hydrology, snow color, and the fourth paradigm. *Eos, Transactions American Geophysical Union* 92(43):373-375.

Dozier, J., E.H. Bair, and R.E. Davis. 2016. Estimating the spatial distribution of snow water equivalent in the world's mountains. *WIREs Water* 3:461-474.

Dozier, J., R.O. Green, A.W. Nolin, and T.H. Painter. 2009. Interpretation of snow properties from imaging spectrometry. *Remote Sensing of Environment* 113:S25-S37.

Duan, Y., A.M. Wilson, and A.P. Barros. 2015. Scoping a field experiment: Error diagnostics of TRMM precipitation radar estimates in complex terrain as a basis for IPHEx2014. *Hydrology and Earth System Sciences* 19(3):1501-1520.

Earl, S.R., and D.W. Blinn. 2003. Effects of wildfire ash on water chemistry and biota in SouthćWestern USA streams. *Freshwater Biology* 48(6):1015-1030.

Easterling, D.R., G.A. Meehl, C. Parmesan, S.A. Changnon, T.R. Karl, and L.O. Mearns. 2000. Climate extremes: Observations, modeling, and impacts. *Science* 289(5487):2068-2074.

Ebel, B.A., J.A. Moody, and D.A. Martin. 2012. Hydrologic conditions controlling runoff generation immediately after wildfire. *Water Resources Research* 48(3):W03529.

Ebtehaj, A.M., R.L. Bras, and E. Foufoula-Georgiou. 2016. Evaluation of ShARP passive rainfall retrievals over snow-covered land surfaces and coastal zones. *Journal of Hydrometeorology* 17(4):1013-1029.

Ek, M.B., and A.A.M. Holtslag. 2004. Influence of soil moisture on boundary layer cloud development. *Journal of Hydrometeorology* 5(1):86-99.

Ek, M.B., and L. Mahrt. 1994. Daytime evolution of relative humidity at the boundary layer top. *Monthly Weather Review* 122(12):2709-2721.

Ekström, M., H. Fowler, C. Kilsby, and P. Jones. 2005. New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 2. Future estimates and use in impact studies. *Journal of Hydrology* 300(1):234-251.

EM-DAT (Emergency Events Database). 2017. "The International Disaster Database." Université catholique de Louvain. http://www.emdat.be/. Accessed April 5, 2018.

Emelko, M.B., M. Stone, U. Silins, D. Allin, A.L. Collins, C.H. Williams, A.M. Martens, and K.D. Bladon. 2015. Sediment-phosphorus dynamics can shift aquatic ecology and cause downstream legacy effects after wildfire in large river systems. *Global Change Biology* 22:1168-1184.

Emmanuel, I., H. Andrieu, E. Leblois, and B. Flahaut. 2012. Temporal and spatial variability of rainfall at the urban hydrological scale. *Journal of Hydrology* 430-431(C):162-172.

Emori, S., and S.J. Brown. 2005. Dynamic and thermodynamic changes in mean and extreme precipitation under changed climate. *Geophysical Research Letters* 32(17):L17706.

Entekhabi, D., and M. Moghaddam. 2007. Mapping recharge from space: Roadmap to meeting the grand challenge. *Hydrogeology Journal* 15(1):105-116.

Entekhabi, D., E.G. Njoku, P.E. O'Neill, K.H. Kellogg, W.T. Crow, W.N. Edelstein, J.K. Entin, et al. 2010. The Soil Moisture Active Passive (SMAP) mission. *Proceedings of the IEEE* 98(5):704-716.

Ericson, J.P., C.J. Vörösmarty, S.L. Dingman, L.G. Ward, and M. Meybeck. 2006. Effective sea-level rise and deltas: Causes of change and human dimension implications. *Global and Planetary Change* 50(1-2):63-82.

Evenson, E.J., and R.C. Orndorff. 2013. *U.S. Geological Survey Water Science Strategy*. U.S. Geological Survey.

Famiglietti, J.S., and M. Rodell. 2013. Water in the balance. *Science* 340(6138):1300-1301.

Fang, B., V. Lakshmi, R. Bindlish, T.J. Jackson, M. Cosh, and J. Basara. 2013. Passive microwave soil moisture downscaling using vegetation index and skin surface temperature. *Vadose Zone Journal* 12(3).

Farid, A., D. Goodrich, R. Bryant, and S. Sorooshian. 2008. Using airborne lidar to predict leaf area index in cottonwood trees and refine riparian water-use estimates. *Journal of Arid Environments* 72(1):1-15.

Farid, A., D. Goodrich, and S. Sorooshian. 2006. Using airborne lidar to discern age classes of cottonwood trees in a riparian area. *Western Journal of Applied Forestry* 21(3):149-158.

Farr, T.G., P.A. Rosen, E. Caro, R. Crippen, R. Duren, S. Hensley, M. Kobrick, et al. 2007. The Shuttle Radar Topography Mission. *Reviews of Geophysics* 45:RG2004.

Faunt, C.C., R.T. Hanson, and K. Belitz. 2009. Introduction, overview of hydrogeology, and textural model of California's Central Valley. Pp. 1-54 in *Groundwater Availability of the Central Valley Aquifer, California* (C.C. Faunt, ed.). Reston VA: U.S. Geological Survey.

Federal Council for Science and Technology. 1962. *Scientific Hydrology*. Washington, DC: U.S. Government Printing Office.

Fichot, C.d.G., B.D. Downing, B.A. Bergamaschi, L. Windham-Myers, M. Marvin-DiPasquale, D.R. Thompson, and M.M. Gierach. 2015. High-resolution remote sensing of water quality in the San Francisco Bay-Delta Estuary. *Environmental Science & Technology* 50(2):573-583.

Field, C.B., V. Barros, T.F. Stocker, Q. Dahe, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, et al., eds. 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX): Special Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Findell, K.L., and E.A.B. Eltahir. 2003. Atmospheric controls on soil moisture-boundary layer interactions. Part I: Framework development. *Journal of Hydrometeorology* 4(3):552-569.

Fisher, J.B. 2014. Land-atmosphere Interactions: Evapotranspiration. Pp. 325-328 in *Encyclopedia of Remote Sensing* (E.G. Njoku, ed.). New York: Springer-Verlag.

Flanner, M.G., C.S. Zender, P.G. Hess, N.M. Mahowald, T.H. Painter, V. Ramanathan, and P.J. Rasch. 2009. Springtime warming and reduced snow cover from carbonaceous particles. *Atmospheric Chemistry and Physics* 9(7):2481-2497.

Fletcher, C.G., P.J. Kushner, A. Hall, and X. Qu. 2009. Circulation responses to snow albedo feedback in climate change. *Geophysical Research Letters* 36:L09702.

Forney, W.M., R.P. Raunikar, R.L. Bernknopf, and S.K. Mishra. 2012. *An Economic Value of Remote-Sensing Information—Application to Agricultural Production and Maintaining Groundwater Quality*. Reston, VA: U.S. Geological Survey.

Foufoula-Georgiou, E., Z. Takbiri, J.A. Czuba, and J. Schwenk. 2015. The change of nature and the nature of change in agricultural landscapes: Hydrologic regime shifts modulate ecological transitions. *Water Resources Research* 51(8):6649-6671.

Frankenberg, C., J. Berry, L. Guanter, and J. Joiner. 2013. Remote sensing of terrestrial chlorophyll fluorescence from space. *SPIE Newsroom* 19.

Frankenberg, C., C. O'Dell, L. Guanter, and J. McDuffie. 2012. Remote sensing of near-infrared chlorophyll fluorescence from space in scattering atmospheres: Implications for its retrieval and interferences with atmospheric CO_2 retrievals. *Atmospheric Measurement Techniques* 5(8):2081-2094.

Galloway, D., D.R. Jones, and S.E. Ingebritsen. 2000. *Land Subsidence in the United States*. Reston, Va.: U.S. Geological Survey.

GDACS (Global Disaster Alert and Coordination System). 2017. "Global Flood Detection System: Version 2." http://www.gdacs.org/flooddetection/. Accessed April 5, 2018.

GFMS (Global Flood Monitoring System). 2017. "Global Flood Monitoring System." http://flood.umd.edu/. Accessed April 5, 2018.

Giglio, L., and J.D. Kendall. 2001. Application of the Dozier retrieval to wildfire characterization: A sensitivity analysis. *Remote Sensing of Environment* 77(1):34-49.

Gleason, K.E., A.W. Nolin, and T.R. Roth. 2013. Charred forests increase snowmelt: Effects of burned woody debris and incoming solar radiation on snow ablation. *Geophysical Research Letters* 40(17):4654-4661.

Gleick, P.H. 2000. A look at twenty-first century water resources development. *Water International* 25(1):127-138.

Goodrich, D.C., D.G. Williams, C.L. Unkrich, J.F. Hogan, R.L. Scott, K.R. Hultine, D. Pool, A.L. Goes, and S. Miller. 2004. Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River Basin, Arizona. Pp. 77-99 in *Groundwater Recharge in a Desert Environment: The Southwestern United States* (J.F. Hogan, F.M. Phillips, and B.R. Scanlon, eds.). Washington, DC: American Geophysical Union.

Gopalan, K., N.Y. Wang, R. Ferraro, and C. Liu. 2010. Status of the TRMM 2A12 land precipitation algorithm. *Journal of Atmospheric and Oceanic Technology* 27(8):1343-1354.

Gourley, J.J., J.M. Erlingis, Y. Hong, and E.B. Wells. 2011. Evaluation of tools used for monitoring and forecasting flash floods in the United States. *Weather and Forecasting* 27(1):158-173.

Gourley, J.J., Y. Hong, Z.L. Flamig, A. Arthur, R. Clark, M. Calianno, I. Ruin, et al. 2013. A unified flash flood database across the United States. *Bulletin of the American Meteorological Society* 94(6):799-805.

Grecu, M., and W.S. Olson. 2008. Precipitating snow retrievals from combined airborne cloud radar and millimeter-wave radiometer observations. *Journal of Applied Meteorology and Climatology* 47(6):1634-1650.

Green, R.O., C. Pieters, P. Mouroulis, M. Eastwood, J. Boardman, T. Glavich, P. Isaacson, et al. 2011. The Moon Mineralogy Mapper (M^3) imaging spectrometer for lunar science: Instrument description, calibration, on-orbit measurements, science data calibration and on-orbit validation. *Journal of Geophysical Research: Planets* 116:E00G19.

Greene, E., K. Birkeland, K. Elder, I. McCammon, M. Staples, and D. Sharaf. 2016. *Snow, Weather, and Avalanches: Observational Guidelines for Avalanche Programs in the United States*. 3rd ed. Victor, Idaho: American Avalanche Association.

Grinsted, A. 2013. An estimate of global glacier volume. *The Cryosphere* 7(1):141-151.

Groisman, P.Y., R.W. Knight, D.R. Easterling, T.R. Karl, G.C. Hegerl, and V.N. Razuvaev. 2005. Trends in intense precipitation in the climate record. *Journal of Climate* 18(9):1326-1350.

Groisman, P.Y., R.W. Knight, and T.R. Karl. 2012. Changes in intense precipitation over the Central United States. *Journal of Hydrometeorology* 13(1):47-66.

Groisman, P.Y., R.W. Knight, T.R. Karl, D.R. Easterling, B. Sun, and J.H. Lawrimore. 2004. Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *Journal of Hydrometeorology* 5(1):64-85.

Guan, M., N. Sillanpää, and H. Koivusalo. 2016. Storm runoff response to rainfall pattern, magnitude and urbanization in a developing urban catchment. *Hydrological Processes* 30(4):543-557.

Guan, B., D.E. Waliser, F.M. Ralph, E.J. Fetzer, and P.J. Neiman. 2016. Hydrometeorological characteristics of rain-on-snow events associated with atmospheric rivers. *Geophysical Research Letters* 43(6):2964-2973.

Guanter, L., Y. Zhang, M. Jung, J. Joiner, M. Voigt, J.A. Berry, C. Frankenberg, et al. 2014. Global and time-resolved monitoring of crop photosynthesis with chlorophyll fluorescence. *Proceedings of the National Academy of Sciences* 111(14):E1327-E1333.

Guilbert, J., A.K. Betts, D.M. Rizzo, B. Beckage, and A. Bomblies. 2015. Characterization of increased persistence and intensity of precipitation in the Northeastern United States. *Geophysical Research Letters* 42(6):1888-1893.

Hallegatte, S., C. Green, R.J. Nicholls, and J. Corfee-Morlot. 2013. Future flood losses in major coastal cities. *Nature Climate Change* 3:802-806.

Harbor, J.M. 1994. A practical method for estimating the impact of land-use change on surface runoff, groundwater recharge and wetland hydrology. *Journal of the American Planning Association* 60(1):95-108.

Harpold, A.A., and N.P. Molotch. 2015. Sensitivity of soil water availability to changing snowmelt timing in the western U.S. *Geophysical Research Letters* 42(19):8011-8020.

Hart, M.R., B.F. Quin, and M.L. Nguyen. 2004. Phosphorus runoff from agricultural land and direct fertilizer effects. *Journal of Environmental Quality* 33(6):1954-1972.

Hedrick, A., H.P. Marshall, A. Winstral, K. Elder, S. Yueh, and D. Cline. 2015. Independent evaluation of the SNODAS snow depth product using regional-scale lidar-derived measurements. *The Cryosphere* 9:13-23.

Hering, J.G., T.D. Waite, R.G. Luthy, J.E. Drewes, and D.L. Sedlak. 2013. A changing framework for urban water systems. *Environmental Science & Technology* 47(19):10721-10726.

Hestir, E.L., V.E. Brando, M. Bresciani, C. Giardino, E. Matta, P. Villa, and A.G. Dekker. 2015. Measuring freshwater aquatic ecosystems: The need for a hyperspectral global mapping satellite mission. *Remote Sensing of Environment* 167:181-195.

Heymsfield, A.J., S.Y. Matrosov, and N.B. Wood. 2016. Toward improving ice water content and snow-rate retrievals from radars. Part I: X and W bands, emphasizing CloudSat. *Journal of Applied Meteorology and Climatology* 55(9):2063-2090.

Hinkelman, L.M., K.E. Lapo, N.C. Cristea, and J.D. Lundquist. 2015. Using CERES SYN surface irradiance data as forcing for snowmelt simulation in complex terrain. *Journal of Hydrometeorology* 16(5):2133-2152.

Hong, Y., R.F. Adler, A. Negri, and G.J. Huffman. 2007. Flood and landslide applications of near real-time satellite rainfall products. *Natural Hazards* 43(2):285-294.

Hong, Y., K.L. Hsu, S. Sorooshian, and X. Gao. 2004. Precipitation estimation from remotely sensed imagery using an artificial neural network cloud classification system. *Journal of Applied Meteorology* 43(12):1834-1853.

Hook, S.J., ed. 2014. *NASA 2014 The Hyperspectral Infrared Imager (HyspIRI)—Science Impact of Deploying Instruments on Separate Platforms*. https://hyspiri.jpl.nasa.gov/downloads/reports_whitepapers/HyspIRI-Separate-Platforms-Whitepaper-140722-1326.pdf.

Hossain, F. 2006. Towards formulation of a space-borne system for early warning of floods: Can cost-effectiveness outweigh prediction uncertainty? *Natural Hazards* 37(3):263-276.

Hossain, F., A. Serrat-Capdevila, S. Granger, A. Thomas, D. Saah, D. Ganz, R. Mugo, et al. 2016. A global capacity building vision for societal applications of Earth observing systems and data: Key questions and recommendations. *Bulletin of the American Meteorological Society* 97(7):1295-1299.

Hou, A.Y., R.K. Kakar, S. Neeck, A.A. Azarbarzin, C.D. Kummerow, M. Kojima, R. Oki, K. Nakamura, and T. Iguchi. 2014. The Global Precipitation Measurement Mission. *Bulletin of the American Meteorological Society* 95(5):701-722.

Howitt, R.E., J. Medellín-Azuara, D. MacEwan, J.R. Lund, and D.A. Sumner. 2015. Economic impact of the 2015 drought on farm revenue and employment. *Agricultural and Resource Economics Update* 18:9-11.

Hsu, K., X. Gao, S. Sorooshian, and H.V. Gupta. 1997. Precipitation estimation from remotely sensed information using artificial neural networks. *Journal of Applied Meteorology* 36(9):1176-1190.

Huete, A., K. Didan, T. Miura, E.P. Rodriguez, X. Gao, and L.G. Ferreira. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment* 83(1):195-213.

Huffman, G.J., R.F. Adler, P. Arkin, A. Chang, R. Ferraro, A. Gruber, J. Janowiak, A. McNab, B. Rudolf, and U. Schneider. 1997. The Global Precipitation Climatology Project (GPCP) combined precipitation dataset. *Bulletin of the American Meteorological Society* 78(1):5-20.

Huffman, G.J., D.T. Bolvin, and E.J. Nelkin. 2017. *Integrated Multi-satellitE Retrievals for GPM (IMERG) Technical Documentation.* Greenbelt, MD: NASA Goddard Space Flight Center.

Huffman, G.J., D.T. Bolvin, E.J. Nelkin, D.B. Wolff, R.F. Adler, G. Gu, Y. Hong, K.P. Bowman, and E.F. Stocker. 2007. The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *Journal of Hydrometeorology* 8(1):38-55.

IFRC (International Federation of Red Cross and Red Crescent Societies). 2000. *World Disasters Report: Focus on Public Health.* http://www.ifrc.org/Global/Publications/disasters/WDR/9000-WDR2000.pdf.

Iguchi, T., S. Seto, R. Meneghini, N. Yoshida, J. Awaka, M. Le, V. Chandrasekar, and T. Kubota. 2016. *GPM/DPR Level-2 Algorithm Theoretical Basis Document*. Greenbelt, MD: NASA Goddard Space Flight Center.

Illingworth, A.J., H. Barker, A. Beljaars, M. Ceccaldi, H. Chepfer, N. Clerbaux, J. Cole, J. Delanoë, C. Domenech, and D.P. Donovan. 2015. The EarthCARE satellite: The next step forward in global measurements of clouds, aerosols, precipitation, and radiation. *Bulletin of the American Meteorological Society* 96(8):1311-1332.

Immerzeel, W.W., L.P.H. van Beek, and M.F.P. Bierkens. 2010. Climate change will affect the Asian Water Towers. *Science* 328(5984):1382-1385.

IPCC (Intergovernmental Panel on Climate Change). 2014. Observations: Cryosphere. Pp. 317-382 in *Climate Change 2013—The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Jasinski, M.F., J.D. Stoll, W.B. Cook, M. Ondrusek, E. Stengel, and K. Brunt. 2016. Inland and near-shore water profiles derived from the high-altitude Multiple Altimeter Beam Experimental Lidar (MABEL). *Journal of Coastal Research* 76:44-55.

Jensen, J.J. 2006. *Remote Sensing of the Environment: An Earth Resource Perspective*. 2nd ed. Upper Saddle River, N.J.: Prentice-Hall.

Jin, M., and R.E. Dickinson. 2010. Land surface skin temperature climatology: Benefitting from the strengths of satellite observations. *Environmental Research Letters* 5(4):044004.

Johnson, L., C. Richards, G. Host, and J. Arthur. 1997. Landscape influences on water chemistry in Midwestern stream ecosystems. *Freshwater Biology* 37(1):193-208.

Joiner, J., Y. Yoshida, A.P. Vasilkov, Y. Yoshida, L.A. Corp, and E.M. Middleton. 2011. First observations of global and seasonal terrestrial chlorophyll fluorescence from space. *Biogeosciences* 8(3):637-651.

Joyce, R.J., J.E. Janowiak, P.A. Arkin, and P. Xie. 2004. CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *Journal of Hydrometeorology* 5(3):487-503.

Kääb, A., E. Berthier, C. Nuth, J. Gardelle, and Y. Arnaud. 2012. Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature* 488(7412):495-498.

Kallis, G. 2008. Droughts. *Annual Review of Environment and Resources* 33:1-481.

Kang, D.H., and A.P. Barros. 2012. Observing system simulation of snow microwave emissions over data sparse regions—Part II: Multilayer physics. *IEEE Transactions on Geoscience and Remote Sensing* 50(5):1806-1820.

Kapnick, S.B., T.L. Delworth, M. Ashfaq, S. Malyshev, and P.C.D. Milly. 2014. Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle. *Nature Geoscience* 7(11):834-840.

Kargel, J.S., G.J. Leonard, D.H. Shugar, U.K. Haritashya, A. Bevington, E.J. Fielding, K. Fujita, et al. 2016. Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake. *Science* 351(6269).

Kaspari, S., T.H. Painter, M. Gysel, S.M. Skiles, and M. Schwikowski. 2014. Seasonal and elevational variations of black carbon and dust in snow and ice in the Solu-Khumbu, Nepal and estimated radiative forcings. *Atmospheric Chemistry and Physics* 14(15):8089-8103.

Kato, S., F.G. Rose, S. Sun-Mack, W.F. Miller, Y. Chen, D.A. Rutan, G.L. Stephens, et al. 2011. Improvements of top-of-atmosphere and surface irradiance computations with CALIPSO-, CloudSat-, and MODIS-derived cloud and aerosol properties. *Journal of Geophysical Research: Atmospheres* 116(D19):D19209.

Kehrwald, N.M., L.G. Thompson, T. Yao, E. Mosley-Thompson, U. Schotterer, V. Alfimov, J. Beer, J. Eikenberg, and M.E. Davis. 2008. Mass loss on Himalayan glacier endangers water resources. *Geophysical Research Letters* 35(22):L22503.

Kelly, R.E., A.T.C. Chang, T. Leung, and J.L. Foster. 2003. A prototype AMSR-E global snow area and snow depth algorithm. *IEEE Transactions on Geoscience and Remote Sensing* 41(2):230-242.

Kelly, R.E.J., and A.T.C. Chang. 2003. Development of a passive microwave global snow depth retrieval algorithm for Special Sensor Microwave Imager (SSM/I) and Advanced Microwave Scanning Radiometer-EOS (AMSR-E) data. *Radio Science* 38(4):8076.

Kennedy, J., D.C. Goodrich, and C.L. Unkrich. 2013. Model enhancements for urban runoff predictions in the South-West United States. Pp. 332-337 in *Predictions in Ungauged Basins* (G. Blöschl, M. Sivapalan, and T. Wagener, eds.). Cambridge: Cambridge University Press.

Kerr, Y.H., A. Al-Yaari, N. Rodriguez-Fernandez, M. Parrens, B. Molero, D. Leroux, S. Bircher, et al. 2016. Overview of SMOS performance in terms of global soil moisture monitoring after six years in operation. *Remote Sensing of Environment* 180:40-63.

Kim, G., and A.P. Barros. 2001. Quantitative flood forecasting using multisensor data and neural networks. *Journal of Hydrology* 246(1-4):45-62.

Kim, S.B., J.J.v. Zyl, J.T. Johnson, M. Moghaddam, L. Tsang, A. Colliander, R.S. Dunbar, et al. 2017. Surface soil moisture retrieval using the L-band synthetic aperture radar onboard the Soil Moisture Active-Passive satellite and evaluation at core validation sites. *IEEE Transactions on Geoscience and Remote Sensing* 55(4):1897-1914.

Kinoshita, A.M., and T.S. Hogue. 2011. Spatial and temporal controls on post-fire hydrologic recovery in Southern California watersheds. *Catena* 87(2):240-252.

Kinoshita, A.M., and T.S. Hogue. 2015. Increased dry season water yield in burned watersheds in Southern California. *Environmental Research Letters* 10(1):014003.

Kirschbaum, D., T. Stanley, and S. Yatheendradas. 2016. Modeling landslide susceptibility over large regions with fuzzy overlay. *Landslides* 13(3):485-496.

Kirschbaum, D.B., R. Adler, Y. Hong, and A. Lerner-Lam. 2009. Evaluation of a preliminary satellite-based landslide hazard algorithm using global landslide inventories. *Natural Hazards and Earth System Sciences* 9(3):673-686.

Kirschbaum, D.B., T. Stanley, and J. Simmons. 2015. A dynamic landslide hazard assessment system for Central America and Hispaniola. *Natural Hazards and Earth System Sciences* 15(10):2257-2272.

Kocin, P.J., and L.W. Uccellini. 2004. A snowfall impact scale derived from Northeast storm snowfall distributions. *Bulletin of the American Meteorological Society* 85(2):177-194.

Konar, M., T.P. Evans, M. Levy, C.A. Scott, T.J. Troy, C.J. Vörösmarty, and M. Sivapalan. 2016. Water resources sustainability in a globalizing world: Who uses the water? *Hydrological Processes* 30(18):3330-3336.

Kongoli, C., H. Meng, J. Dong, and R. Ferraro. 2015. A snowfall detection algorithm over land utilizing high‐frequency passive microwave measurements—Application to ATMS. *Journal of Geophysical Research: Atmospheres* 120(5):1918-1932.

Korhonen, L., I. Korpela, J. Heiskanen, and M. Maltamo. 2011. Airborne discrete-return lidar data in the estimation of vertical canopy cover, angular canopy closure and leaf area index. *Remote Sensing of Environment* 115(4):1065-1080.

Kulie, M.S., and R. Bennartz. 2009. Utilizing spaceborne radars to retrieve dry snowfall. *Journal of Applied Meteorology and Climatology* 48(12):2564-2580.

Kulie, M.S., M.J. Hiley, R. Bennartz, S. Kneifel, and S. Tanelli. 2014. Triple-frequency radar reflectivity signatures of snow: Observations and comparisons with theoretical ice particle scattering models. *Journal of Applied Meteorology and Climatology* 53(4):1080-1098.

Kumar, S.V., C.D. Peters-Lidard, Y. Tian, P.R. Houser, J. Geiger, S. Olden, L. Lighty, et al. 2006. Land Information System: An interoperable framework for high resolution land surface modeling. *Environmental Modelling & Software* 21(10):1402-1415.

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson. 1998. The Tropical Rainfall Measuring Mission (TRMM) sensor package. *Journal of Atmospheric and Oceanic Technology* 15(3):809-817.

Kummerow, C.D., D.L. Randel, M. Kulie, N.Y. Wang, R. Ferraro, S.J. Munchak, and V. Petkovic. 2015. The evolution of the Goddard profiling algorithm to a fully parametric scheme. *Journal of Atmospheric and Oceanic Technology* 32(12):2265-2280.

Kunkel, K.E., D.R. Easterling, K. Redmond, and K. Hubbard. 2003. Temporal variations of extreme precipitation events in the United States: 1895-2000. *Geophysical Research Letters* 30(17):1900.

Lakshmi, V. 2016. Beyond GRACE: Using satellite data for groundwater investigations. *Groundwater* 54(5):615-618.

Lakshmi, V., J. Susskind, and B.J. Choudhury. 1998. Determination of land surface skin temperatures and surface air temperature and humidity from TOVS HIRS2/MSU data. *Advances in Space Research* 22(5):629-636.

Lang, T.J., and A.P. Barros. 2004. Winter storms in the Central Himalayas. *Journal of the Meteorological Society of Japan* 82(3):829-844.

Langlois, A., A. Royer, C. Derksen, B. Montpetit, F. Dupont, and K. Goïta. 2012. Coupling the snow thermodynamic model SNOWPACK with the microwave emission model of layered snowpacks for subarctic and arctic snow water equivalent retrievals. *Water Resources Research* 48(12):W12524.

Lee, C.M., M.L. Cable, S.J. Hook, R.O. Green, S.L. Ustin, D.J. Mandl, and E.M. Middleton. 2015. An introduction to the NASA Hyperspectral InfraRed Imager (HyspIRI) mission and preparatory activities. *Remote Sensing of Environment* 167:6-19.

Lee, C.M., T. Orne, and B. Schaeffer. 2014. Remote sensing of water quality: Bridging operational and applications communities. *Eos, Transactions American Geophysical Union* 95(39):354.

Lefsky, M.A., W.B. Cohen, G.G. Parker, and D.J. Harding. 2002. Lidar remote sensing for ecosystem studies. *BioScience* 52(1):19-30.

Lemke, P., J. Ren, R.B. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fujii, G. Kaser, P. Mote, R.H. Thomas, and T. Zhang. 2007. Observations: Changes in snow, ice and frozen ground. Pp. 337-383 in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, eds.). Cambridge and New York: Cambridge University Press.

Lettenmaier, D.P., D. Alsdorf, J. Dozier, G.J. Huffman, M. Pan, and E.F. Wood. 2015. Inroads of remote sensing into hydrologic science during the WRR era. *Water Resources Research* 51:7309-7342.

Levis, S., G.B. Bonan, and P.J. Lawrence. 2007. Present-day springtime high-latitude surface albedo as a predictor of simulated climate sensitivity. *Geophysical Research Letters* 34(17):L17703.

Levizzani, V., S. Laviola, and E. Cattani. 2011. Detection and measurement of snowfall from space. *Remote Sensing* 3(1):145-166.

Li, D., M. Durand, and S.A. Margulis. 2015. Quantifying spatiotemporal variability of controls on microwave emission from snow-covered mountainous regions. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 8(9):4478-4488.

Li, Z., H. Guo, and J. Shi. 2001. Retrieving dry snow density with SIR-C polarimetric SAR data. *Chinese Science Bulletin* 46(14):1211-1214.

Libertino, A., A. Sharma, V. Lakshmi, and P. Claps. 2016. A global assessment of the timing of extreme rainfall from TRMM and GPM for improving hydrologic design. *Environmental Research Letters* 11(5):054003.

Lim, K., P. Treitz, M. Wulder, B. St-Onge, and M. Flood. 2003. Lidar remote sensing of forest structure. *Progress in Physical Geography* 27(1):88-106.

Liu, G. 2008. Deriving snow cloud characteristics from CloudSat observations. *Journal of Geophysical Research: Atmospheres* 113:D00A09.

Lobl, E.S., K. Aonashi, M. Murakami, B. Griffith, C. Kummerow, G. Liu, and T. Wilheit. 2007. Wakasa Bay: An AMSR precipitation validation campaign. *Bulletin of the American Meteorological Society* 88(4):551-558.

Long, D., B.R. Scanlon, L. Longuevergne, A.Y. Sun, D.N. Fernando, and H. Save. 2013. GRACE satellite monitoring of large depletion in water storage in response to the 2011 drought in Texas. *Geophysical Research Letters* 40(13):3395-3401.

Long, D.G., and M.J. Brodzik. 2016. Optimum image formation for spaceborne microwave radiometer products. *IEEE Transactions on Geoscience and Remote Sensing* 54(5):2763-2779.

López-Moreno, J.I., S.R. Fassnacht, J.T. Heath, K.N. Musselman, J. Revuelto, J. Latron, E. Morán-Tejeda, and T. Jonas. 2013. Small scale spatial variability of snow density and depth over complex alpine terrain: Implications for estimating snow water equivalent. *Advances in Water Resources* 55:40-52.

Lowman, L.E.L., and A.P. Barros. 2016. Interplay of drought and tropical cyclone activity in SE U.S. gross primary productivity. *Journal of Geophysical Research: Biogeosciences* 121(6):1540-1567.

Lundquist, J.D., S.E. Dickerson-Lange, J.A. Lutz, and N.C. Cristea. 2013. Lower forest density enhances snow retention in regions with warmer winters: A global framework developed from plot-scale observations and modeling. *Water Resources Research* 49(10):6356-6370.

Magnusson, L., and E. Källén. 2013. Factors influencing skill improvements in the ECMWF forecasting system. *Monthly Weather Review* 141(9):3142-3153.

Mandel, R., and E. Noyes. 2012. Beyond the NWS: Inside the thriving private weather forecasting industry. *Weatherwise* 66(1):12-19.

Mankin, J.S., D. Viviroli, D. Singh, A.Y. Hoekstra, and N.S. Diffenbaugh. 2015. The potential for snow to supply human water demand in the present and future. *Environmental Research Letters* 10(11):114016.

Mao, D., and K.A. Cherkauer. 2009. Impacts of land-use change on hydrologic responses in the Great Lakes region. *Journal of Hydrology* 374(1-2):71-82.

Margulis, S.A., G. Cortés, M. Girotto, L.S. Huning, D. Li, and M. Durand. 2016. Characterizing the extreme 2015 snowpack deficit in the Sierra Nevada (USA) and the implications for drought recovery. *Geophysical Research Letters* 43(12):6341-6349.

Marks, D., J. Domingo, D. Susong, T. Link, and D. Garen. 1999. A spatially distributed energy balance snowmelt model for application in mountain basins. *Hydrological Processes* 13(12-13):1935-1959.

Marks, D., and J. Dozier. 1992. Climate and energy exchange at the snow surface in the alpine region of the Sierra Nevada: 2. Snow cover energy balance. *Water Resources Research* 28(11):3043-3054.

Marks, D., J. Dozier, and R.E. Davis. 1992. Climate and energy exchange at the snow surface in the alpine region of the Sierra Nevada: 1. Meteorological measurements and monitoring. *Water Resources Research* 28(11):3029-3042.

Masiello, G., C. Serio, and P. Antonelli. 2012. Inversion for atmospheric thermodynamical parameters of IASI data in the principal components space. *Quarterly Journal of the Royal Meteorological Society* 138(662):103-117.

Mast, M.A., and D.W. Clow. 2008. Effects of 2003 wildfires on stream chemistry in Glacier National Park, Montana. *Hydrological Processes* 22(26):5013-5023.

Mathew, J., D.G. Babu, S. Kundu, K.V. Kumar, and C.C. Pant. 2014. Integrating intensity-duration-based rainfall threshold and antecedent rainfall-based probability estimate towards generating early warning for rainfall-induced landslides in parts of the Garhwal Himalaya, India. *Landslides* 11(4):575-588.

Matson, M., and J. Dozier. 1981. Identification of subresolution high temperature sources using a thermal IR sensor. *Photogrammetric Engineering and Remote Sensing* 47:1311-1318.

Matte, S., M.A. Boucher, V. Boucher, and T.C. Fortier Filion. 2017. Moving beyond the cost-loss ratio: Economic assessment of streamflow forecasts for a risk-averse decision maker. *Hydrology and Earth System Sciences* 21:2967-2986.

McCabe, M.F., M. Rodell, D.E. Alsdorf, D.G. Miralles, R. Uijlenhoet, W. Wagner, A. Lucieer, et al. 2017. The future of Earth observation in hydrology. *Hydrology and Earth System Sciences* 21(7):3879-3914.

McKenzie, D., and J.S. Littell. 2017. Climate change and the eco‐hydrology of fire: Will area burned increase in a warming western USA? *Ecological Applications* 27(1):26-36.

Meddens, A.J.H., J.A. Hicke, and C.A. Ferguson. 2012. Spatiotemporal patterns of observed bark beetle-caused tree mortality in British Columbia and the western United States. *Ecological Applications* 22(7):1876-1891.

Meierdiercks, K.L., J.A. Smith, M.L. Baeck, and A.J. Miller. 2010. Analyses of urban drainage network structure and its impact on hydrologic response. *JAWRA Journal of the American Water Resources Association* 46(5):932-943.

Meromy, L., N.P. Molotch, T.E. Link, S.R. Fassnacht, and R. Rice. 2013. Subgrid variability of snow water equivalent at operational snow stations in the western USA. *Hydrological Processes* 27(17):2383-2400.

Meroni, M., M. Rossini, L. Guanter, L. Alonso, U. Rascher, R. Colombo, and J. Moreno. 2009. Remote sensing of solar-induced chlorophyll fluorescence: Review of methods and applications. *Remote Sensing of Environment* 113(10):2037-2051.

Meyer, V., N. Becker, V. Markantonis, R. Schwarze, J.C.J.M. van den Bergh, L.M. Bouwer, P. Bubeck, et al. 2013. Assessing the costs of natural hazards—state of the art and knowledge gaps. *Natural Hazards and Earth System Sciences* 13(5):1351-1373.

Mikkelson, K.M., L.A. Bearup, R.M. Maxwell, J.D. Stednick, J.E. McCray, and J.O. Sharp. 2013. Bark beetle infestation impacts on nutrient cycling, water quality and interdependent hydrological effects. *Biogeochemistry* 115(1):1-21.

Min, S.K., X. Zhang, F.W. Zwiers, and G.C. Hegerl. 2011. Human contribution to more-intense precipitation extremes. *Nature* 470(7334):378-381.

Mitchell, K.E., D. Lohmann, P.R. Houser, E.F. Wood, J.C. Schaake, A. Robock, B.A. Cosgrove, et al. 2004. The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. *Journal of Geophysical Research: Atmospheres* 109(D7):D07S90.

Mitchell, P.J., P.N.J. Lane, and R.G. Benyon. 2012. Capturing within catchment variation in evapotranspiration from montane forests using lidar canopy profiles with measured and modelled fluxes of water. *Ecohydrology* 5(6):708-720.

Mitchell, V.G., T.A. McMahon, and R.G. Mein. 2003. Components of the total water balance of an urban catchment. *Environmental Management* 32(6):735-746.

Mitchell, V.G., R.G. Mein, and T.A. McMahon. 2001. Modelling the urban water cycle. *Environmental Modelling & Software* 16(7):615-629.

Moller, D., K.M. Andreadis, K.J. Bormann, S. Hensley, and T.H. Painter. 2017. Mapping snow depth from Ka-band interferometry: Proof of concept and comparison with scanning lidar retrievals. *IEEE Geoscience and Remote Sensing Letters* 14(6):886-890.

Moller, D., S. Hensley, G.A. Sadowy, C.D. Fisher, T. Michel, M. Zawadzki, and E. Rignot. 2011. The Glacier and Land Ice Surface Topography Interferometer: An airborne proof-of-concept demonstration of high-precision Ka-band single-pass elevation mapping. *IEEE Transactions on Geoscience and Remote Sensing* 49(2):827-842.

Moran, M.S., G.E. Ponce-Campos, A. Huete, M.P. McClaran, Y. Zhang, E.P. Hamerlynck, D.J. Augustine, et al. 2014. Functional response of U.S. grasslands to the early 21st-century drought. *Ecology* 95(8):2121-2133.

Morgan, P., E.K. Heyerdahl, and C.E. Gibson. 2008. Multi‐season climate synchronized forest fires throughout the 20th century, northern Rockies, USA. *Ecology* 89(3):717-728.

Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2005. Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society* 86(1):39-49.

Mouroulis, P., R.O. Green, B. Van Gorp, L.B. Moore, D.W. Wilson, and H.A. Bender. 2016. Landsat swath imaging spectrometer design. *Optical Engineering* 55(1):015104-015104.

Mueller, B., S.I. Seneviratne, C. Jimenez, T. Corti, M. Hirschi, G. Balsamo, P. Ciais, et al. 2011. Evaluation of global observations-based evapotranspiration datasets and IPCC AR4 simulations. *Geophysical Research Letters* 38(6):L06402.

NASA EOS (NASA Earth Observing System). 2017. "Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (EVI-3) (TROPICS)." https://eospso.nasa.gov/missions/time-resolved-observations-precipitation-structure-and-storm-intensity-constellation. Accessed April 23, 2017.

NRC (National Research Council). 1991. *Opportunities in the Hydrologic Sciences*. Washington, DC: National Academy Press.

NRC. 1999. *Hydrologic Science Priorities for the U.S. Global Change Research Program: An Initial Assessment*. Washington, DC: National Academy Press.

NRC. 2002. *Estimating Water Use in the United States: A New Paradigm for the National Water-Use Information Program*. Washington, DC: The National Academies Press.

NRC. 2003. *Fair Weather: Effective Partnerships in Weather and Climate Services*. Washington, DC: The National Academies Press.

NRC. 2004. *Groundwater Fluxes Across Interfaces*. Washington, DC: The National Academies Press.

NRC. 2007a. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. Washington, DC: The National Academies Press.

NRC. 2007b. *Elevation Data for Floodplain Mapping*. Washington, DC: The National Academies Press.

NRC. 2008. *Integrating Multiscale Observations of U.S. Waters*. Washington, DC: The National Academies Press.

NRC. 2012. *Challenges and Opportunities in the Hydrologic Sciences*. Washington, DC: The National Academies Press.

NRC. 2013. *Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program*. Washington, DC: The National Academies Press.

Nayak, A., D. Marks, D.G. Chandler, and M. Seyfried. 2010. Long-term snow, climate, and streamflow trends at the Reynolds Creek Experimental Watershed, Owyhee Mountains, Idaho, United States. *Water Resources Research* 46:W06519.

Nguyen, P., A. Thorstensen, S. Sorooshian, K. Hsu, A. AghaKouchak, H. Ashouri, H. Tran, and D. Braithwaite. 2017. Global precipitation trends across spatial scales using satellite observations. *Bulletin of the American Meteorological Society*. https://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-17-0065.1.

NOAA (National Oceanic and Atmospheric Administration). 2015. *Summary of Natural Hazard Statistics for 2015 in the United States*. http://www.nws.noaa.gov/om/hazstats/sum15.pdf.

NOAA NCDC (National Climatic Data Center). 2017. "U.S. Billion-Dollar Weather & Climate Disasters 1980-2017." https://www.ncdc.noaa.gov/billions/events.pdf.

NOAA NCEI (National Centers for Environmental Information). 2017. "Data Access." https://www.ncdc.noaa.gov/data-access. Accessed April 5, 2018.

NOAA USCRN (U.S. Climate Reference Network). 2017. "U.S. Climate Reference Network." https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/us-climate-reference-network-uscrn. Accessed April 5, 2018.

Novotny, E.V., and H.G. Stefan. 2007. Stream flow in Minnesota: Indicator of climate change. *Journal of Hydrology* 334(3-4):319-333.

NRCS (Natural Resources Conservation Service). 2017. "Soil Climate Analysis Network (SCAN) Data & Products." https://www.wcc.nrcs.usda.gov/scan/. Accessed April 5, 2018.

NSIDC (National Snow and Ice Data Center). 2016. *Snow Data Assimilation System (SNODAS) Data Products at NSIDC*. Boulder, CO: National Snow and Ice Data Center.

Oki, T., and S. Kanae. 2006. Global hydrological cycles and world water resources. *Science* 313(5790):1068-1072.

Olsen, J.R., ed. 2015. *Adapting Infrastructure and Civil Engineering Practice to a Changing Climate*, *Books*. Reston, VA: American Society of Civil Engineers.

ORNL (Oak Ridge National Laboratory). 2007. "The FLUXNET 2007 Synthesis Workshop." https://fluxnet.ornl.gov/. Accessed February 13, 2017.

Padowski, J.C., and J.W. Jawitz. 2009. The future of global water scarcity: Policy and management challenges and opportunities. *Seton Hall Journal of Diplomacy and International Relations* 10:99.

Pagano, T.C., A.W. Wood, M.H. Ramos, H.L. Cloke, F. Pappenberger, M.P. Clark, M. Cranston, D. Kavetski, T. Mathevet, S. Sorooshian, and J.S. Verkade. 2014. Challenges of operational river forecasting. *Journal of Hydrometeorology* 15(4):1692-1707.

Painter, T.H., A.P. Barrett, C.C. Landry, J.C. Neff, M.P. Cassidy, C.R. Lawrence, K.E. McBride, and G.L. Farmer. 2007. Impact of disturbed desert soils on duration of mountain snow cover. *Geophysical Research Letters* 34(12):L12502.

Painter, T.H., D.F. Berisford, J.W. Boardman, K.J. Bormann, J.S. Deems, F. Gehrke, A. Hedrick, et al. 2016. The Airborne Snow Observatory: Fusion of scanning lidar, imaging spectrometer, and physically-based modeling for mapping snow water equivalent and snow albedo. *Remote Sensing of Environment* 184:139-152.

Painter, T.H., M. Flanner, B. Marzeion, G. Kaser, R. VanCuren, and W. Abdalati. 2013. End of the Little Ice Age in the Alps forced by black carbon. *Proceedings of the National Academy of Sciences* 110(38):15216-15221.

Petley, D. 2012. Global patterns of loss of life from landslides. *Geology* 40:927-930.

Pfeffer, W.T., A.A. Arendt, A. Bliss, T. Bolch, J.G. Cogley, A.S. Gardner, J.O. Hagen, et al. 2014. The Randolph Glacier Inventory: A globally complete inventory of glaciers. *Journal of Glaciology* 60(221):537-552.

Poff, N.L., C.M. Brown, T.E. Grantham, J.H. Matthews, M.A. Palmer, C.M. Spence, R.L. Wilby, M. Haasnoot, G.F. Mendoza, and K.C. Dominique. 2016. Sustainable water management under future uncertainty with eco-engineering decision scaling. *Nature Climate Change* 6:25-34.

Pollacco, J.A.P., and B.P. Mohanty. 2012. Uncertainties of water fluxes in soil-vegetation-atmosphere transfer models: Inverting surface soil moisture and evapotranspiration retrieved from remote sensing. *Vadose Zone Journal* 11(3).

Post, V.E.A., J. Groen, H. Kooi, M. Person, S.M. Ge, and W.M. Edmunds. 2013. Offshore fresh groundwater reserves as a global phenomenon. *Nature* 504(7478):71-78.

Price, J.C. 1984. Land surface temperature measurements from the split window channels of the NOAA 7 Advanced Very High Resolution Radiometer. *Journal of Geophysical Research: Atmospheres* 89(D5):7231-7237.

Qui, J. 2008. China: The third pole. *Nature* 454:393-396.

Radić, V., A. Bliss, A.C. Beedlow, R. Hock, E. Miles, and J.G. Cogley. 2014. Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. *Climate Dynamics* 42(1):37-58.

Radić, V., and R. Hock. 2010. Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data. *Journal of Geophysical Research: Earth Surface* 115(F1):F01010.

Raffa, K.F., B.H. Aukema, B.J. Bentz, A.L. Carroll, J.A. Hicke, M.G. Turner, and W.H. Romme. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: The dynamics of bark beetle eruptions. *BioScience* 58(6):501-517.

Ray, R.D., and G. Foster. 2016. Future nuisance flooding at Boston caused by astronomical tides alone. *Earth's Future* 4(12):578-587.

Rhoades, C.C., D. Entwistle, and D. Butler. 2011. The influence of wildfire extent and severity on streamwater chemistry, sediment and temperature following the Hayman Fire, Colorado. *International Journal of Wildland Fire* 20(3):430-442.

Rice, R., and R.C. Bales. 2010. Embedded sensor network design for snowcover measurements around snow-pillow and snow-course sites in the Sierra Nevada of California. *Water Resources Research* 46:W03537.

Richey, A.S., B.F. Thomas, M.-H. Lo, J.T. Reager, J.S. Famiglietti, K. Voss, S. Swenson, and M. Rodell. 2015. Quantifying renewable groundwater stress with GRACE. *Water Resources Research* 51:5217-5238.

Rienecker, M.M., M.J. Suarez, R. Gelaro, R. Todling, J. Bacmeister, E. Liu, M.G. Bosilovich, et al. 2011. MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. *Journal of Climate* 24(14):3624-3648.

Riggan, P.J., R.N. Lockwood, P.M. Jacks, C.G. Colver, F. Weirich, L.F. DeBano, and J.A. Brass. 1994. Effects of fire severity on nitrate mobilization in watersheds subject to chronic atmospheric deposition. *Environmental Science & Technology* 28(3):369-375.

Rittger, K., E.H. Bair, A. Kahl, and J. Dozier. 2016. Spatial estimates of snow water equivalent from reconstruction. *Advances in Water Resources* 94:345-363.

Rizwan, A.M., L.Y.C. Dennis, and C. Liu. 2008. A review on the generation, determination and mitigation of urban heat island. *Journal of Environmental Sciences* 20(1):120-128.

Roberts, D.A., M. Gardner, R. Church, S.L. Ustin, G. Scheer, and R.O. Green. 1998. Mapping chaparral in the Santa Monica Mountains using multiple endmember spectral mixture models. *Remote Sensing of Environment* 65(3):267-279.

Robichaud, P.R. 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. *Journal of Hydrology* 231:220-229.

Rodell, M., H.K. Beaudoing, T.S. L'Ecuyer, W.S. Olson, J.S. Famiglietti, P.R. Houser, R. Adler, et al. 2015. The observed state of the water cycle in the early twenty-first century. *Journal of Climate* 28(21):8289-8318.

Rodell, M., P.R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.J. Meng, K. Arsenault, et al. 2004. The Global Land Data Assimilation System. *Bulletin of the American Meteorological Society* 85(3):381-394.

Rollins, M.G. 2009. LANDFIRE: A nationally consistent vegetation, wildland fire, and fuel assessment. *International Journal of Wildland Fire* 18(3):235-249.

Rose, S., and N.E. Peters. 2001. Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): A comparative hydrological approach. *Hydrological Processes* 15(8):1441-1457.

Rosen, P., S. Hensley, S. Shaffer, W. Edelstein, Y. Kim, R. Kumar, T. Misra, R. Bhan, R. Satish, and R. Sagi. 2016. "An Update on the NASA-ISRO Dual-Frequency DBF SAR (NISAR) Mission." 2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), July 10-15.

Rulli, M.C., and R. Rosso. 2007. Hydrologic response of upland catchments to wildfires. *Advances in Water Resources* 30(10):2072-2086.

Russia Today. 2012. "Post-Apocalyptic Krymsk: Russia's Southern City Destroyed by flood." https://www.rt.com/news/krymsk-russia-flood-devastation-655/.

Saleeby, S.M., and W.R. Cotton. 2005. A large-droplet mode and prognostic number concentration of cloud droplets in the Colorado State University Regional Atmospheric Modeling System (RAMS), Part II: Sensitivity to a Colorado winter snowfall event. *Journal of Applied Meteorology* 44(12):1912-1929.

Saleeby, S.M., and S.C. van den Heever. 2013. Developments in the CSU-RAMS aerosol model: Emissions, nucleation, regeneration, deposition, and radiation. *Journal of Applied Meteorology and Climatology* 52(12):2601-2622.

Sättele, M., M. Bründl, and D. Straub. 2015. Reliability and effectiveness of early warning systems for natural hazards: Concept and application to debris flow warning. *Reliability Engineering & System Safety* 142:192-202.

Scanlon, B.R., I. Jolly, M. Sophocleous, and L. Zhang. 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. *Water Resources Research* 43(3):W03437.

Scanlon, B.R., K.E. Keese, A.L. Flint, L.E. Flint, C.B. Gaye, W.M. Edmunds, and I. Simmers. 2006. Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes* 20(15):3335-3370.

Scanlon, B.R., R.C. Reedy, C.C. Faunt, D. Pool, and K. Uhlman. 2016. Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. *Environmental Research Letters* 11(3):035013.

Schaeffer, B.A., J.D. Hagy, R.N. Conmy, J.C. Lehrter, and R.P. Stumpf. 2012. An approach to developing numeric water quality criteria for coastal waters using the SeaWiFS satellite data record. *Environmental Science & Technology* 46(2):916-922.

Schaeffer, B.A., J.D. Hagy, and R.P. Stumpf. 2013. Approach to developing numeric water quality criteria for coastal waters: Transition from SeaWiFS to MODIS and MERIS satellites. *Journal of Applied Remote Sensing* 7(1):073544-073544.

Schilling, K.E., K.S. Chan, H. Liu, and Y.K. Zhang. 2010. Quantifying the effect of land use land cover change on increasing discharge in the Upper Mississippi River. *Journal of Hydrology* 387(3-4):343-345.

Schmidt, S., C. Kemfert, and P. Höppe. 2009. Tropical cyclone losses in the USA and the impact of climate change—A trend analysis based on data from a new approach to adjusting storm losses. *Environmental Impact Assessment Review* 29(6):359-369.

Scott, R.L., W.J. Shuttleworth, T.O. Keefer, and A.W. Warrick. 2000. Modeling multiyear observations of soil moisture recharge in the semiarid American Southwest. *Water Resources Research* 36(8):2233-2247.

Seid-Green, Y. 2016. *Understanding the Water Landscape of the United States: A Review of Science and Policy Recommendations: An AMS Policy Program Study*. Washington, DC: American Meteorological Society.

Sheffield, J., and E.F. Wood. 2011. *Drought: Past Problems and Future Scenarios*. New York: Routledge.

Sheffield, J., E.F. Wood, and M.L. Roderick. 2012. Little change in global drought over the past 60 years. *Nature* 491(7424):435-438.

Shekhar, M.S., H. Chand, S. Kumar, K. Srinivasan, and A. Ganju. 2010. Climate-change studies in the western Himalaya. *Annals of Glaciology* 51(54):105-112.

Sheng, J., and J.P. Wilson. 2009. Watershed urbanization and changing flood behavior across the Los Angeles metropolitan region. *Natural Hazards* 48(1):41-57.

Shi, J., and J. Dozier. 2000a. Estimation of snow water equivalence using SIR-C/X-SAR, Part I: Inferring snow density and subsurface properties. *IEEE Transactions on Geoscience and Remote Sensing* 38(6):2465-2474.

Shi, J., and J. Dozier. 2000b. Estimation of snow water equivalence using SIR-C/X-SAR, Part II: Inferring snow depth and grain size. *IEEE Transactions on Geoscience and Remote Sensing* 38(6):2475-2488.

Shi, J., C. Xiong, and L. Jiang. 2016. Review of snow water equivalent microwave remote sensing. *Science China Earth Sciences* 59:1-15.

Skofronick-Jackson, G., W.A. Petersen, W. Berg, C. Kidd, E.F. Stocker, D.B. Kirschbaum, R. Kakar, et al. 2016. The Global Precipitation Measurement (GPM) Mission for science and society. *Bulletin of the American Meteorological Society* Early online release.

Slinski, K.M., T.S. Hogue, A.T. Porter, and J.E. McCray. 2016. Recent bark beetle outbreaks have little impact on streamflow in the Western United States. *Environmental Research Letters* 11(7):074010.

Smith, H.G., G.J. Sheridan, P.N. Lane, P. Nyman, and S. Haydon. 2011. Wildfire effects on water quality in forest catchments: A review with implications for water supply. *Journal of Hydrology* 396(1):170-192.

Spracklen, D.V., L.J. Mickley, J.A. Logan, R.C. Hudman, R. Yevich, M.D. Flannigan, and A.L. Westerling. 2009. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *Journal of Geophysical Research: Atmospheres* 114(D20):D20301.

Stanley, T., and D.B. Kirschbaum. 2017. A heuristic approach to global landslide susceptibility mapping. *Natural Hazards* 87(1):145-164.

Stein, E.D., J.S. Brown, T.S. Hogue, M.P. Burke, and A. Kinoshita. 2012. Stormwater contaminant loading following Southern California wildfires. *Environmental Toxicology and Chemistry* 31(11):2625-2638.

Stephens, G.L., and C.D. Kummerow. 2007. The remote sensing of clouds and precipitation from space: A review. *Journal of the Atmospheric Sciences* 64(11):3742-3765.

Stephens, G.L., D.G. Vane, R.J. Boain, G.G. Mace, K. Sassen, Z. Wang, A.J. Illingworth, E.J. O'Connor, W.B. Rossow, and S.L. Durden. 2002. The CloudSat mission and the A-Train: A new dimension of space-based observations of clouds and precipitation. *Bulletin of the American Meteorological Society* 83(12):1771-1790.

Stewart, I.T. 2009. Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes* 23(1):78-94.

Sun, G., S.G. McNulty, J.A. Moore Myers, and E.C. Cohen. 2008. "Impacts of Climate Change, Population Growth, Land Use Change, and Groundwater Availability on Water Supply and Demand Across The Conterminous US." Hydrology and Watershed Management Technical Committee. Middleburg, VA: American Water Resources Association.

Sun, X., and A.P. Barros. 2014. Isolating the role of surface evapotranspiration on moist convection along the eastern flanks of the tropical Andes using a quasi-idealized approach. *Journal of the Atmospheric Sciences* 72(1):243-261.

Susskind, J., C.D. Barnet, and J.M. Blaisdell. 2003. Retrieval of atmospheric and surface parameters from AIRS/AMSU/HSB data in the presence of clouds. *IEEE Transactions on Geoscience and Remote Sensing* 41(2):390-409.

Svoboda, M., D. LeComte, M. Hayes, R. Heim, K. Gleason, J. Angel, B. Rippey, et al. 2002. The Drought Monitor. *Bulletin of the American Meteorological Society* 83(8):1181-1190.

Syvitski, J.P.M., A.J. Kettner, I. Overeem, E.W.H. Hutton, M.T. Hannon, G.R. Brakenridge, J. Day, C. Vörösmarty, Y. Saito, L. Giosan, and R.J. Nicholls. 2009. Sinking deltas due to human activities. *Nature Geoscience* 2(10):681-686.

Tabatabaeenejad, A., M. Burgin, X. Duan, and M. Moghaddam. 2015. P-band radar retrieval of subsurface soil moisture profile as a second-order polynomial: First AirMOSS results. *IEEE Transactions on Geoscience and Remote Sensing* 53(2):645-658.

Tao, J., and A.P. Barros. 2013. Prospects for flash flood forecasting in mountainous regions—An investigation of Tropical Storm Fay in the Southern Appalachians. *Journal of Hydrology* 506:69-89.

Tao, J., and A.P. Barros. 2014a. Coupled prediction of flood response and debris flow initiation during warm- and cold-season events in the Southern Appalachians, USA. *Hydrology and Earth System Sciences* 18(1):367-388.

Tao, J., and A.P. Barros. 2014b. *The Integrated Precipitation and Hydrology Experiment. Part I: Quality High-Resolution Landscape Attributes Datasets.* EPL-2013-IPHEX-H4SE-1. Durham, NC: Duke University.

Tao, J., D. Wu, J. Gourley, S.Q. Zhang, W. Crow, C. Peters-Lidard, and A.P. Barros. 2016. Operational hydrological forecasting during the IPHEx-IOP campaign—Meet the challenge. *Journal of Hydrology* 541A:434-456.

Tao, W.K., D. Wu, S. Lang, J.D. Chern, C. Peters-Lidard, A. Fridlind, and T. Matsui. 2016. High-resolution NU-WRF simulations of a deep convective-precipitation system during MC3E: Further improvements and comparisons between Goddard microphysics schemes and observations. *Journal of Geophysical Research: Atmospheres* 121(3):1278-1305.

Tapley, B.D., S. Bettadpur, J.C. Ries, P.F. Thompson, and M.M. Watkins. 2004. GRACE measurements of mass variability in the Earth system. *Science* 305(5683):503-505.

Tebaldi, C., B.H. Strauss, and C.E. Zervas. 2012. Modelling sea level rise impacts on storm surges along US coasts. *Environmental Research Letters* 7:014032.

Tessler, Z.D., C.J. Vörösmarty, M. Grossberg, I. Gladkova, H. Aizenman, J.P.M. Syvitski, and E. Foufoula-Georgiou. 2015. Profiling risk and sustainability in coastal deltas of the world. *Science* 349(6248):638-643.

Thiboult, A., F. Anctil, and M.H. Ramos. 2017. How does the quantification of uncertainties affect the quality and value of flood early warning systems? *Journal of Hydrology* 55:365-373.

Trenberth, K.E. 2011. Changes in precipitation with climate change. *Climate Research* 47(1-2):123-138.

Trenberth, K.E., and G.R. Asrar. 2014. Challenges and opportunities in water cycle research: WCRP contributions. *Surveys in Geophysics* 35(3):515-532.

Trenberth, K.E., A. Dai, G. van der Schrier, P.D. Jones, J. Barichivich, K.R. Briffa, and J. Sheffield. 2014. Global warming and changes in drought. *Nature Climate Change* 4:17-22.

Trepanier, J.C., M.J. Roberts, and B.D. Keim. 2015. Trends and spatial variability in dry spells across the South-Central United States. *Journal of Applied Meteorology and Climatology* 54(11):2261-2272.

Turner, A.G., and H. Annamalai. 2012. Climate change and the South Asian summer monsoon. *Nature Climate Change* 2(8):587-595.

Turpie, K.R., V.V. Klemas, K. Byrd, M. Kelly, and Y.H. Jo. 2015. Prospective HyspIRI global observations of tidal wetlands. *Remote Sensing of Environment* 167:206-217.

UNISDR (United Nations Office for Disaster Risk Reduction). 2009. *Drought Risk Reduction Framework and Practices: Contributing to the Implementation of the Hyogo Framework for Action*. Geneva.

Usali, N., and M.H. Ismail. 2010. Use of remote sensing and GIS in monitoring water quality. *Journal of Sustainable Development* 3(3):228-238.

USGS (U.S. Geological Survey). 2016. “How much do landslides cost?” https://www2.usgs.gov/faq/categories/9752/2607. Accessed April 5, 2018.

Vander Jagt, B.J., M.T. Durand, S.A. Margulis, E.J. Kim, and N.P. Molotch. 2013. The effect of spatial variability on the sensitivity of passive microwave measurements to snow water equivalent. *Remote Sensing of Environment* 136:163-179.

Varble, A., E.J. Zipser, A.M. Fridlind, P. Zhu, A.S. Ackerman, J.P. Chaboureau, S. Collis, J. Fan, A. Hill, and B. Shipway. 2014. Evaluation of cloud-resolving and limited area model intercomparison simulations using TWP-ICE observations: 1. Deep convective updraft properties. *Journal of Geophysical Research: Atmospheres* 119(24):13,891-813,918.

Vince, G. 2011. An epoch debate. *Science* 334(6052):32-37.

Vitousek, P.M., H.A. Mooney, J. Lubchenco, and J.M. Melillo. 1997. Human domination of Earth’s ecosystems. *Science* 277(5325):494-499.

Wada, Y., L.P.H. van Beek, N. Wanders, and M.F.P. Bierkens. 2013. Human water consumption intensifies hydrological drought worldwide. *Environmental Research Letters* 8(3):034036.

Wada, Y., D. Wisser, and M.F.P. Bierkens. 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. *Earth System Dynamics* 5(1):15-40.

Wagner, W., S. Hahn, R. Kidd, T. Melzer, Z. Bartalis, S. Hasenauer, J. Figa-Saldaña, et al. 2013. The ASCAT soil moisture product: A review of its specifications, validation results, and emerging applications. *Meteorologische Zeitschrift* 22:5-33.

Waliser, D., and B. Guan. 2017. Extreme winds and precipitation during landfall of atmospheric rivers. *Nature Geoscience* 10(3):179-U183.

Wan, Z., and Z.-L. Li. 1997. A physics-based algorithm for retrieving land-surface emissivity and temperature from EOS/MODIS data. *IEEE Transactions on Geoscience and Remote Sensing* 35(4):980-996.

Warren, S.G. 1982. Optical properties of snow. *Reviews of Geophysics* 20(1):67-89.

Warren, S.G., and R.E. Brandt. 2008. Optical constants of ice from the ultraviolet to the microwave: A revised compilation. *Journal of Geophysical Research: Atmospheres* 113:D14220.

Weiss, J.L., C.L. Castro, and J.T. Overpeck. 2009. Distinguishing pronounced droughts in the southwestern United States: Seasonality and effects of warmer temperatures. *Journal of Climate* 22(22):5918-5932.

Wen, Y., P. Kirstetter, J. Gourley, Y. Hong, A. Behrangi, and Z. Flamig. 2017. Evaluation of MRMS snowfall products over the western United States. *Journal of Hydrometeorology* 18(6): 1707-1713.

Wentz, F.J., L. Ricciardulli, K. Hilburn, and C. Mears. 2007. How much more rain will global warming bring? *Science* 317(5835):233-235.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase western US forest wildfire activity. *Science* 313(5789):940-943.

Westerling, A.L., M.G. Turner, E.A. Smithwick, W.H. Romme, and M.G. Ryan. 2011. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of Sciences* 108(32):13165-13170.

Wetlaufer, K., J. Hendrikx, and L. Marshall. 2016. Spatial heterogeneity of snow density and its influence on snow water equivalence estimates in a large mountainous basin. *Hydrology* 3(1):3.

White, M.D., and K.A. Greer. 2006. The effects of watershed urbanization on the stream hydrology and riparian vegetation of Los Penasquitos Creek, California. *Landscape and Urban Planning* 74(2):125-138.

Wild, M., D. Folini, M.Z. Hakuba, C. Schär, S.I. Seneviratne, S. Kato, D. Rutan, C. Ammann, E.F. Wood, and G. König-Langlo. 2015. The energy balance over land and oceans: an assessment based on direct observations and CMIP5 climate models. *Climate Dynamics* 44(11):3393-3429.

Wilhite, D.A. 2000. Drought as a natural hazard: Concepts and definitions. Pp. 3-18 in *Droughts: A Global Assesment* (D.A. Wilhite, ed.). New York: Routledge.

Wilhite, D.A., M.D. Svoboda, and M.J. Hayes. 2007. Understanding the complex impacts of drought: A key to enhancing drought mitigation and preparedness. *Water Resources Management* 21(5):763-774.

Williams, A.P., C.D. Allen, C.I. Millar, T.W. Swetnam, J. Michaelsen, C.J. Still, and S.W. Leavitt. 2010. Forest responses to increasing aridity and warmth in the southwestern United States. *Proceedings of the National Academy of Sciences* 107(50):21289-21294.

Williams, M.W., and J.M. Melack. 1991a. Precipitation chemistry in and ionic loading to an alpine basin, Sierra Nevada. *Water Resources Research* 27(7):1563-1574.

Williams, M.W., and J.M. Melack. 1991b. Solute chemistry of snowmelt and runoff in an alpine basin, Sierra Nevada. *Water Resources Research* 27(7):1575-1588.

Williamson, A.K., D.E. Prudic, and L.A. Swain. 1989. "Ground-Water Flow in the Central Valley, California." Professional Paper 1401-D. Reston, VA: U.S. Geological Survey.

Willis, K.J., and S.A. Bhagwat. 2009. Biodiversity and climate change. *Science* 326(5954):806-807.

Wilson, A.M., and A.P. Barros. 2014. An investigation of warm rainfall microphysics in the Southern Appalachians: Orographic enhancement via low-level seeder-feeder interactions. *Journal of the Atmospheric Sciences* 71(5):1783-1805.

Wilson, A.M., and A.P. Barros. 2017. Orographic land-atmosphere interactions and the diurnal cycle of low-level clouds and fog. *Journal of Hydrometeorology* 18(5):1513-1533.

WMO (World Meteorological Organization). 2017. "The Global Telecommunication System (GTS)." http://www.wmo.int/pages/prog/www/TEM/GTS/index_en.html. Accessed April 23, 2017.

Wood, E.F., S.D. Schubert, A.W. Wood, C.D. Peters-Lidard, K.C. Mo, A. Mariotti, and R.S. Pulwarty. 2015. Prospects for advancing drought understanding, monitoring, and prediction. *Journal of Hydrometeorology* 16(4):1636-1657.

Wu, H., R.F. Adler, Y. Tian, G.J. Huffman, H. Li, and J. Wang. 2014. Real-time global flood estimation using satellite-based precipitation and a coupled land surface and routing model. *Water Resources Research* 50(3):2693-2717.

Wu, H.T.J., and W.K.M. Lau. 2016. Detecting climate signals in precipitation extremes from TRMM (1998-2013)—Increasing contrast between wet and dry extremes during the "global warming hiatus." *Geophysical Research Letters* 43(3):1340-1348.

Xie, P., and P.A. Arkin. 1997. Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bulletin of the American Meteorological Society* 78(11):2539-2558.

Xie, P., J.E. Janowiak, P.A. Arkin, R. Adler, A. Gruber, R. Ferraro, G.J. Huffman, and S. Curtis. 2003. GPCP pentad precipitation analyses: An experimental dataset based on gauge observations and satellite estimates. *Journal of Climate* 16(13):2197-2214.

Xie, P., R. Joyce, S. Wu, S.H. Yoo, Y. Yarosh, F. Sun, and R. Lin. 2017. Reprocessed, bias-corrected CMORPH global high-resolution precipitation estimates from 1998. *Journal of Hydrometeorology* 18(6):1617-1641.

Xie, Y., Z. Sha, and M. Yu. 2008. Remote sensing imagery in vegetation mapping: A review. *Journal of Plant Ecology* 1(1):9-23.

Yang, D., D. Kane, Z. Zhang, D. Legates, and B. Goodison. 2005. Bias corrections of long-term (1973-2004) daily precipitation data over the northern regions. *Geophysical Research Letters* 32(19):L19501.

Yang, Q., H. Tian, X. Li, B. Tao, W. Ren, G. Chen, C. Lu, J. Yang, S. Pan, K. Banger, and B. Zhang. 2015. Spatiotemporal patterns of evapotranspiration along the North American east coast as influenced by multiple environmental changes. *Ecohydrology* 8(4):714-725.

Yao, T., L.G. Thompson, V. Mosbrugger, F. Zhang, Y. Ma, T. Luo, B. Xu, et al. 2012. Third Pole Environment (TPE). *Environmental Development* 3:52-64.

Zhang, Y., M. Pan, and E.F. Wood. 2016. On creating global gridded terrestrial water budget estimates from satellite remote sensing. *Surveys in Geophysics* 37(2):249-268.

Zhang, Y.K., and K.E. Schilling. 2006. Increasing streamflow and baseflow in Mississippi River since the 1940s: Effect of land use change. *Journal of Hydrology* 324(1-4):412-422.

Zhou, T., B. Nijssen, H. Gao, and D.P. Lettenmaier. 2016. The contribution of reservoirs to global land surface water storage variations. *Journal of Hydrometeorology* 17(1):309-325.

Zimmerman, J.B., J.R. Mihelcic, and J.A. Smith. 2008. Global stressors on water quality and quantity. *Environmental Science and Technology* 42(12):4247-4254.

Zolina, O., C. Simmer, K. Belyaev, S.K. Gulev, and P. Koltermann. 2013. Changes in the duration of European wet and dry spells during the last 60 years. *Journal of Climate* 26(6):2022-2047.

7

Weather and Air Quality: Minutes to Subseasonal

INPUT SUMMARY

Weather and air quality simulations have greatly improved over the past decade. These advances are in large part due to improved data assimilation, atmospheric physics and chemistry models, faster computers, and observations that improve, validate, evaluate, and initialize deterministic and ensemble forecast models. National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS) forecasters issue lifesaving warnings with as much lead time as scientifically possible, and work with researchers to improve forecast and warning lead times with better geographic precision and reduced false alarms for all hazardous weather (Uccellini, 2017). The Environmental Protection Agency (EPA), industrial stakeholders, as well as state and local governments rely on accurate air quality simulations to identify cost-effective strategies to improve health.

Over the next decade data assimilation and modeling efforts will emphasize simulating a number of coupled components of the Earth system rather than just the individual atmosphere, ocean, sea-ice, land (including ice and snow), and atmospheric composition components. These efforts are aimed at extending skillful forecasts into the subseasonal range (up to 60 days), and on delivering lifesaving and economic societal benefits. Satellite observations, combined with data assimilation and numerical prediction models, will be essential components of this fully coupled Earth system framework. There are numerous scientific, computational, and observational challenges associated with achieving such an integrated weather and air quality prediction system, but the societal benefits associated with more skillful weather forecasts across all lead times would truly be transformative.

The Panel on Weather and Air Quality: Minutes to Subseasonal identified 10 primary science questions and quantified objectives to address these challenges, all of which will require observations from both research and operational satellite systems. In particular, observations from research satellites will be

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NOTE: This chapter was written by members of the Panel on Weather and Air Quality: Minutes to Subseasonal and is provided for reference only. Any study finding or consensus recommendation will appear in Chapters 1-5, the report from the survey steering committee.

essential for advancing capabilities, while observations from operational systems will be critical to sustaining forecast systems.

Table 7.1 summarizes the panel's scientific/application priorities, as addressed in its questions/goals and the corresponding measurement objectives.

For an Earth system framework, representing the lowest part of the atmosphere (the planetary boundary layer, or PBL) is crucial for weather and air quality forecasting because this is where people live and work, and because it is integral to the exchange of energy, momentum, and mass between the atmosphere and the surface (land, ocean, and ice). Due to the strong diurnal cycles of boundary layer processes, and their implications for air quality, convective initiation, and severe weather outbreaks, a combination of geostationary and polar-orbiting satellites, airborne platforms, and ground-based networks will be needed for the measurements. These include satellite infrared and microwave sounders, and radio occultation from the Global Navigation Satellite System (GNSS). In particular, three-dimensional (3D) horizontal wind vector measurements from spaceborne wind profilers (Baker et al., 2014) would be transformative to weather and air quality forecasting, both in the PBL and in the free troposphere. High-temporal-resolution vertical profiling of the PBL and throughout the free troposphere at a national scale would improve severe weather (a national priority)[1] and air quality forecasting.

Local variations in Earth's surface characteristics also affect the exchange of energy, moisture, and pollutants between the surface and the free atmosphere through changes in the PBL turbulence, local convergence, and vertical motion (Kilpatrick et al., 2016). Over the oceans, the average magnitude of vertical transport due to these inhomogeneities is roughly 10 to 100 times the magnitude of the long-term mean flux needed to warm the oceans (Steffen, 2014; IPCC AR5 Report, 2015). Locally, and on short time scales, there are much larger variations in energy, moisture, and air pollutant transport from the PBL into the free atmosphere and vice versa, and this impacts local weather and air quality (Steffen, 2014). These surface spatial variations also modify precipitation and contribute to local temperature extremes, which are important considerations for the hydrological cycle, human health, and agriculture; these in turn can modify the surface air temperature (Kilpatrick and Xie, 2015).

It is vital to know where, when, and how clouds form, whether they precipitate or not, and how they affect the radiative balance at the surface. Improvements in our ability to assess the availability of freshwater from precipitation and to examine the occurrence and characteristics of extreme precipitation events will require considerable improvement in the accuracy of cloud precipitation (and cloud-aerosol-radiative balance) processes in Earth system models at scales from microphysical to regional to global. Cloud Resolving Models (CRMs) cannot be improved without observational constraints to assess the fidelity of existing microphysical schemes and processes (Stephens and Ellis, 2008; Hagos et al., 2014). High-quality measurements of cloud precipitation particles, microphysical properties, and vertical motions (velocities and areal extent of vertical updrafts) will be needed to constrain these models as they become capable of explicitly resolving cloud microphysical processes at the convective updraft scales.

This collective of new observations will lead to improved weather forecasts—namely, by improving the initialization (through data assimilation) and representation of key atmospheric processes (e.g., deep convective energy exchanges between the PBL and the upper troposphere, aerosol-cloud-precipitation interactions, and convective initiation) and Earth system couplings (e.g., land-, ocean-, and ice-surface conditions and boundary layer processes). New observations such as these would, for example, allow time-resolved monitoring of convective processes to improve their representation in numerical weather models—from small-scale cloud-resolving models to the global-scale weather and climate. Such improvements are crucial for extending our predictions into the subseasonal range; for improving around-the-clock

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[1] H.R. 353—Weather Research and Forecasting Innovation Act of 2017, 115th Congress.

TABLE 7.1 Summary of Science and Applications Questions and Their Priorities

Science and Applications Questions		Highest Priority Measurement Objectives (MI=Most Important, VI=Very Important)
W-1	What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean, and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations?	**(MI) W-1a.** Determine the effects of key boundary layer processes on weather, hydrological, and air quality forecasts at minutes to subseasonal time scales.
W-2	How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months?	**(MI) W-2a.** Improve the observed and modeled representation of natural, low-frequency modes of weather/climate variability (e.g., MJO, ENSO), including upscale interactions between the large-scale circulation and organization of convection and slowly varying boundary processes to extend the lead time of useful prediction skills by 50% for forecast times of 1 week to 2 months.
W-3	How do spatial variations in surface characteristics (influencing ocean and atmospheric dynamics, thermal inertia, and water) modify transfer between domains (air, ocean, land, cryosphere) and thereby influence weather and air quality?	**(VI) W-3a.** Determine how spatial variability in surface characteristics modifies regional cycles of energy, water, and momentum (stress) to an accuracy of 10 W/m^2 in the enthalpy flux, and 0.1 N/m^2 in stress, and observe total precipitation to an average accuracy of 15% over oceans and/or 25% over land and ice surfaces averaged over a 100 × 100 km region and 2- to 3-day time period.
W-4	Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?	**(MI) W-4a.** Measure the vertical motion within deep convection to within 1 m/s and heavy precipitation rates to within 1 mm/hour to improve model representation of extreme precipitation and to determine convective transport and redistribution of mass, moisture, momentum, and chemical species.
W-5	What processes determine the spatiotemporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?	**(MI) W-5a.** Improve the understanding of the processes that determine air pollution distributions and aid estimation of global air pollution impacts on human health and ecosystems by reducing uncertainty to <10% of vertically resolved tropospheric fields (including surface concentrations) of speciated particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2).
W-6	What processes determine the long-term variations and trends in air pollution and their subsequent long-term recurring and cumulative impacts on human health, agriculture, and ecosystems?	The objective associated with this question was ranked Important. See subsequent sections for details.
W-7	What processes determine observed tropospheric ozone (O_3) variations and trends, and what are the concomitant impacts of these changes on atmospheric composition/chemistry and climate?	The objective associated with this question was ranked Important. See subsequent sections for details.
W-8	What processes determine observed atmospheric methane (CH_4) variations and trends, and what are the subsequent impacts of these changes on atmospheric composition/chemistry and climate?	The objective associated with this question was ranked Important. See subsequent sections for details.
W-9	What processes determine cloud microphysical properties and their connections to aerosols and precipitation?	The objective associated with this question was ranked Important. See subsequent sections for details.
W-10	How do clouds affect the radiative forcing at the surface and contribute to predictability on time scales from minutes to subseasonal?	The objective associated with this question was ranked Important. See subsequent sections for details.

lifesaving prediction of the timing, location, and threat level of severe weather (minutes to days); and for providing for more skillful and comprehensive "environmental" forecasts.

The current health and economic costs (e.g., human morbidity and mortality, ecosystem degradation, and crop yield reductions) of air pollution are large and growing, particularly in developing countries. While satellite measurements have significantly advanced atmospheric composition and health assessment research over the last decade, the current observational networks for tropospheric methane, particulates, and ozone have deficiencies that do not allow for characterization of their 3D distributions, especially at "nose-level." Nor are the measurements of these important pollutants and key climate change species sufficiently accurate to monitor their variations and trends. These deficiencies include poor spatiotemporal coverage, limited information on particulate speciation, and insufficient measurements of ozone and secondary particulate precursor species. These deficiencies further impact our ability to develop strategies to mitigate the adverse health, economic, and environmental damage done by air pollution. A particular concern is that there are no replacements planned for several aging U.S. satellite instruments[2] that, when gone, will leave atmospheric and health scientists with a greatly diminished capability to quantify 3D particulate concentrations and chemical speciation. Continuation of the current data records, the power of which increases as the records lengthen, is critical for assessing the long-term effects of particulate pollution, ozone, and methane on air quality, human health, ecosystems, and climate.

Space-based remote sensing provides key information on weather and air quality of the Earth system on global and local scales. These measurements are a vital component in the global monitoring and prediction of the state of our atmosphere. New measurements and observations will be needed to address the science objectives identified by this panel. In Table 7.2, the highest priority science and application objectives are mapped to the Targeted Observables that will strongly contribute to addressing those objectives.[3] Note that most measurements will contribute data needed for more than one objective, and thus coordinated planning, such as formation flying, could substantially enhance each individual measurement. In addition to the new observations, planned operational weather satellites are also key in achieving these objectives, as these satellite systems can help with specifying the environmental conditions of the event being monitored by the new technologies. Advancing the science and applications of weather and air quality will also require combining the satellite measurements with the appropriate data assimilation and numerical model simulations. These fundamental science questions can be addressed only with advanced capabilities in observations, modeling and data assimilation systems, instrument platforms, and computing facilities.

This chapter identifies a set of challenges that must be addressed by collaboration of research and operational agencies to advance weather and air quality research. The National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), U.S. Geological Survey (USGS), other government agencies, academia, and private industry all engage in weather research. NASA, perhaps best exemplified by the competitively driven investments of the Earth Science Technology Office (ESTO), has the unique role and capability in instrument technology development and new mission conceptualization. NASA has repeatedly demonstrated the capacity, when leveraged, to pioneer the next generations of instrument platforms, formation flying, and quality measurements that address relevant technologies, science questions, and applications. NOAA and USGS need to play two roles: agile on-ramping and adaption of these new technologies into operational systems, and deployment of the operational systems in support of new research endeavors.

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[2] For example, collocated Moderate-Resolution Imaging Spectroradiometer (MODIS) and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) observations provide a three-dimensional (3D) distribution of aerosols on a global scale; both instruments are far beyond their designed life span.

[3] Not mapped here are cases where the Targeted Observables may provide a narrow or an indirect benefit to the objective, although such connections may be cited elsewhere in this report.

TABLE 7.2 Priority Targeted Observables Mapped to the Science and Applications Objectives That Were Ranked as Most Important (MI) or Very Important (VI)

Priority Targeted Observables	Science and Applications Objectives
Aerosol Vertical Profiles	W-1a, W-2a, W-5a
Aerosol Properties	W-1a, W-2a, W-3a, W-4a, W-5a
Temperature, Water Vapor, PBL Height	W-1a, W-2a, W-3a, W-4a
Atmospheric Winds	W-1a, W-2a, W-4a
Precipitation and Clouds	W-1a, W-2a, W-3a, W-4a
Ice Elevation	W-2a, W-3a
Surface Characteristics	W-3a
Snow Depth and Snow Water Equivalent	W-2a, W-3a
Soil Moisture	W-2a, W-3a
Ocean Surface Winds and Currents	W-1a, W-2a, W-3a
Vegetation, Snow, and Surface Energy Balance	W-3a
Cloud Microphysics and Vertical Motion	W-4a

INTRODUCTION AND VISION

Motivation

> *Perhaps someday in the dim future it will be possible to advance the computations faster than the weather advances and at a cost less than the saving to mankind due to the information gained. But that is a dream.*[4]

The air above us influences our lives through both its movement (i.e., weather) and its quality. The National Centers for Environmental Information (NCEI) tracks and evaluates weather events that have great economic and societal impact. NCEI estimates that between 1980 and 2016, the United States sustained 200 weather-related disasters where overall costs reached or exceeded $1 billion for each event (including a consumer price index adjustment to 2016; NOAA NCEI, 2017). In 2015 there were 522 fatalities and 2,143 injuries from weather-related events in the United States, with losses totaling over $4.8 billion (see Figure 7.1). Floods and heat waves are two weather phenomena that have contributed to significant economic loss over the last several years and caused more than half of the fatalities and injuries. The 10-year (2006-2015) average flood casualty in the United States is 82 deaths per year. High temperatures and drought can cost billions of dollars to agriculture industries. Heat waves strain the healthcare system and can cause traffic hazards as highway and railroad buckle under extreme heat.

During August and September 2017, the United States experienced three major disasters associated with the landfall of Hurricanes Harvey, Irma, and Maria. Harvey contributed to epic flooding in coastal Texas and Louisiana, with at least 30 fatalities in Houston alone. Irma resulted in more than 134 deaths, with mass evacuations and destruction in Florida and across the Caribbean. A direct hit on Puerto Rico by Hurricane Maria devastated the island's electrical grid and caused significant damage to the infrastructure and economy, with numerous fatalities reported along the hurricane's path. Additional disasters were asso-

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[4] In 1922, well before the advent of digital computing, Lewis Richardson published the visionary "Weather Prediction by Numerical Process," and with it the first true numerical weather forecast.

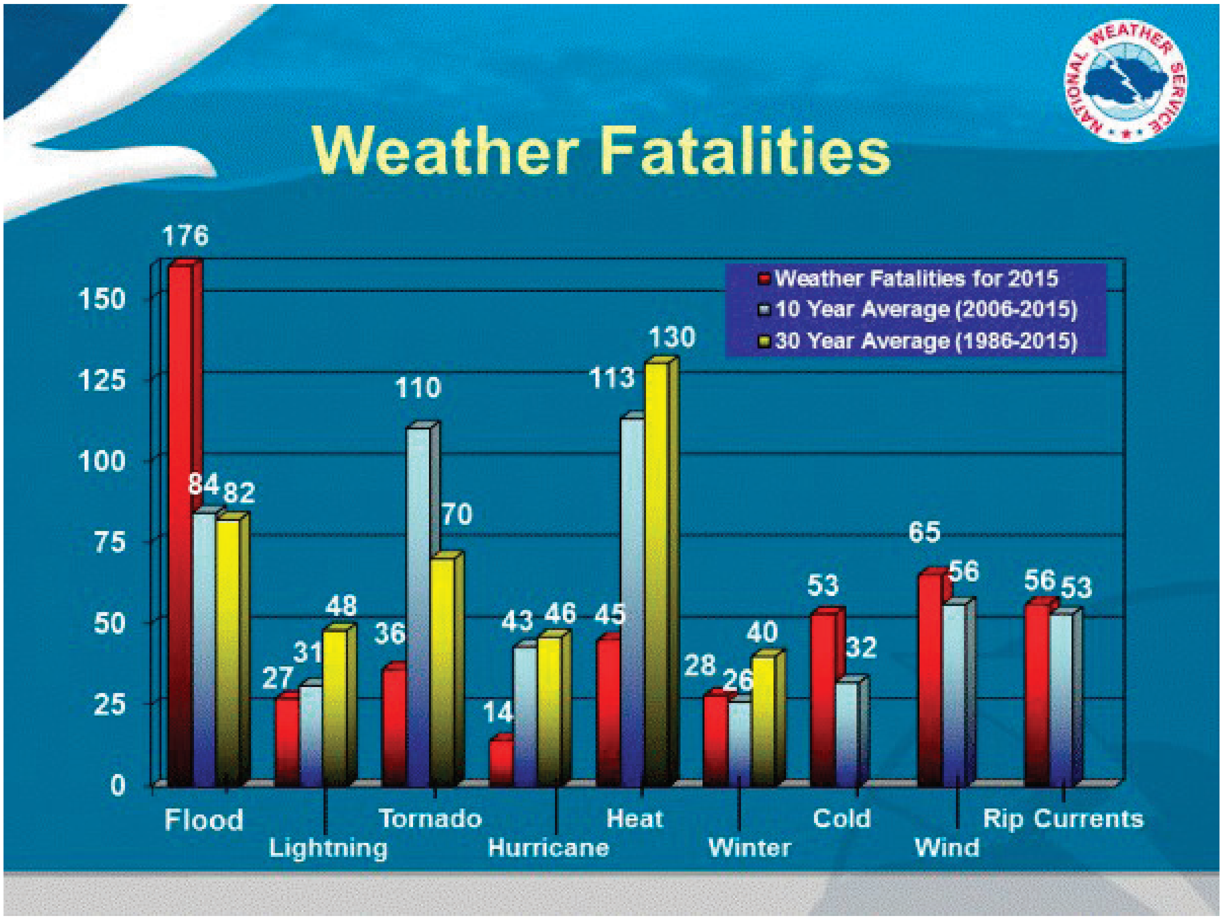

FIGURE 7.1 Weather fatalities statistics compiled by the Office of Services and the National Climatic Data Center from information contained in Storm Data, a report comprising data from National Weather Service (NWS) forecast offices in the 50 states, Puerto Rico, Guam, and the Virgin Islands. SOURCE: From NOAA, "Weather Fatalities 2016," last updated May 11, 2017, http://www.nws.noaa.gov/om/hazstats.shtml.

ciated with multiple significant wildfires in drought-parched northwest U.S. states (with many areas rated as in an exceptional drought), as well as northern California, where wildfire blazes driven by high winds killed dozens of people, wiped out communities and livelihoods, and destroyed thousands of homes and other structures.

Poor outdoor air quality, due to both gaseous and particulate matter (PM) constituents, contributes to millions of premature deaths annually worldwide and also negatively impacts agriculture yields and can degrade infrastructure. Poor air quality is a leading cause of premature deaths due to environmental and occupational risks (Figure 7.2). In the United States roughly $65 billion is spent annually on mitigating air pollution, resulting in $2 trillion in benefits, including over 160,000 cases of reduced infant and adult premature mortality (US EPA, 2011). By 2060, 6 to 9 million premature deaths worldwide are expected in association with poor air quality, with the associated annual global welfare costs projected to rise from U.S.

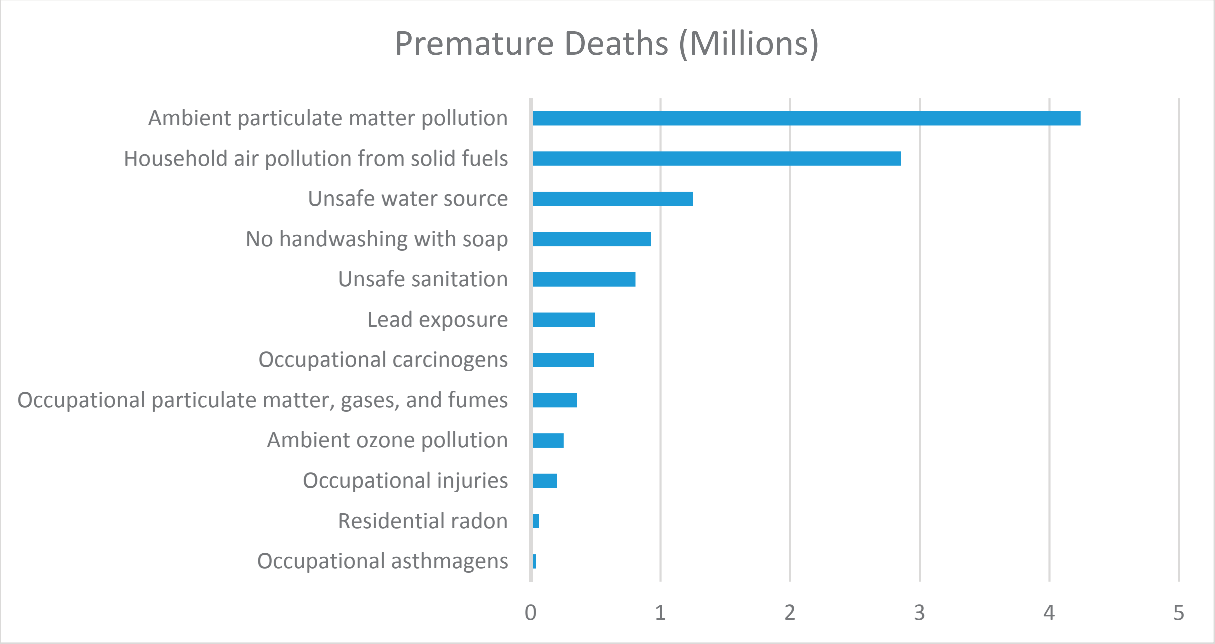

FIGURE 7.2 Leading causes of premature deaths due to environmental and occupational risks for 2015, for all age groups worldwide. SOURCE: WHO (2016) and Cohen et al. (2017).

$3 trillion in 2015 to U.S. $18 to $25 trillion in 2060 (OECD, 2016). Even in the United States, where air quality is relatively good, in comparison with other parts of the world, air pollution is still a leading health risk factor (Lim et al., 2012), and there remain areas across the United States that are still not attaining air quality standards needed to protect health and the environment (US EPA, 2016).

Furthermore, we cannot characterize weather-related economic issues exclusively in terms of cost or loss avoidance. Improved forecast capability will reduce losses to property and life, but the economic benefits will also include new business development (e.g., the benefits from improved energy production and utilization). Enhanced remote sensing ability and capacity will undoubtedly create new commercial opportunities and jobs. Just as information content from past generations of satellites were partially responsible for the creation of U.S. weather industries, future space-based developments will spawn new industries and corporations as well. When looking across sectors ranging from insurance to manufacturing, the U.S. economy is reported to receive at least $30 billion per year from such earth observation products as satellite-derived weather information (Wigbels, 2008). This will only increase as we pursue advanced new remote sensing capabilities.

Advances in our understanding of weather and air quality processes rely on careful and precise measurements of key variables. Observations are essential for developing numerical representations of the relevant processes that model-based predictions are based on and for providing the initial conditions for the model simulations. Space-based remote sensing provides essential measurements on the state of our atmosphere, notably by providing routine and consistent national observations for short-term forecasting (i.e., minutes to hours to several days), as well as global measurements that are essential for medium-to long-range global forecasts (i.e., 7 to 14 days). Since their introduction nearly 60 years ago, satellite measurements have substantially improved our forecasts and are a cornerstone of modern numerical weather prediction (NWP; WMO, 2012). Accurate forecast challenges still remain: forecasting convective initiation earlier, pinpointing the exact location of severe weather outbreaks, anticipating heat waves and dry periods, and better predicting hurricanes and other extreme weather events particularly in a changing climate (Powell and Aberson, 2001; NASEM, 2016b; NHC, 2016). Quantitative and heavy precipitation forecasts remain challenging, leading to significant societal implications with regard to reservoir and dam management, impacts on agriculture and on some modes of transportation. Extending weather prediction accuracy out to two weeks and beyond will have immense positive societal impacts by providing confident information to planning by decision makers and emergency managers.

Our ability to simulate the dynamics and chemistry that shape atmospheric composition, including air quality forecasts, has improved with advances in weather modeling and availability of satellite data of tropospheric trace gases and pollutants. Satellite data allow pollutant emissions and concentrations to be constrained, pollution plumes to be tracked throughout the troposphere, and photochemical processes to be inferred. As a result of the improved spatial coverage and reduced uncertainty in air quality products from satellite measurements, the health community has explored the use of these satellite data for applications that draw strong statistical inferences between pollutants and health outcomes. Satellite data of air pollutants and robust air quality modeling and forecasting allow for the development of effective pollution mitigation strategies to protect human and ecosystem health, including crops. For example, recent estimates of U.S. NO_x emissions from automobiles inferred from satellite observations are about a factor of two lower than in current emission inventories (Travis et al., 2016), which, if proven to be true, will have ramifications in terms of future pollutant controls costs.

Addressing the objectives and goals described in this chapter will contribute to societal benefits that range from information for short-term needs, such as accurate severe weather forecasts and air quality simulations that protect life and property, to improved monthly to subseasonal precipitation and temperature outlooks that anticipate extremes in heat, droughts, and flooding, to a longer-term scientific understanding necessary for future applications that will benefit society in ways still to be realized.

Contextual Issues

Our ability to simulate the past, current, and future state of the atmosphere has improved over the past decade (Bauer et al., 2015) These advances are in large part due to improved atmospheric physics and chemistry models and data assimilation methods, faster computers, and observations that improve, validate, and initialize deterministic and ensemble forecast models. Maintaining and improving our weather forecasting and air quality monitoring and simulation capabilities require observations from both research and operational satellite systems. NASA research missions explore cutting-edge flight missions with newly matured technologies with managed risk. NOAA and USGS necessarily follow risk-averse paths that do not allow for interruption of measurements critical to their core atmospheric, hydrologic, terrestrial, ecosystems, and oceanic stewardship mandates. History has shown that these diverse strategic approaches can be complementary. While a challenge, due to limited resources, operational requirements, and data distribution, there have been successful transitions from research instruments to operational applications.

Observations from research satellites are essential for advancing and demonstrating capabilities, while observations from operational systems are critical to sustaining forecast systems; their synergistic use also is critically important. The operational utilization of new research instruments has led to improved weather and air quality forecasts. For example, observations from the Moderate-Resolution Imaging Spectroradiometer (MODIS) and Atmospheric Infrared Sounder (AIRS) are routinely incorporated in operational numerical weather prediction models (Bormann and Thépaut, 2004). Observations from geostationary satellites provide the environmental perspective needed for interpreting observations from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and CloudSat (Mitrescu et al., 2008). The ability to leverage research and operational satellite observations for mutual benefit is crucial. The increasing demands for timely and accurate forecasts require new remote sensing technologies and sampling strategies from both research and operational satellite systems. Geostationary sensors provide high temporal resolution over a given hemisphere, while low-Earth orbiters provide global coverage with higher spatial resolution than if placed in geostationary orbits. Small satellites and CubeSats can provide opportunities not only to test new technologies and focus sampling strategies but also to fly low-cost missions and constellations. The Afternoon Constellation (A-Train) and Cyclone Global Navigation Satellite System (CYGNSS) constellations demonstrate the value of formation flying and should pave the way for future mission collaborations (Ardanuy, 2011).

The upcoming decade will likely experience an exponential growth in MicroSat, NanoSat, and CubeSat instrumentation, flights, and observations (NASEM, 2016a), with the potential for a commensurate explosive surge in collective contribution to Earth system science, application, and operations—from space weather to hydrology, spanning the atmosphere, ocean, and land surface. The emergence of "U-class" miniaturized satellites could significantly transform how we plan and conduct future Earth and space science research and operations. These new observations are rapidly increasing in observational capability and will need to be effectively incorporated into prediction models.

Improved satellite observations must keep pace with improved computing technologies and software development. Increased computer power and improved software engineering will enable data assimilation systems and forecasting models to move steadily toward exascale computing with commensurate higher fidelity, wider range of represented physical processes representation, increased temporal and spatial resolution, increased number of high-resolution ensembles, and longer lead times. Applications' demands will also require global high-resolution modeling and forecasting. To take full advantage of these computational advances, it is essential that future satellite observations obtain data at the spatial resolution and temporal refresh that best initialize these models.

Observations are also needed to understand processes that contribute to creating an integrated understanding of our atmosphere and its interactions with the surface. While both weather and air quality models are improving through direct inclusion of more physical processes, some key physics are still not fully resolved in our models. Observations are needed to support process studies that provide the understanding necessary for appropriate model parameterizations. For example, precipitation formation results from complex relationships between air motion, aerosol type and concentration, and microphysical processes within the cloud system. The dynamics of the cloud system respond to and drive the microphysical responses, yet the microphysical processes within the system feed back on the dynamics through downdrafts, entrainment, precipitation, and radiation (Stevens and Seifert, 2008; Stevens and Feingold, 2009). Today's models are unable to accurately represent how the potential energy is built up by deep convection, or how it gets intermittently transferred to the extratropical wave train in localized bursts, influencing weather far downstream (Haddad et al., 2016). An appropriate suite of measurements, perhaps flown in formation, can provide the necessary observational constraints to understand these relationships.

Benefits of Prior Efforts

In the last decade, we have witnessed enormous benefits from a number of weather and air quality-focused satellite missions. A few limited examples are listed here (more are available in the 2015 NASA Senior Review):

- A demonstration that high-spectral resolution infrared instruments such as the EOS-era Atmospheric Infrared Sounder (AIRS; launched in 2002) provide significant improvement and impact on numerical weather forecasting by providing critical initial condition information on temperature and humidity profiles. Similar capabilities from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Infrared Atmospheric Sounding Interferometer (IASI; launched in 2006, 2012) and the NOAA/NASA Cross-track Infrared Sounder (CrIS; launched in 2011) have augmented this crucial observational resource. A time sequence of atmospheric profiles enables a consistent analysis of the preconvective and convective environment across the entire region of the storm system, providing the necessary data to improve the timeliness of severe storm predictions (Weisz et al., 2015) As noted in the 2015 NASA Earth Science Senior Review, AIRS data are also of significant importance to the FAA and aviation community. AIRS, IASI, and the Ozone Monitoring Instrument (OMI; launched in 2004) provided sulfur dioxide and ash data for airline traffic safety and management during the Eyjafjallajökull eruption in 2010 that disrupted air travel for several weeks.
- The Earth System Science Pathfinder (ESSP) CloudSat mission (launched in 2006) flies in the A-Train and was the first radar in space designed to elucidate the internal structure of clouds, including estimates of their vertically resolved liquid and ice contents, and providing unique information on light precipitation and snowfall. CloudSat observations have been instrumental for clarifying fundamental processes such as cloud-radiation feedbacks, including aerosol-cloud-rainfall interactions (Lebo et al., 2017), and the linkages between the water cycle and radiative forcing (J.-L. Li et al., 2013; Andrews et al., 2010; Waliser, et al., 2013). CloudSat data have been used for the evaluation of existing parameterizations of clouds, convection, precipitation, and related microphysical processes in numerical weather prediction and climate projection models (Stephens et al., 2010; Matus, 2015).
- Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO; launched in 2006) provides unique cloud and aerosol products, including vertical profiles of the backscatter and polarization. The use of CALIPSO data in combination with CloudSat, Moderate-Resolution Imaging Spectroradiometer (MODIS), and Cloud-Earth Radiant Energy System (CERES) observations led to more than 500 peer-reviewed publications between the 2013 and the 2015 Senior Reviews. CALIPSO aerosol vertical profiles are used in data assimilation tests at the U.S. Naval Research Laboratory, the European Centre for Medium Range Weather Forecasts (ECMWF), and the Japanese Meteorological Agency (JMA). Detection of volcanic ash plumes by CALIPSO is used in support of commercial aviation operations. The U.S. Environmental Protection Agency (EPA) and several state agencies are using aerosol CALIPSO data to assess air quality and develop strategies to mitigate pollution-induced reduction to visibility.
- The Quick Scatterometer satellite (QuikSCAT; launched in 1999) provided wide areal coverage of ocean-surface wind speed and direction that proved extremely valuable for atmospheric and ocean forecasts as well as nowcasting of extreme weather for many of the national agencies routinely identified in NASA's Senior Reviews. Although developed as a NASA research mission, QuikSCAT supplied data that were routinely assimilated into operational numerical weather forecast models. QuikSCAT also provide information on the water content in vegetation's upper canopy and on the age and motion of sea ice, and improved the tracking of icebergs. Recent studies have shown that these observations are useful for identifying areas of ocean upwelling and higher productivity.
- A unique and valuable addition to the observational characterization of the atmosphere and the advancement of weather forecasting came from the Global Navigation Satellite System (GNSS) radio occultation sounding (often referred to as Global Positioning System Radio Occultation or GPSRO).

The technique was first applied in 1995, and came to fuller fruition with the 2006 launch of the relatively low cost Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission composed of six microsatellites. The data include electron counts in the ionosphere and, key for weather, atmospheric profiles of temperature, moisture, and pressure in the troposphere and stratosphere. These soundings have had a significant positive impact on weather forecasting, especially above the oceans, within the polar regions, and in other areas hard to sample with in situ means (such as upper troposphere and lower stratosphere; Collard and Healy, 2003).

- Over the last decade, the use of satellite data of air pollutants, such as OMI nitrogen dioxide and OMI sulfur dioxide, for scientific research and health and air quality applications has grown dramatically. Ongoing retrieval algorithm development is not only improving existing data sets of pollutants but also allowing for new data sets to be developed, such as for AIRS ammonia (Warner et al., 2017), an air toxin. These improved data sets are now at a quality to demonstrate the efficacy of environmental legislation, to inform the development of mitigation strategies, and to constrain emission fluxes and concentrations of some important air pollutants (Krotkov et al., 2016).
- OMI and the Ozone Mapping Profiler Suite (OMPS; launched in 2012) continue to monitor the health of the stratospheric ozone layer, a record begun in 1970 with Nimbus-4/Backscatter Ultraviolet (BUV). The satellite data indicate that the size and depth of the ozone hole seem to have stabilized over the last decade. Observations from the Microwave Limb Sounder (MLS; launched in 2004) make vital contributions to our understanding of the chemical and dynamical processes that affect the stratospheric ozone layer.
- The goal of the Tropical Rainfall Measuring Mission (TRMM; launched in 1997) was to provide monthly averages of rainfall over the Earth's surface in large grid boxes. This was achieved with a complementary suite of active and passive sensors flown on the one satellite. The extended lifetime mission of 17 years yielded rainfall estimates at a higher spatial resolution, every 3 hours and in near real time. The longer record enabled observations to study synoptic variability of precipitation more fully. The observations provided a first description of the diurnal cycle of precipitation over the oceans and tropical land areas (e.g., Nesbitt and Zipser, 2003). The assimilation experiments of Hou et al. (2004) demonstrated the value of using the TRMM observations to yield more realistic storm features and better 5-day storm track prediction and precipitation forecasts for Hurricanes Bonnie and Floyd. Lien et al. (2016) also demonstrated that the assimilation of the TRMM project derived data improved 5-day global model forecasts. The Global Precipitation Measurement (GPM; mission launched in February 2014) succeeds and improves upon the TRMM project. Both missions are joint projects of NASA and the Japan Aerospace Exploration Agency (JAXA).

A major challenge to the continued use of the current Earth Science Division (ESD) satellite missions is spacecraft health and safety (NASA, 2015), along with additional risks associated with old software and aging operating systems. A rapid decline in capability of these missions will have adverse consequences on our observing capability. This will weaken our understanding of our atmosphere and slow down the steady gains in weather and air quality forecasts achieved over the last two decades (Box 7.1). This will reduce our ability to respond to hazardous weather and air quality conditions (Box 7.2). New missions that address the objectives and questions in the next section will help the nation address the reducing capability of these aging missions.

Science and Applications Challenges

Satellite measurements of meteorological variables are essential to sustaining and improving skill in forecasts of weather and air quality. Additionally, satellite observations of trace gases and aerosols, along with accurate representation of meteorological processes, are critical for our understanding of how natural processes and anthropogenic emissions influence air quality and climate. Improving models often requires looking to the past, and satellite observations are routinely used in hindcasts to improve modeling capabilities through sensitivity studies or to trace emissions to their sources. This section outlines several important scientific and application challenges that, once addressed, will enable further improvements in weather and air quality modeling.

There is a need for observations that improve our understanding of complex atmospheric physical and chemical processes and their interactions with the land and oceans. Observing, understanding, and modeling atmospheric boundary layer physical and chemical processes have long been wanting, including measuring basic state variables such as temperature, humidity, and wind. Quite often our current retrieval capabilities are limited to a single coarse-grained observation of the lowest 1,000 m, which is insufficient to describe and resolve the physical and chemical processes in this key region. It is an observational and technological challenge to make these observations on a global scale.

BOX 7.1 SATELLITES IN WEATHER FORECASTING

Over the past 40 years the numerical weather prediction skill at the operational centers has steadily increased, and forecasts beyond 2 weeks are now seen as possible. These advances have been attributed to more accurate initial conditions owing to better data assimilation methods and more observational data (e.g., Vitart et al., 2014; Buizza and Leutbecher, 2015; NASEM, 2016), advances in understanding and modeling of physical processes including some components of subseasonal predictability, coupled modeling (e.g., dynamical ocean and ocean waves), and a shift from deterministic medium-range (i.e., 4 to 10 days) forecasts to ensemble-based forecasts. Dynamical subseasonal forecasts are beginning to demonstrate skill and provide a path to useful 2-week to 2-month forecasts (Vitart et al., 2012; NASEM, 2016). These nascent but promising capabilities enable a new paradigm of forecast products and decision support, for early preparation against high-impact weather events, and to benefit society in areas of food security, agriculture, water and energy management, hazard preparation and response, transportation planning and safety, and so on.

In the last decade research and development (i.e., experimental) environmental satellites have contributed significantly to operational weather forecasting, both in terms of assimilation of the data and as pathfinder instruments. A prime example is found in the Earth Observing System (EOS) Terra and Aqua platforms, which introduced high spectral resolution infrared sounders as well as multispectral imagers with land, ocean, and atmospheric applications in the early 2000s. The Atmospheric Infrared Sounder (AIRS) advanced IR sounder on the Aqua satellite was the pathfinder hyperspectral IR sounder for the subsequent Infrared Atmospheric Sounding Interferometer (IASI) and Cross-track Infrared Sounder (CrIS). The example in Figure 7.1.1 illustrates the impact of various observing systems on the 24-hour global forecast error reduction computed using the Forecast Sensitivity Observation Impact (FSOI) (Langland and Baker, 2004; Zhu and Gelaro, 2008; Cardinali, 2009b; Gelaro and Zhu, 2009; Lorenc and Marriott, 2014) for the UK Met Office forecast system. A larger total percentage impact implies a more beneficial contribution by observing types in reducing the 24-hour global forecast error. The hyperspectral IR sounders have the highest beneficial impact for global forecasting, followed by the MW sounder plus imagers and atmospheric motion vectors (AMVs) from geostationary and polar-orbit-

BOX 7.1 CONTINUED

ing imagers. Note that the relative impact of different observing types depends on the forecast lead time (i.e., 1 day versus 5 days) and the data assimilation and forecast system. Moreover, some of the observation types provide complementary information content, while others have redundant information, and still others are important anchoring observations, with the aggregate being crucial for a well-performing data assimilation system.

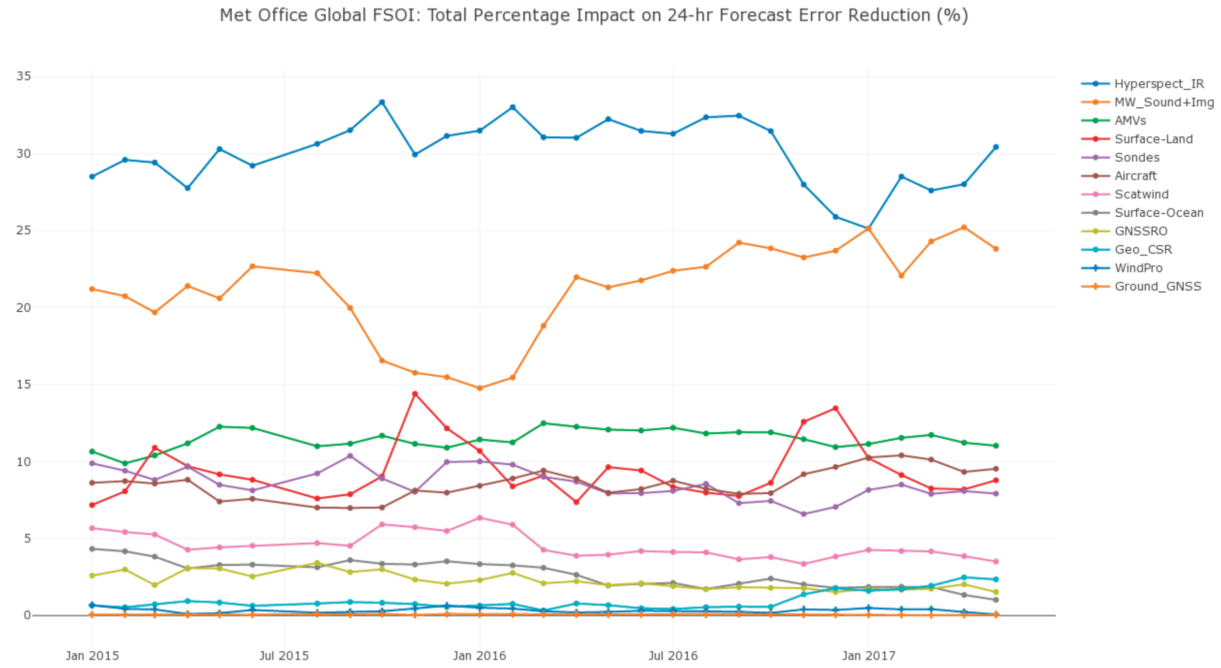

FIGURE 7.1.1 Forecast Sensitivity Observation Impact (FSOI) expressed as total percentage impact on the 24-hour forecast error reduction grouped by observing sensors with Hyperspectral IR including AIRS, IASI, CrIS; MW Sounder + Imager including ATOVS, ATMS, MTSAPHIR, MWHS-1/2, AMSR-2, SSMIS; Sondes including TEMP, TEMP SHIP, dropsondes, PILOT; Surface-Land including SYNOP, METAR; and Surface-Ocean including moored buoys, drifting buoys, ships, platforms. SOURCE: Met Office, U.K., private communication, June 2017.

Another challenge is to bridge the gap between weather forecasts and seasonal outlooks to enable meaningful forecast skill that extends well into and through the subseasonal range of 2 weeks to 2 months. Improved understanding of the sources of subseasonal predictability (e.g., El Niño Southern Oscillation [ENSO], Madden-Julian Oscillation [MJO]), require better observations of the coupled Earth system, and better modeling and data assimilation of the coupled system (NASEM, 2016c). Dynamical subseasonal forecasts are beginning to demonstrate skill and provide a path to useful 1-week to 2-month forecasts. Advances in this area offer great potential to impact decision support for early preparation against high-impact weather events and to benefit society in areas of food security, agriculture, water and energy management, hazard preparation and response, transportation planning and safety, and so on.

BOX 7.2 SATELLITE OBSERVATIONS FOR AIR QUALITY AND HEALTH APPLICATIONS

Over the last decade the use of satellite measurements of air pollutants for scientific research and health and air quality applications has grown because of improved data quality resulting from retrieval algorithm development. These improved data sets now have the necessary quality to demonstrate the efficacy of environmental legislation, inform the development of mitigation strategies, and constrain emission fluxes and concentrations of some important air pollutants, such as criteria pollutants, nitrogen dioxide, and sulfur dioxide (Figure 7.2.1). Ongoing retrieval algorithm development is not only improving existing data sets of other pollutants but also allowing for new data sets to be developed, such as for ammonia, an air toxin.

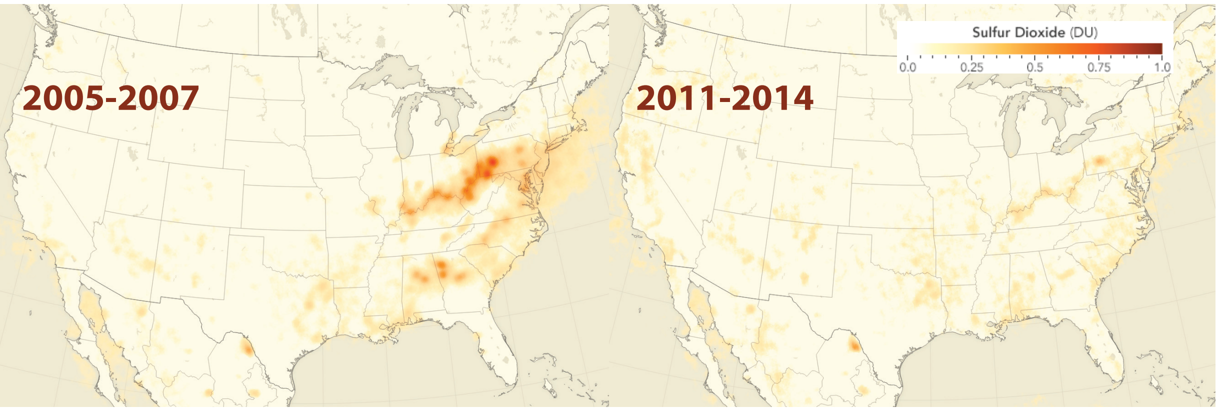

FIGURE 7.2.1 Large observed decreases in sulfur dioxide by the Ozone Monitoring Instrument (OMI) are associated with compliance with environmental rules. The left map shows the average sulfur dioxide for 2005-2007 in Dobson Units (DU); the right map shows the average for 2011-2014. Most of the sulfur dioxide hot spots are associated with coal-fired power plants or other industrial facilities that burn coal with high sulfur content. NOTE: See website for larger images. SOURCE: NASA Earth Observatory, "Sulfur Dioxide over the United States," December 22, 2015, https://earthobservatory.nasa.gov/IOTD/view.php?id=87182; NASA Earth Observatory maps by Joshua Stevens and Jesse Allen, NASA, using data provided courtesy of the Aura OMI science team.

Convection and precipitation play a primary role in many high-impact weather events over a broad range of temporal and spatial scales (e.g., severe storms, tropical cyclones, floods, etc.). These high-impact events have proven particularly difficult to accurately simulate and forecast in part because convective clouds often exist at scales that are only partially resolved by observations and regional/global models. Furthermore, it is difficult to observe and represent the multiscale interactions that are critical to convective organization and evolution.

A major challenge for air quality simulation is to better understand these convective systems, and in particular to resolve mesoscale organization and processes that are often associated with air quality episodes. These processes include lake-, bay-, and ocean-breeze circulations and complex terrain-induced circulations. Our ability to run cloud-resolving models that account for this finer scale convection organization over the globe requires new computing technologies. The White House-led agreement between the Department of Energy (DOE), National Science Foundation (NSF), and Department of Commerce (DOC) establishes a path to exascale computing that could enable 1 km mesh grids capable of resolving deep convection in about one decade (Holdren and Donovan, 2016).

There is a need to incorporate new observations and gained knowledge into research and operational weather and air quality models. Improving weather and air quality predictive capabilities requires a strong connection between observations from research satellites and their use in operational data assimilation and forecast systems. The challenge is that there is a significant difference in culture and risk tolerance between NASA and NOAA/USGS. While NASA's strategy embraces the advancement of "understanding of Earth and develop technologies to improve the quality of life on our home planet," NOAA's "science serving society" focus is more applied: "To understand and predict changes in climate, weather, oceans and coasts. . . . To conserve and manage coastal and marine ecosystems and resources." Similarly, the USGS mission is to serve "the Nation by providing reliable scientific information to describe and understand the Earth; minimize loss of life and property from natural disasters; manage water, biological, energy, and mineral resources; and enhance and protect our quality of life." History has shown that these diverse strategic approaches can be highly complementary. NASA has historically succeeded when charged with proving new technologies—advancing their technological maturity to a level where operational agencies can harvest them to realize cost savings and quality improvements. The operational agencies must put high priority on rapidly advancing the utilization of new measurements when they are first available.

There is a need to create and maintain comprehensive observations of meteorology and atmospheric composition that are required to initialize and constrain forecasts and accurately capture how emissions and weather impact air quality. The atmosphere is coupled to surface processes through fluxes of heat, momentum, radiation, and constituents (e.g., water, methane). However, observational estimates of these fluxes from space are deficient. To improve the estimates of these fluxes and to better understand the interaction of atmospheric boundary layer with clouds and convection, better measurements from space of temperature, water vapor, and vector wind in the free troposphere and boundary layer are necessary.

A big challenge in improving our understanding of clouds and precipitation is gaining insights into the processes that govern where precipitation forms and its intensity. Specifically, we need to document the environmental factors that determine the relative contributions of various ice and liquid phase processes to precipitation development and how these processes relate to convective motions in the atmosphere. These are the processes that are currently very crudely parameterized in most weather models, yet ultimately predict precipitation and consequently societal impacts. Observations are needed that can more directly constrain these rates on various weather scales and quantify their dependence on the environment.

A major challenge for using satellite data for the quantitative determination of the health effects of pollutants over time is accurately inferring the correspondence between the observed quantity (e.g., aerosol optical depth in the atmospheric column) and aerosol type, surface concentrations, and surface fluxes. These linkages have important implications for many applications, including those of the health, air quality, atmospheric composition, ecosystems (including crop yields), weather, and climate communities. Typically, models are used to estimate the vertical distribution of trace gases and aerosols (which is strongly affected by boundary layer processes) and to convert aerosol optical depth to particulate matter, and this adds additional uncertainty to observational uncertainty.

There is a wide recognition on the need to reduce the uncertainties associated with methane sources (e.g., wetlands, energy extraction, and permafrost thaw), not only because of its importance as a climate gas but also for its contribution to degrading air quality by elevating tropospheric ozone. Consequently, reducing global methane concentrations has been proposed as way to mitigate ozone pollution. Methane budget uncertainties have confounded emission estimates and attribution of observed variations and trends in regional and global methane concentrations, and have led to a wide range of methane source and regional emissions. Because of these large budget uncertainties, there is a need for the development of a comprehensive, long-term methane observing strategy, including of the processes that affect methane emissions.

There is a need for adequate computing power to assimilate the data into numerical weather predication and air quality models and run deterministic and ensemble forecasts at sufficiently high fidelity, resolution, and lead times. Data assimilation, including for coupled systems, is needed to blend the model fields with the observations. Satellite observations provide information, usually in the form of radiances or reflectivity, about the atmosphere and surface. Models provide physically and chemically consistent information, but are prone to systematic errors. Accurate estimates of the model background and satellite observation error statistics are essential for optimally combining the information from both observations and models via data assimilation and thus provide accurate initial conditions and retrospective analyses. Meteorological reanalyses are essential to understand weather processes and to infer atmospheric composition and greenhouse gas fluxes from atmospheric observations. Chemical reanalysis is increasing as the necessary tools, needed observations, and computing power are becoming available to conduct these analyses.

With the huge data volume from observing system and data assimilation outputs, building accessible data archives, with analytic services, is also needed. The transition of research (new findings and discoveries, new measurements, new modeling components) to operations and applications needs to be accelerated. This requires improved support for collaboration between model/assimilation and observation specialists.

Opportunities exist to address the preceding challenges and realize significant benefits in key scientific and applications areas. These opportunities are provided by (1) new instruments, technology, and platforms; (2) the combination of research and operational measurements from different platforms (e.g., spaceborne, airborne, and ground based); and (3) enhanced modeling capabilities with improved data assimilation capabilities.

Opportunities

An opportunity to improve our weather and air quality monitoring and forecasting capabilities requires observations from both research and operational satellite systems. Observations from research satellites are critical for advancing capabilities, while observations from operational systems are essential to sustaining forecast systems; their synergistic use also is critically important. The ability to leverage research and operational satellite observations for mutual benefit is imperative in conducting weather and air quality remote sensing research. The increasing demands for timely and accurate forecasts require new remote sensing technologies and sampling strategies from both research and operational satellite systems. Geostationary sensors provide high temporal resolution over a given hemisphere, while low-Earth orbiters provide global coverage with higher spatial resolution than if placed in geostationary orbits. Small satellites and CubeSats can provide opportunities to not only test new technologies and focus sampling strategies but also to fly low-cost missions and constellations.

In its evolution of environmental remote sensing capabilities, NOAA (formerly the Environmental Science Services Administration—ESSA) relied on new technology demonstrations by NASA that were subsequently transferred into NOAA missions. The earliest examples include the Nimbus satellite series, which demonstrated new capabilities for ESSA implementation (one example is the High-resolution Infra-Red Sounder [HIRS] on Nimbus 5, which became the operational sounder on the Television Infrared Observation Satellite Program [TIROS]). This Operational Satellite Improvement Program (OSIP) started in the 1970s and continued in the 1980s, when NASA added a sounding capability to the NOAA geostationary imager; the Visible Infrared Spin-Scan Radiometer (VISSR) became the VISSR Atmospheric Sounder (VAS) in 1980. OSIP was canceled in 1982.

As noted in the National Academies report *From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death* (2000), a replacement for OSIP was never developed. Instead, NOAA continued with a procurement practice of specifying the instrument performance and having the contractor deliver the instrument for flight on the operational satellites. This procedure limits the iterative development process that was so successful in the OSIP program.

There is now an opportunity to resurrect an OSIP-like agreement between NASA and NOAA, and NASA and USGS. One such approach would be to exploit the capabilities offered by the NASA Earth Science Technology Office (ESTO) through a multiagency funding and coordination mechanism. The intent would be to resurrect an interagency technology maturation process to provide atmospheric observing technology "on-ramps" that would account for the strengths of the two agencies: NOAA's low-risk and sustainable measurement set evolving as NASA matures new observing technologies to a high technology readiness level.

PRIORITIZED SCIENCE OBJECTIVES AND ENABLING MEASUREMENTS

New instruments and technologies may provide observations critical for understanding fundamental atmospheric processes. For example, current passive sensors (e.g., MODIS) enable wind estimation by feature tracking (e.g., clouds) in time sequences of images; these wind vectors have been widely used in weather forecasting. Active sensors (e.g., Doppler wind lidars from spaceborne platforms) will be able to track motions indicated by molecular, aerosol, and dust backscatter and measure the vertical profile of the horizontal wind vector. (Note that the Atmospheric Dynamics Mission [ADM]-Aeolus mission will measure line-of-sight winds, not the horizontal wind vector.) Combining the strengths of both active and passive techniques, particularly when co-located (either with sensors on the same satellite platform or flying in formation), can provide insight on the development and evolution of cloud and precipitation particles, and the influences from aerosols. Similarly, active and passive sensing of methane could advance the substantial efforts to close the methane budget. Most likely, uncertainties in other important budgets could also be reduced.

Based on these challenges and opportunities, the following scientific questions and goals in weather and air quality were deemed important, and were categorized as Most Important (MI), Very Important (VI), and Important (I).

- *W-1.* What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean, and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations? (MI)
- *W-2.* How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months? (MI)
- *W-3.* How do spatial variations in surface characteristics (influencing ocean and atmospheric dynamics, thermal inertia, and water) modify transfer between domains (air, ocean, land, and cryosphere) and thereby influence weather and air quality? (VI)
- *W-4.* Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do? (MI)
- *W-5.* What processes determine the spatiotemporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems? (MI)
- *W-6.* What processes determine the long-term variations and trends in air pollution and their subsequent long-term recurring and cumulative impacts on human health, agriculture, and ecosystems? (I)
- *W-7.* What processes determine observed tropospheric ozone (O_3) variations and trends, and what are the concomitant impacts of these changes on atmospheric composition/chemistry and climate? (I)
- *W-8.* What processes determine observed atmospheric methane (CH_4) variations and trends, and what are the subsequent impacts of these changes on atmospheric composition/chemistry and climate? (I)

- *W-9.* What processes determine cloud microphysical properties and their connections to aerosols and precipitation? (I)
- *W-10.* How do clouds affect the radiative forcing at the surface and contribute to predictability on time scales from minutes to subseasonal? (I)

W-1: Planetary Boundary Layer Dynamics

Question W-1. What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean, and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations?

People live and work in the PBL, or the lowest layer of the atmosphere that is directly influenced by its contact with the surface. The vast majority of the economy, agriculture, aquaculture, water management, transportation, and tourism, are sensitive to weather. Cloud and precipitation forecasts are driven by the exchange of water vapor through the PBL. This near-surface layer of the atmosphere is relatively poorly modeled, as is the exchange of energy, moisture, and pollutants between this layer, the surface, and the free atmosphere. These exchanges are critical to weather and climate because the bulk of the interactions with solar heating and evaporation that drive the atmosphere and ocean take place within the PBL rather than the free atmosphere. For forecasts longer than a few days, errors in these exchanges lead to substantial and growing errors in weather forecast models. As an added benefit, more accurate representation of PBL processes in weather prediction models and improved estimates of particulate matter (PM) size distributions and composition can improve modeling of cloud formation and atmospheric radiative transfer.

In recognition of the importance of the PBL for weather and air quality forecasting, this goal and objective was categorized as Most Important.

Objective W-1a. Determine the effects of key boundary layer processes on weather, hydrological, and air quality forecasts at minutes to subseasonal time scales.

In order to adequately represent the key boundary layer processes responsible for the exchange of energy, moisture, and pollutants between the surface and the free troposphere, high-resolution, diurnally resolved, 3D measurements of horizontal wind, temperature, humidity, and aerosol and trace gases are required.

Measurement Objectives

PBL processes show a strong diurnal cycle. For instance, the PBL height can increase by an order of magnitude from near sunrise to midafternoon over land (Stull, 1998). Additionally, satellite measurements of global PBL processes are challenging because the remotely sensed signals from the PBL also contain information about the surface and the cloud-free troposphere. Geostationary satellites can fully resolve the diurnal cycle over a specific region but, without hyperspectral temperature and humidity sounding capability, have difficulty in resolving the vertical structure of the PBL. It is challenging even for polar-orbiting satellites to resolve the vertical structure of the PBL. PBL processes also vary from day to day, but the variations are generally not as strong as the diurnal variations.

Measurement Approaches

Because of the strong diurnal cycles of PBL processes, a combination of geostationary and polar orbiting satellites, airborne platforms, and ground-based networks (e.g., wind profilers and radiometers) are needed for PBL measurements. Also needed are satellite infrared and microwave sounders and radio occultation measurements from the Global Navigation Satellite System (GNSS). This heterogeneous observing network would provide the needed global observations of PBL at the appropriate vertical resolution.

The measurement basis of the key PBL variables includes three-dimensional (3D) temperature, water vapor, and horizontal wind vector, and aerosol and trace gas (e.g., ozone) concentrations. They also include two-dimensional (2D; in the horizontal direction) PBL height, cloud liquid water path, cloud base, and precipitation.

Three-dimensional variables (except wind) can be measured by a variety of instruments on board polar-orbiting and geostationary satellites, airborne platforms (e.g., Aircraft Meteorological Data Relay [AMDAR]), and ground-based networks (e.g., wind profilers, Atmospheric Emitted Radiance Interferometer [AERI], Raman lidars), and through data assimilation using a meteorological model (including chemical processes). For the 3D horizontal wind vector, scatterometer measurements of near-surface wind over ocean are available, and multiangle VIS/IR measurements may occasionally reach the PBL. At present, ground-based networks are crucial for the measurements of air quality variables and horizontal vector (e.g., wind profilers over land and offshore structures, and on ocean buoys). The 3D horizontal wind vector measurements from spaceborne wind profilers will be transformative to weather and air quality forecasting.

Two-dimensional variables can be measured by a variety of instruments on board polar-orbiting and geostationary satellites and ground-based networks (e.g., radiosonde, microwave radiometer, ceilometer, disdrometer, and radar). For instance, PBL height can be measured by lidars (e.g., from CALIPSO), while cloud base can be observed by combining CloudSat radar and CALIPSO lidar measurements.

For trade space analysis, a vertical resolution of 0.2 km for all 3D variables is requested to resolve the vertical structure, as the PBL can be as shallow as a few tens of meters. This requirement can be relaxed during the daytime when the PBL is deep (e.g., over semiarid regions in summer).

Considering the large spatial variation of aerosol and trace gas concentrations (partly due to surface heterogeneities, such as urban-rural or land-water contrast), a horizontal resolution of 5 km is requested for these variables. Consistent with the requirement from other objectives, a horizontal resolution of 10 km is requested for precipitation. For all other variables, 20 km resolution is requested. A reduced horizontal resolution of 20 km for all variables would have reduced effectiveness but would still be beneficial.

A 3-hourly temporal resolution is requested for all variables except air quality variables (for which 2-hourly resolution is requested to better resolve the diurnal cycle). Less frequent sampling than 3-hourly would have difficulty in realistically resolving the diurnal cycle.

To make the measurements most useful, the uncertainty requirement differs for different variables. For instance, it is 1 m/s for horizontal wind vector, 0.3 g/kg for humidity, 0.3 K for temperature, and 20 percent for precipitation.

Comparing Program of Record (POR) versus new measurements, continuing operation of current (U.S. and international) missions (e.g., VIIRS, CrIS, AMSR, CALIPSO, GOES-16) will contribute to all measurements discussed here. The panel anticipates that measurements as listed in the Science and Applications Traceability Matrix (SATM; e.g., precipitation) will be continued. Also helpful are planned missions from international partners. For instance, the ESA ADM-Aeolus mission (Reitebuch, 2012; to be launched in 2018) will provide the Doppler lidar wind profile measurements.

To fully address our measurement needs, however, new measurement capabilities are needed. These capabilities build upon existing or planned missions and hence have a high technology readiness level with fewer risks than brand-new technologies. In particular, with the experience to be gained from the ADM-Aeolus wind profiling mission, a new wind profiling mission is needed to provide sufficient vertical resolution in the PBL and in the troposphere. This is addressed as an identified need/gap and associated Candidate Measurement Approach in Targeted Observable 4 (TO-4) in Appendix C. More useful than GPM alone would be a combined GPM + CloudSat mission for cloud and precipitation measurements. This is similarly addressed in TO-5 in Appendix C.

Recognizing the cross-panel importance of the PBL and the challenges of obtaining 3D measurements of horizontal wind, temperature, humidity, and aerosol and trace gases in the PBL, optimal approaches could be as follows:

- To combine Doppler lidar wind profiling with hyperspectral infrared sounding to provide the 3D structure of horizontal wind. This can be further combined with near-surface microwave scatterometer wind over ocean and ground-based wind profiling, high vertical resolution profiles from radiosondes, and commercial aircraft measurements during takeoff and landing.
- To combine microwave and hyperspectral infrared sounding with GNSS radio occultation to provide the 3D temperature and humidity. This can be further combined with ground-based systems (e.g., Raman lidar) and high vertical resolution profiles from radiosondes and commercial aircraft measurements during takeoff and landing (including water vapor measurements from commercial aircraft).
- To combine with the PBL measurement approaches for trace gases and aerosols as described later in the subsections on air pollution and methane.
- To bring Doppler lidar and hyperspectral infrared observations together in a dynamically consistent way through data assimilation and numerical modeling.

Connections and Linkages to Other Panels

Because the PBL interacts with surface processes, the priorities here are important to the objectives of the Global Hydrological Cycles and Water Resources Panel (through near-surface atmospheric quantities such as wind speed and surface quantities such as precipitation) and the Marine and Terrestrial Ecosystems and Natural Resource Management Panel (through near-surface atmospheric quantities such as wind speed and aerosol and trace gases).

Furthermore, the priorities here are important to all five integrating themes: carbon cycle and water cycle (as mentioned earlier); extreme events (some of which are closely linked to PBL processes, such as air pollution); technological innovation (e.g., wind profile measurements); and applications (as human activities occur primarily in the lower part of the PBL).

W-2: Longer Range Environmental Predictions

Question W-2. How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months?

There are increasingly more demands to extend operational environmental forecasts beyond the typical 7- to 10-day weather forecasts into useful multiweek subseasonal forecasts. Significant progress toward useful subseasonal forecasts has been made in the past few years, as sources of predictability have become better understood and modeled (Barnston et al., 2009; Brunet et al., 2010; Gottschalck et al., 2010; Lin et al., 2010; Vitart et al., 2010; Marshall et al., 2011; Waliser, 2011; Zhang, 2013; Marshall et al., 2014;

Scaife et al., 2014; Mo and Lyon, 2015). Examples of benefits and applications include information on changes in the risks of extreme events, and opportunities for optimizing resource decisions with regard to water security (availability, quality, and management), food security (agriculture, livestock, and fisheries), energy security (demand and production), hazard preparation and response, human health (air quality episodes, urban heat stress, and disease vectors), ecosystems stewardship, and so on.

Although many scientific and technological challenges remain, a great return on investment can be expected if scientific understanding and modeling capabilities associated with subseasonal prediction can be advanced. These advances hinge on maintaining relevant, and in some cases enabling new, satellite-based observing resources. The challenges include the following:

- Improving the observations and data assimilation techniques to significantly reduce errors in the atmospheric initial state that amplify and propagate during the course of the forecast;
- Developing accurate models and parameterizations of complex subgrid scale processes that have significant importance to subseasonal phenomena and predictability, including deep convection and mesoscale organization of storm systems, convective vertical mass transport and propagation of tropical potential energy into the midlatitudes, atmospheric boundary layer processes, aerosol-cloud-precipitation interactions, ocean mixed-layer and sea-ice processes, land-surface and land-atmosphere interactions involving root zone and surface soil moisture, snow processes and vegetation dynamics, stratosphere-troposphere interactions;
- Identifying and characterizing sources of subseasonal predictability, including natural modes of variability (e.g., ENSO, MJO, IOD, QBO), slowly evolving Earth system components, and some elements of "external forcing" (e.g., annual phenological cycle, natural and anthropogenic emissions of aerosols);
- Understanding and quantifying how the preceding sources individually and collectively influence the development of disruptive and extreme events (e.g., MJO and ENSO influences on tropical cyclone locations and frequency, midlatitude blocking events, sudden stratospheric warming events, multiscale variations of the monsoons);
- Identifying the essential elements for coupling Earth system components that, when modeled, will fully exploit the available predictability for applications and societal benefits; and
- Improving data assimilation methods using all observations to improve prediction accuracy from short-range to subseasonal time scale.

This science question/objective was categorized as Most Important by the Weather and Air Quality Panel.

Objective W-2a. Improve the observed and modeled representation of natural, low-frequency modes of weather/climate variability (e.g., MJO, ENSO), including upscale interactions between the large-scale circulation and organization of convection and slowly varying boundary processes to extend the lead time of useful prediction skill by 50 percent for forecast times of 1 week to 2 months.

While a number of operational forecast centers have developed subseasonal forecast systems, most are experimental. National and international community efforts, such as the North America Multi-Model Ensemble (NMME; Kirtman et al., 2013); the NOAA Modeling, Analysis, Predictions and Projections (MAPP) program Subseasonal-to-Seasonal (S2S) Task Force; and the World Climate Research Programme (WCRP)-World Weather Research Program (WWRP) joint S2S Prediction Project (Vitart et al., 2012), are under way to develop and improve these systems, and define useful metrics (e.g., Wheeler and Hendon, 2004; Neena et al., 2014; and Vitart, 2017). Along with the intrinsic science challenges highlighted earlier, additional challenges emphasizing the need for space-based observations are as follows:

- Developing/improving the initialization of atmospheric variables (particularly global tropospheric horizontal vector winds, and including better utilization of data in cloudy/precipitating regions) and surface variables critical to subseasonal prediction (e.g., sea ice, snow, soil moisture, ocean mixed layer) that are significantly underobserved today.
- Developing optimal strategies for initializing deterministic and ensemble subseasonal forecasting systems, considering the roles and predictability associated with the atmosphere, ocean, land, and cryosphere.
- Constructing initial conditions that better utilize satellite data in cloudy and precipitating regions where significant challenges remain in data assimilation methodology. Similarly, contending with anthropogenic sources of microwaves (e.g., radio frequency interference) that limit use of passive microwave observations (e.g., for soil moisture, freeze-thaw).
- Reducing systematic model errors in the underlying physical processes and subseasonal relevant phenomena that affect subseasonal forecast skill.
- Defining appropriate metrics to quantify increases in subseasonal prediction skill.
- Developing coupled atmosphere-land-ocean data assimilation methodologies.

Addressing this objective requires building on research and development advances in observing systems, including interagency and other programmatic considerations.

Measurement Objectives

Observations are critical to sustaining and more fully developing subseasonal predictions for societal benefits. This requires (1) sustaining current observations relevant to subseasonal prediction; (2) establishing and sustaining new observations that enable more-accurate, longer-lead subseasonal forecasts; and (3) demonstrating new research-oriented observations that will improve our understanding and predicting of subseasonal processes and phenomena. Advances across these areas require improved relevant global initial atmospheric, boundary layer, and surface conditions; and process understanding and assimilation/modeling capabilities of atmospheric convection, mesoscale storm organization, and atmosphere and ocean boundary layers, including surface characteristics. *Space-based observations need to be complemented by in situ networks and research campaigns for synergistic use in process research, satellite measurement validation, and development and validation of subseasonal forecast models.*

This section focuses on observations of the vertical profiles of atmospheric temperature, humidity, and horizontal winds, as the other observational requirements are discussed elsewhere in this chapter (see also the details for item W-2 in the Consolidated SATM in Appendix B).

Measurement Approaches

Temperature, humidity, and horizontal vector wind profiles for subseasonal forecasting improvements have requirements for 1 km vertical resolution, with horizontal resolution goals of 5 km (near-term goal) and 3 km (longer-term goal). In addition, there are near-term goals for 3-hour refresh and longer-term goals for 90-minute refresh (NOAA, 1999; WMO, 2017). The POR polar-orbiting and geostationary imagers and sounders partially satisfy these requirements, but complementary observing system enhancements are needed to meet them.

Trade Space for Horizontal Vector Wind Fields

Atmospheric motion vectors (AMVs) are produced by tracking cloud features and water vapor gradients using time sequences of geostationary images or overlapping images from polar orbiting satellites. The polar orbiting satellites generally provide winds over the polar regions, although global AMVs have been generated using the Advanced Very High Resolution Radiometer (AVHRR) on the dual Meteorological Operational Satellite Program (MetOp)-A/B satellites separated in orbit by ~45 minutes. These AMVs lack vertical coverage and resolution; the associated uncertainty in the vector height attribution is the primary contributor to AMV observation error (Velden and Bedka, 2009). Further, they rely on the assumption that tracked cloud or moisture features are indicative of atmospheric motions. In the tropics, where upper-air wind measurements from radiosonde observations are scarce, observation of the 3D horizontal vector winds is more critical than in the mid- and high-latitudes, as the geostrophic balance relationship does not apply and the mass and wind fields become uncorrelated. Such data, were they to become available, would have a significant impact (ECMWF, 2016; Lillo and Parsons, 2017) on extended-range weather prediction.

To meet the long-standing need for 3D wind fields, the options are geostationary hyperspectral infrared sounders, polar-orbiting Doppler wind lidars, and small hyperspectral IR imaging sounders on a low Earth orbit (LEO) satellite constellation (several satellites each in multiple orbit planes). Five to six evenly spaced geostationary satellites would provide near global coverage (between approximately +/–55 degrees latitude). The World Meteorological Organization (WMO) "Vision for the GOS in 2025" recommended at least six IR hyperspectral geostationary sounders separated by no more than 70 degrees of longitude (WMO, 2017). Tracking features in hyperspectral radiance retrievals in clear skies (from soundings with vertical resolution of roughly 1 km) and cloudy skies (with cloud tops defined within 0.5 km) minimizes altitude assignment errors, thus addressing a major problem of motion vectors. Tracking atmospheric motions with wind lidars—as indicated by molecular, aerosol, and dust backscatter—offers good coverage in clear regions. While the early demonstration of this active remote sensing by Aeolus expected later this decade will provide only the radial component of the wind vector, full vector resolution is anticipated, given recent advances in laser technology.

Trade Space for Temperature and Moisture Profiles

The POR advanced infrared polar-orbiting sounders (e.g., AIRS, IASI, or CrIS) provide global temperature and moisture soundings with ~15 km horizontal and ~1 km vertical resolution under clear sky conditions. These hyperspectral IR sounders provide forecast impacts per instrument that are greater than any other single satellite instrument, highlighting the value of increased vertical resolution. Under cloudy conditions microwave sounders provide temperature and humidity profiles, but with less vertical and horizontal resolution. The POR has only two orbits (midmorning and early afternoon), which is less than the recommended ~4-hour revisit obtained with three optimally spaced orbits.

Rapid advancements in CubeSat technologies have led to hyperspectral IR sounder mission concepts (e.g., CubeSat Infrared Atmospheric Sounder—CIRAS) for relatively inexpensive missions that could be flown in the immediate future—either as demonstrations or as a new operational series with a suitable sustainment strategy.

Global Navigation Satellite System-Radio Occultation (GNSS-RO) provides soundings with excellent vertical resolution but inadequate horizontal resolution due to the occultation geometry. Constellations of hundreds of GNSS-RO satellites to increase the temporal sampling have been suggested.

For improved temperature and moisture profile temporal resolution, geostationary satellites must be considered. High spectral (and hence vertical) resolution geostationary IR sounders with rapid scanning would enable monitoring of important low-level information (including PBL evolution and convective initiation), and offer better estimation of surface temperature and emissivity. Numerical experiments (Sieglaff et al., 2009; J.-L. Li et al., 2011; Li et al., 2012; Revercomb, 2012; Weisz et al., 2015) have shown that such observations, were they to be available over the continental United States, would lead to a profound improvement in NOAA's ability to forecast convective initiation and confidently deliver lifesaving severe storm warnings on forecast. Europe is launching a geostationary hyperspectral IR sounder in 2021 with a spatial resolution of 4 km; the higher spatial resolution enables better clear sky sounding coverage but biases the soundings away from cloudy skies. A geostationary microwave capability would offer coverage in cloudy regions, but with poorer vertical resolution. The anticipated 50 km resolution also poses a challenge for achieving definition of small-scale features.

Connections and Linkages to Other Panels

The subseasonal objectives are closely linked to those in the PBL (see the preceding subsection), slowly varying surface properties (see the following subsection), and improved understanding of physical processes associated with convection, clouds, and radiation (discussed later, in the subsections on Questions W-4, W-9, and W-10). In addition they are linked to the Hydrology Panel objectives related to hazardous event preparedness and mitigation via long-lead forecast information (e.g., floods, droughts, wildfire potential). The objectives to improve subseasonal forecasts and the modeling of coupled processes (e.g., soil moisture, snowpack, sea-ice, near surface ocean conditions) are linked to climate objectives to improve seasonal and longer-term forecasts. The climate objectives related to connections between weather/climate extremes and large-scale circulation patterns are also critical to subseasonal forecasting and sources of predictability.

W-3: Surface Spatial Variations Impacts on Mass and Energy Transfers

Question W-3. How do spatial variations in surface characteristics (influencing ocean and atmospheric dynamics, thermal inertia, and water) modify transfer between domains (air, ocean, land, and cryosphere) and thereby influence weather and air quality?

Local variations in surface characteristics affect the exchange of energy, moisture, and pollutants between the surface and the free-atmosphere through changes in the PBL turbulence, local convergence, and vertical motion (Kilpatrick, 2016). These exchanges are critical to weather and climate prediction because the bulk of the interactions with solar heating and evaporation that drive the atmosphere and ocean take place in the boundary layer rather than the free atmosphere. Air quality is also strongly influenced by small-scale weather events related to small spatial scale differences in elevation and surface characteristics, such as at the interfaces between land, ocean, bays, and large lakes (Lyons and Cole, 1976; Wilczak and Glendening, 1988; Banta et al., 2005, 2011; Loughner et al., 2014). One of the greatest weaknesses in air quality forecasts is the inability to properly capture these local variabilities, leading to poorly forecasted air quality events.

The Weather and Air Quality Panel categorized this science question/objective as Very Important.

Objective W-3a. Determine how spatial variability in surface characteristics modifies regional cycles of energy, water, and momentum (stress) to an accuracy of 10 W/m^2 in the enthalpy flux, and 0.1 N/m^2 in stress, and observe total precipitation to an average accuracy of 15 percent over oceans or 25 percent over land and ice surfaces averaged over a 100 × 100 km region and 2- to 3-day time period.

Over the ocean, the average magnitude of vertical transport due to these variations in surface properties is roughly 10 to 100 times the magnitude of the long-term mean flux needed to warm the oceans (Steffen, 2014; IPCC AR5 Report, 2015). Local daily increases in surface fluxes of energy, moisture and air pollutant increase the exchange between the boundary layer and the free atmosphere, and impact weather and air quality locally and downwind (Song et al., 2009; Kilpatrick and Xie, 2015). These surface spatial variations also modify precipitation and local temperature extremes, which are important considerations for agriculture and for the hydrological cycle, which in turn modify the surface air temperature (Kilpatrick and Xie, 2015).

Measurement Objectives

The relevant surface characteristics are roughness, temperature, soil moisture, snow water equivalent (SWE), sea-ice thickness, surface type (soil, vegetation, snow, water, ice, etc.), ocean mixed-layer depth and current vectors (Figure 7.3).

The required accuracy and several new variables are unique for each domain (land, ocean, and ice). Note that the science objective could be achieved with regional- or domain-specific measurements, and that finer spatial temporal scale observations than listed earlier are expected to be needed to meet the accuracy requirements. This objective must leverage the POR (e.g., altimetry, IR sea-surface temperature [SST], land brightness temperatures) and in situ observations (e.g., land-type data sets, Argo).

Measurement Approaches

This goal focuses on observations over large regions of the world, tying small-scale surface variability to the synoptic and global scale for weather, water availability, and the energy cycle. There are a vast number of measurements that could be made to increase the understanding of key processes and their consequences in the boundary layer. Some of the required parameters are already known in a broad sense or are routinely measured as part of the in situ observing network or the satellite POR. Most of the in situ observations will continue to be acquired over land. Open-ocean in situ surface observations from ships and buoys are limited; fortunately, the ocean surface is more amenable to satellite observations than land and sea ice. Subsurface ocean observations—specifically, Argo (Freeland et al., 2010)—have been remarkably successful and are expected to continue. While many variables are needed for this goal, and are well served by the POR and are of low risk, there are a few innovative satellite observations that are not part of the POR.

The *new* satellite-based observations (listed in the order in which they appear in the following text) are the height of the boundary layer, and high-resolution (~5 km) ocean surface winds and ocean surface currents. The following technological developments would be useful: (1) microwave sounders designed to determine near-surface air temperature and humidity as well as continue the passive microwave observations of SST and sea-ice coverage; (2) Ku- or Ka-band radars to measure upper canopy characteristics and snow depth; (3) Doppler radar measurements of ice motion; and (4) the depth of the ocean's mixed layer.

Trade Space for Atmospheric Observations

Columnar water vapor (all sky) can be measured with polar-orbiting and geostationary IR and microwave sounders combined with GNSS-RO. Cloud fraction is measured with polar-orbiting and geostationary radiometers. High resolution of roughly 300 m is highly desirable, but the rapid refresh from geostationary satellites is more important. Lidar (e.g., CALIPSO) can also measure boundary-layer height, but the spatial coverage is very limited for a nadir-pointing instrument. The high-resolution requirement is essential to accurately observe gradients. Measurement of the boundary-layer height is innovative, but it is a highly useful rather than a crucial measurement for this objective. The accuracy requirements have not been investigated in detail to determine the accuracy needs and observational uncertainty.

Trade Space for Land Observations

The following observations are expected from the in situ and ground-based systems: near-surface air temperature and humidity, surface pressure, and surface vector winds. These observations are not available with sufficient spatial density in most locations.

Land-surface temperature can be determined from satellite IR radiometers complemented by modeling or microwave radiances. However, land temperature changes are highly dependent on cloud cover and

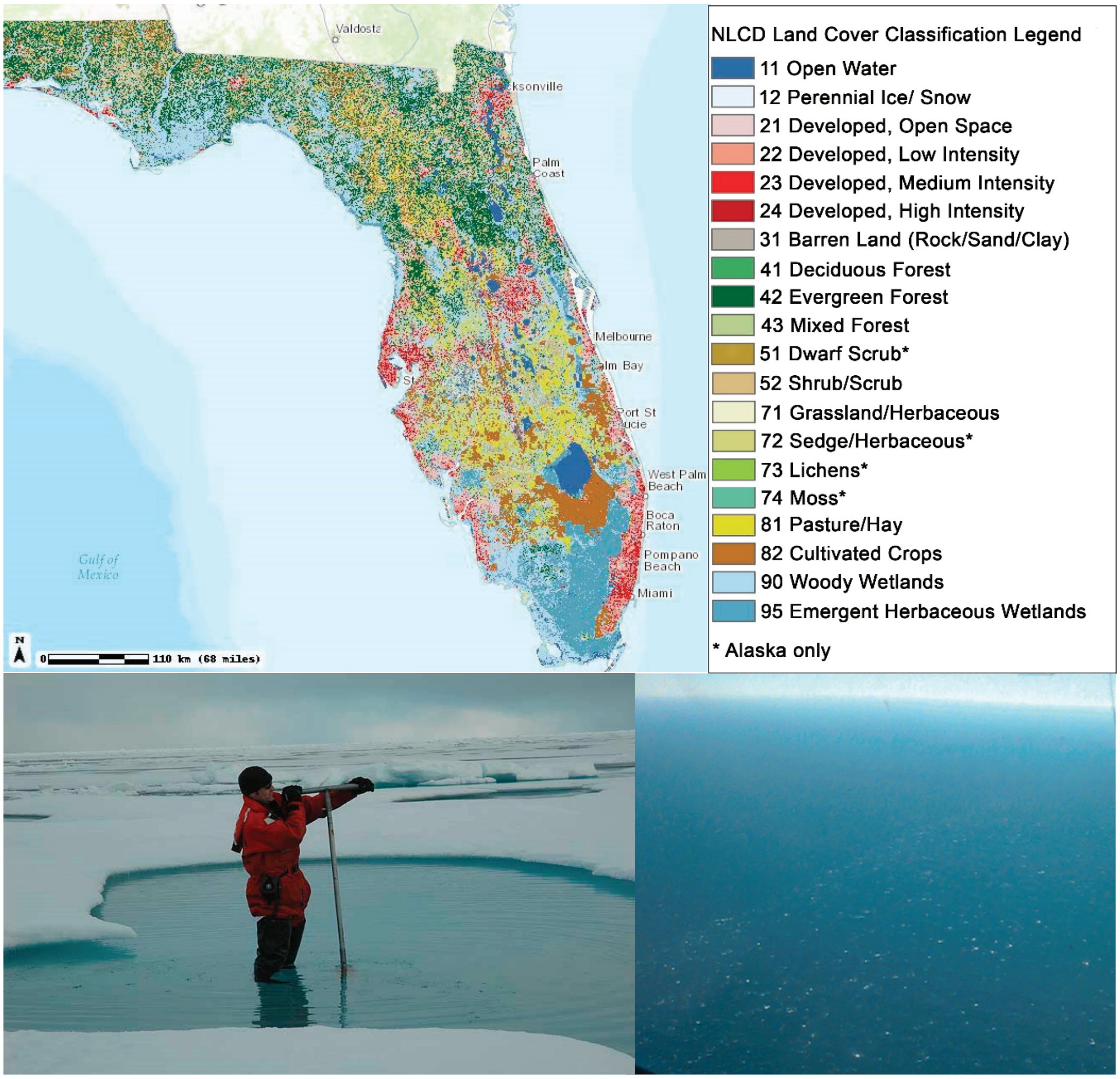

FIGURE 7.3 Small spatial scale changes in surface characteristics that will influence local weather and heat and moisture budgets. These changes in surface characteristics modify the local wind and transport of material such as pollutants and sea salt. *Top:* Land use on a 30 km grid. SOURCE: https://www.mrlc.gov/nlcd2011.php. *Bottom left:* Meltwater ponds on the Arctic sea ice, which can change albedo by 60 percent. SOURCE: Photograph courtesy of Donald Perovich. *Bottom right:* Changes in white-capping (hence roughness and surface fluxes) due to the moving and warmer water in the Gulf Stream. SOURCE: Photograph courtesy of Paul S. Chang.

type, which are not well captured in the models, and clouds degrade the IR observations. Soil moisture (corresponding to a few cm depth) can be measured from multichannel radiometry (Jackson et al., 2010—with L-band—and from scatterometry (Brocca et al., 2011)—where C-band has the greater utility (Wagner et al., 2013). These are demonstrated technologies; however, the observations do not penetrate the surface as far as desired. These observations can be obtained from the scatterometry POR; however, sufficient innovation in spatial and temporal resolution would lead to improved accuracy and utility. Land-surface emissivity can be measured with a multiangle multichannel radiometer (e.g., Multi-angle Imaging Spectroradiometer [MISR]) and modeling (Z.L. Li et al., 2013). These are used for converting brightness temperatures to temperatures, and beam filling is the largest source of error for these observations. More study is required to assess the capability and risk associated with the proposed application.

Upper canopy moisture content can be measured through multichannel radiometers (Zhang and Zhou, 2015) or scatterometers at high inclination angle (Steele-Dunne et al., 2012; Saatchi et al., 2013)—e.g., a QuikSCAT-like design for Ka- or Ku-band—or both types of instruments (Arakelyan et al., 2009). The scatterometer has the advantage of seeing through cloud cover, but the radiometer can provide additional detail about the canopy. Both techniques observe the upper canopy unless the viewing angle is too close to nadir, in which case lower level canopies and the soil influence the observations. The radiometer observations can be obtained through the POR. Much finer resolution scatterometer and radiometer observations would be innovative and very helpful in achieving the science objectives.

Two-dimensional precipitation can be measured by dual-frequency radiometers, satellite radar, surface weather radar, and rain gauges. A sampling of half an hour is desired, which can be done only with a constellation of many satellites or from rain gauges and weather radar. In the continental United States, this is better achieved with weather radar, but for most of the world the satellite constellation is required.

Trade Space for Ocean Observations

Scatterometer observations are well suited for measuring ocean surface vector winds (Wentz et al., 2016), and have a strong heritage. There are many approaches to determine wind speed, but most science applications require wind vector. For example, a polarimetric radiometer can accurately retrieve wind direction if the wind speed is >3 m/s (Wentz et al., 2013), and have greater wind direction uncertainty than scatterometers at higher wind speeds (Rucciardulli et al., 2012). SAR can provide wind vectors (Zhang et al., 2012), but with inadequate directional accuracy.

High spatial resolution is needed to observe closer to the coast and to determine spatial derivatives. A spatial resolution of 5 km could be achieved with relative cost-effectiveness by using Ka-band, with similar accuracy to the Ku-band used on prior U.S., Japanese, and Indian instruments. This higher resolution allows innovation while continuing the climate record. A Ka-band instrument has moved through the NASA ESTO development program, and foreign countries have expressed interest in partnering on a launch of a vector wind sensor. Future scatterometer orbits are planned to be near the 6 AM/6 PM equatorial crossing time, and these will supplement the coverage from the advanced scatterometer (ASCAT). However, temporal variability of the winds over the oceans is so great that additional coverage is needed to meet WMO and science needs (Bourassa et al., 2010).

Ocean surface currents are one of the least well-observed ocean essential climate variables (Simmons et al., 2015). Novel approaches to measuring ocean-surface vector currents have been developed using a Doppler scatterometer (see preceding paragraph) or Synthetic Aperture Radar (SAR; Rouault et al., 2010); however, SAR provides only one vector component (away from the sensor), which is not adequate because currents vary on the inertial scale and full vectors are needed for science and applications. The addition of Doppler capability to a Ka-band scatterometer is the only addition needed to allow such a scatterometer to measure vector currents. This application is sensitive to the wavelength. A 10 km resolution with 5 km in-swath spacing is desired to resolve currents and derivatives of currents (Bourassa and McBeth-Ford, 2010; Rodriguez et al., 2017). The risks associated with an instrument have been reduced through successful completion of the ESTO program (Kumar and Bauer, 2016). Subsurface currents are provided by in situ measurements.

Sea-ice motion has been inferred from passive microwave observations (Kwok et al., 1998) and from active sensors such as SAR (Curlander et al., 1985) and scatterometers (Zhao et al., 2002). This is accomplished through feature tracking; therefore, routine SAR resolution or high-resolution scatterometers are desirable. A Doppler scatterometer should be quite capable because the signal from ice is much stronger than the signal from open water; however, the risk has not been assessed. The passive microwave approach has the advantage of continuing a long time series; however, there is not an established POR for these measurements. The Doppler scatterometer approach is innovative and it is the same instrument as noted for ocean-surface currents. The risks are much greater for Doppler approach than for other methods. A high resolution, Ka- or Ku-band scatterometer would be very effective for feature tracking, largely mitigating this risk.

Sea-surface temperature can be measured from a radiometer at IR or microwave frequencies (Wentz, 2000). IR has the advantage of higher resolution, but microwaves have the large advantage of seeing through clouds that often block IR observations. Ideally, IR and microwave observations would be obtained together to better determine errors in the historical record. There is no POR for microwave observations. Subsurface ocean temperatures are provided by in situ measurements.

Significant wave height (SWH; Young et al., 2011) and sea-surface height (SSH; Chelton et al., 2001) can be measured through satellite radar altimetry (Hemer et al., 2010; Masters et al., 2012). However, coverage is so sparse that SWH is typically estimated from vector wind observations and wave models (Simmons et al., 2015). Wide-swath vector wind observations can be combined with models to determine wave parameters with far better sampling than altimetry (Cardone et al., 2004). These are well-tested approaches. The sampling density of wind observations is less than WMO requirements, but much better than SWH observations.

The vertically integrated energy (ocean heat content) requires altimetry for the column thickness and in situ observations of temperature, salinity, and ocean bottom pressure profiles. They are linked to SSH through the density of the water column and measurement of mass by gravity observations.

Sea-surface salinity can be measured by L-band radiometry, provided there are coincident observations of sea-surface temperature and surface roughness (historically from a scatterometer, without vector capability). The in situ system currently measures salinity substantially more accurately (Belward et al., 2016); therefore, these observations are not optimal to be taken from space unless doing so is justified through other variables (e.g., soil moisture). Salinity observations are not part of the POR or crucial for the proposed science. Subsurface salinity profiles are provided by in situ measurements.

Near-surface air temperature and humidity can be usefully determined from microwave radiometry, provided there is a spectral channel sensitivity to sea-surface temperature (Bourassa et al., 2010; Jackson and Wick, 2010; Roberts et al., 2010; Smith et al., 2012). Satellite observations are slightly noisier than buoy observations, but have much better spatial sampling. These observations can be taken in a manner that is synergetic with other microwave observations.

Trade Space for Cryosphere Observations

Sea-ice surface temperature is determined from IR and microwave radiometers complemented by modeling (Comiso, 2002), while ice-surface emissivity can be measured by a multichannel radiometer. Cloud cover substantially limits the usefulness of these IR observations, but in the absence of clouds will be more accurate than historical microwave observations. Two additional problems are contaminants on the surface and distinguishing ice from water. Accuracy needs are coarse for these observations.

Snow coverage can be measured with visible and microwave radiometry (Armstrong and Brodzik, 2001). The depth and snow water equivalent can be estimated under different conditions from passive microwave, high-frequency radar, and lidar. High resolution is desired because of the lack of uniformity of the depth and snow type. Snow albedo (Stroeve et al., 2005) and emissivity are estimated from a combination of radiometric observations of IR, microwaves, and visible light. Snow coverage, albedo, and emissivity observations are well established. Snow water equivalent and depth measurements are innovative and crucial for a variety of applications (e.g., hydrology and subseasonal forecasting), but they are not essential for the science goal.

Floating sea ice thickness can be estimated from freeboard (height of the ice surface above the sea surface) observations from satellite radar and laser altimetry (Laxon et al., 2003), although snow cover on the ice is an issue. However, the current temporal and spatial sampling is inadequate for the shorter weather, subseasonal, and climate extremes time scales.

Connections and Linkages to Other Panels

This objective is related to the Hydrology and Climate chapter objectives (Chapters 6 and 9) because the small-scale surface features, including man-made changes, cause changes in weather patterns and consequently the energy and water cycles (NASEM, 2016). Extreme weather and air quality events are important parts of Hydrology and Climate, and require similarly high temporal and spatial observing strategies. Surface characteristics influence the local and regional ecosystems that are important for ecosystems and Solid Earth objectives. These surface characteristics serve as the bottom boundary conditions for the PBL and subseasonal forecasts, and they change in response to variability in the PBL, subseasonal variations, and cloud distributions. Spatial gradients in surface features also occur in areas that are prone to rainfall, and in some cases contribute to the differences in local rainfall. Rain-related extremes and disasters including landslides are important for Hydrology, Solid Earth, and Climate. The small differences in surface features can also cause areas of greater likelihood of extreme surface pollution (see the subsections on W-5 and W-6). The local variability in wind stress influences local sea-level height, and the energy and mass budgets at the ice-ocean and ice-air interfaces are influenced by small-scale differences of ice-water change, ocean temperature and salinity change, and most importantly, by the change in albedo associated with melt ponds. The smaller scale spatial changes influence the spatial and seasonal bias in air-sea turbulent energy fluxes, which are sufficiently large to impact the ocean's mode water and atmospheric water vapor, and hence impact the energy budget.

W-4: Convective Storm Formation Processes

Question W-4. Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?

Predicting the occurrence and location of convective storms, and how they evolve into severe weather, is critical for accurate forecasting of hazardous weather. Better predictions of atmospheric water at all spatial and temporal scales is needed to predict hazardous weather with lead times of minutes, to days, to weeks. Reliable longer lead time (>30 minutes) warnings for severe weather events will remain elusive without adequate measurement and modeling of the convective transport parameters throughout their life cycle.

In addition to its role in local severe weather, convection also impacts the large-scale atmospheric circulations, which then influence weather across the globe. For example, the Madden-Julian Oscillation (MJO), a fluctuation of organized convection near the equator, can force midlatitude circulation patterns that lead to weather extremes such as droughts, floods, heat waves, and extended cold snaps. Thus, the timing and location of organized convection in one location may have immediate impacts on convective and nonconvective weather elsewhere. These predictions are also integral to air quality forecasting, as convection can effectively ventilate pollutants in the planetary boundary layer to the free troposphere.

Over the next decade, the resolution of weather and climate models will improve to explicitly represent cloud and convective processes. High-resolution weather modeling is necessary to reliably project the rainfall extremes that are important for predicting future flood risk, and hence, for informing decisions regarding urban planning, flood protection, and the design of resilient infrastructure. Climate modeling experiments are now being run at very high (<5 km grid spacing) resolution and provide potential added value to future projections of convective precipitation (Kendon et al., 2014).

The Weather and Air Quality Panel categorized this science question/objective as Most Important.

Objective W-4a. Measure the vertical motion within deep convection to within 1 m/s and heavy precipitation rates to within 1 mm/hour to improve model representation of extreme precipitation and to determine convective transport and redistribution of mass, moisture, momentum, and chemical species.

Convective processes redistribute water, heat, and momentum through the depth of the troposphere. To improve the prediction of convective processes, observations of the various physical mechanisms within the clouds and local environment that act to produce precipitation are needed. This includes the cloud microphysical properties and the vertical motions within convective storms that are associated with heavy precipitation. These process-oriented measurements should enable new insights to inform the next generation of cloud and precipitation models for weather forecasting. It is imperative that these measurements constrain and define these processes that are critical for more accurate weather forecasts and predictions of the water cycle.

In addition, the interactions between aerosols, trace constituents, and convection are not well understood, particularly with respect to the specific type, scales, and strengths of the convection and the transformation of types of aerosols (dust, black carbon, sulfate, and nitrate). This will require satellite observations to obtain the global context, along with enhanced ground-based networks and suborbital measurements to sample the full vertical profile of aerosol through both the boundary layer and free atmosphere.

Measurement Objectives

Current cloud-resolving models typically overpredict convective updrafts and the associated production of snow and graupel (Varble et al., 2014; Fan et al., 2015). This misrepresentation of precipitation rates biases model depictions of the tails of the precipitation distribution and adversely affects forecasts of extreme precipitation events, including flooding and long-term droughts.

Current global weather forecast models use convective parameterization schemes based on statistics to resolve convective motions rather than simulate the dynamical processes themselves. These deep convection parameterizations are not generally designed to operate in kilometer-scale models (despite recent scale-aware parameterizations; Grell and Freitas, 2014), and many of the assumptions of these schemes (e.g., that the cloud coverage is small compared to the grid square) are violated at these resolutions.

To improve the prediction of convective processes in both cloud-resolving models and larger scale models using convective parameterizations, observations of the various physical mechanisms within clouds that act to produce precipitation are required. Precipitation processes fundamentally couple vertical velocities to hydrometeor production. Thus, measurements must establish relationships between microphysical processes and cloud-scale dynamics. Accurate measurements of cloud water content and surface precipitation at cloud-process-resolving scales is needed along with estimates of particle size distributions and phase. Determining updraft strength for storms provides a foundation for assessing the transport of water vapor, chemical species, and aerosols from the lower troposphere into the middle and upper troposphere.

Measurement Approaches

Liquid and ice particles have significantly different backscatter and attenuation characteristics at different frequencies. Multifrequency active and passive observations can distinguish between hydrometeor types. Wideband passive observations at frequencies ≦ 37 GHz are sensitive to heavy rain, 37-166 GHz observations are sensitive to moderate and light rain, and frequencies greater than 89 GHz are sensitive to scattering by ice particles. An example baseline radar system would include a three-frequency system centered upon scanning Ku-, Ka-, and W-band (e.g., 13, 35, and 94 GHz) radars, with Doppler capability at all frequencies.

Addressing this objective requires measurement of particle vertical velocities ideally with ~20 cm/s accuracy or better in cloud and stratiform precipitation, and at least 50 cm/s accuracy inside deep convection. Radar reflectivity of ice particles should be measured with a sensitivity of approximately –30 dBZ in cloud and –10 dBZ in precipitation (Jackson et al., 2016). The mean particle diameter estimated from multifrequency reflectivity observations can be used to estimate the terminal fall speed and density and habit. Measurements should be acquired at a vertical resolution of at least 250 m to resolve the vertical structure in the storm, and a horizontal resolution of 1 km in cloud and light precipitation. A horizontal resolution of 2 km is preferred to resolve convection. All measurements are to be acquired over a swath of a few tens of kilometers to sufficiently cover the convective-scale storm system.

The TRMM, GPM, and CloudSat missions together have demonstrated the utility of satellite-based Ku-, Ka-, and W-band (14, 35, and 94 GHz) radar observations. The only planned international mission with Doppler capability is the ESA/JAXA EarthCARE mission. The planned Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats (TROPICS) mission proposes a constellation of CubeSats to provide passive multispectral microwave observations for precipitation estimates. Formation flying, as in the A-Train, can also provide needed observations from a combined platform.

Characterizing the prestorm environment is also important, particularly the vertical distribution of the horizontal wind, temperature, and moisture. This can be accomplished over oceanic areas largely with operational weather satellites. The observations need to be made at a temporal and spatial resolution that enables interpretation of the environment and the life cycle of the storm and in conjunction with the active sensors. Given that most heavy convection occurs in the nonpolar regions, hyperspectral observations on geostationary satellites can provide the needed profiles of temperature, moisture, and horizontal winds at the required space and time scales. Observations of cloud boundaries (e.g., cloud top and areal coverage) will also be needed and can be attained from visible and infrared images on operational geostationary and polar orbiting satellites.

Connections and Linkages to Other Panels

This weather objective links to the Climate, Hydrology, Ecosystem, and Solid Earth panels. Current forecast models are unable to reproduce spatial patterns and frequency of precipitation events, which is critical for understanding the change in extreme weather events (Sun et al., 2007). Additionally, most models underestimate the intensity of precipitation, which in turn affects the characterization of extreme flooding (Stephens et al., 2012). At the same time surface processes (e.g., topography, soil moisture, and vegetation heterogeneities) are crucial for the initiation of deep convection.

W-5: Air Pollution Processes and Distributions

Question W-5. What processes determine the spatiotemporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?

One out of every nine premature deaths is related to conditions linked to air pollution. Of those deaths around 4 million/year are related to outdoor air pollution (WHO, 2016; Cohen et al., 2017) costing the global economy about $225 billion in lost labor income annually and more than $5 trillion in welfare losses (World Bank, 2016). Just one fire season in Indonesia in 2015 led to an estimated 100,000 excess deaths from severe haze (Koplitz et al., 2016). Wildfire pollution also affects large U.S. populations (Figure 7.4). The degradation of air quality in many countries over the last decade has been well documented by satellite air pollutant data (Duncan et.al, 2016; Geddes et al., 2016; Ma et al., 2016). By 2060, 6 to 9 million annual premature deaths are expected, with annual global welfare costs projected to rise to U.S. $18 to $25 trillion (OECD, 2016). Ecosystem health is also degraded by air pollution (Figure 7.5), such as acid rain, eutrophication of water bodies, and oxidation of plant tissue by ozone (O_3). Global crop yield reductions are estimated at about 10 percent annually, costing tens of billions (USD) in economic losses

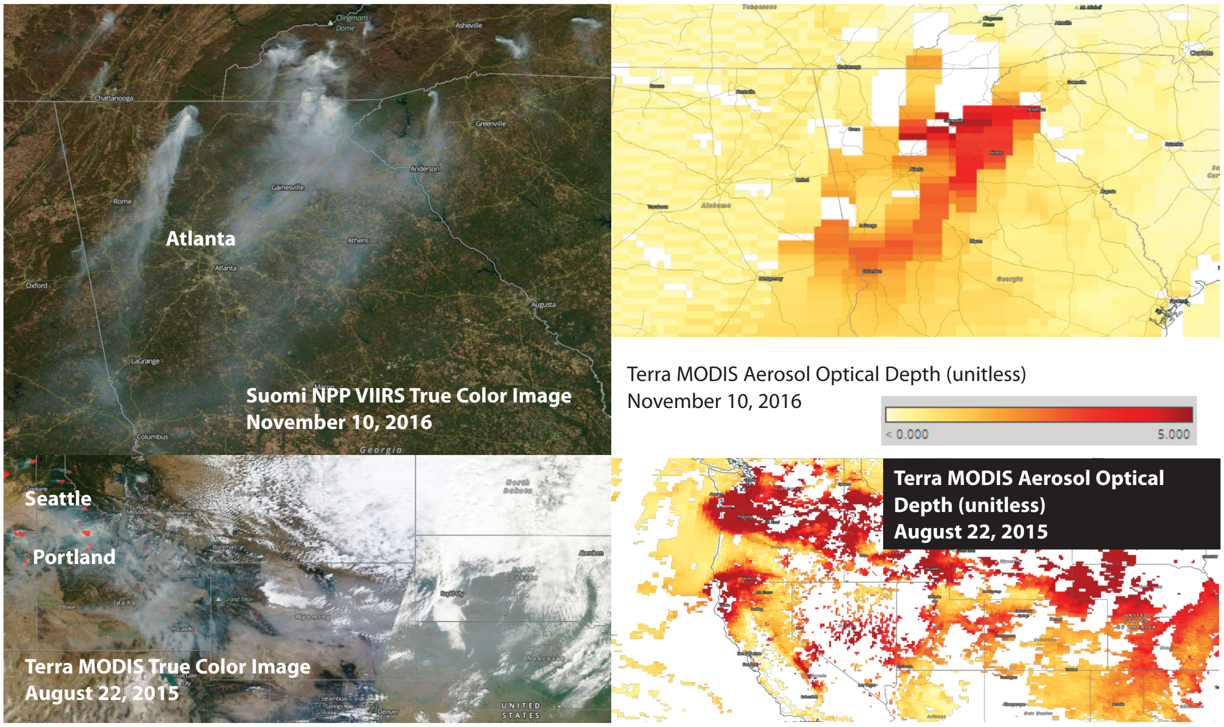

FIGURE 7.4 *Left:* True color images of widespread wildfire smoke over the southeastern United States (top), which intermittently degraded air quality in several major cities, including Atlanta, over a period of several weeks in 2016, and western United States (bottom), where wildfires are common. *Right:* Aerosol optical depth (unitless) data illustrate the widespread impact of these wildfires and allow for the inference of surface concentrations using an atmospheric model and exposure estimates for human health studies. SOURCE: NASA Worldview, at https://go.nasa.gov/2w3vl3N, https://go.nasa.gov/2w6f0kg, and https://go.nasa.gov/2tPqpZc, and https://go.nasa.gov/2tPv4KJ.

FIGURE 7.5 Bronze-colored stippling indicates O_3 damage to green bean plants. Air pollution has negative effects on agriculture with important economic implications. For example, it is estimated that a few billion dollars are lost annually in the United States because of O_3 damage for just one crop, soybeans (Fishman et al., 2010). Yield reductions are thought to be as high as 50 percent for some crops in highly polluted areas (Burney and Ramanathan, 2014). Global, annual economic losses are estimated to be about \$11 to \$26 billion (in U.S. 2000 dollars; see Van Dingenen et al., 2009; Avnery et al., 2011). SOURCE: Photo courtesy of Bryan Duncan (NASA).

(Van Dingenen et al., 2009; Avnery et al., 2011). Despite the social and economic costs, there is little or no current reliable information on air pollution levels and the associated health risks for most of the world's population (de Sherbinin et al., 2014).

The Weather and Air Quality Panel categorized this science question/objective as Most Important.

Objective W-5a. Improve the understanding of the processes that determine air pollution distributions and aid estimation of global air pollution impacts on human health and ecosystems by reducing uncertainty to <10 percent of vertically resolved tropospheric fields (including surface concentrations) of speciated particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2).

Knowledge of the processes driving the spatial distribution of pollutants, especially surface concentrations of particulate matter (PM; e.g., smoke, dust, and oxidized chemicals), ozone (O_3), and nitrogen dioxide (NO_2), is a key motivation for using satellite data for health and air quality research with direct applications to effective mitigation strategy development.

PM impacts human health more than any other pollutant, and plays major roles in climate, weather, and environmental damage. It is also the most complex pollutant, as the particles come in sizes that span orders of magnitude, can contain thousands of species, can be of different phases, and interact continuously with their surrounding gaseous environment. Particles can also be both primary (directly emitted) and secondary (formed) in the atmosphere. Composition, phase, and size influence their health and environmental effects. Exposure to high levels of O_3 reduces lung function, causes breathing problems, aggravates asthma, and damages plants. NO_2 affects lung function, contributes to both O_3 and PM formation, and adds to acid rain and eutrophication.

Measurement Objectives

Assessment of the effects of air pollution on ecosystem and human health and the development of effective mitigation strategies require the establishment and maintenance of a robust observing strategy for both the spatial distribution of pollutants as well as the ancillary data that are necessary to estimate emissions and understand chemical/dynamical processes that determine pollutant distributions. First, a comprehensive observing strategy for the spatial distribution of PM (including speciation), O_3, and NO_2 within the boundary layer and lower free troposphere can be best met by a combination of space-based observations, and expansion of aircraft and ground-based observations in conjunction with chemical transport modeling to capture surface levels. Current in situ networks have limited spatial and temporal coverage and do not capture the chemistry and transport that often occur above the boundary layer, but impact "nose-level" concentrations. However, they measure surface PM properties, such as speciation, and surface O_3, which are not currently inferable from space-based instruments. Given the variety of uses, the accuracy of the estimated pollutant concentrations from the system of satellites, ground-based networks, and models should be within 10 percent. Second, another critical component of this observing strategy is the measurements that are necessary to estimate pollutant emissions, which may be inferred from satellite observations of their spatial distributions in conjunction with chemical transport model. Space, suborbital and high-quality ancillary observations of PM and O_3 precursors (e.g., sulfur dioxide [SO_2], NO_2, carbon monoxide [CO]) are important for better characterizing emission sources that impact PM and O_3. Some pollutant losses (e.g., deposition) may also be estimated from satellite observations of their concentrations. Third, robust meteorological observations are necessary to constrain a chemistry transport models' dynamical processes that influence pollutant transport. Last, other ancillary data that are required include both in situ and satellite observations of ecosystems that may be used to assess their health. The required meteorological and ecosystem observations are presented in the Consolidated Science and Applications Traceability Matrix in Appendix B and discussed elsewhere in this report.

Measurement Approaches

Identifying the major pollution sources of aerosols, both anthropogenic and natural, requires hourly observations at a spatial scale of at least 1 km^2. Passive imagers making measurements at visible and ultraviolet wavelengths and lidars are two approaches to take from satellite platforms. Horizontal resolution for monitoring trace gas species will be at a resolution that depends upon the pollutant, but should be smaller than approximately 10 km. Satellite observations, along with suborbital and ground-based observations, and atmospheric models, are required to provide spatiotemporal 3D pollutant fields. Improved satellite observations will increase the resolution and accuracy beyond that currently achieved with the available systems. New satellite observations would enhance horizontal information at resolutions necessary to ultimately resolve human and ecosystem exposures and important atmospheric processes at relevant scales, recognizing that the models can provide more detailed horizontal resolutions along with vertical structure than achieved by satellite observations alone.

Observations from the current, but aging, Moderate-Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging Spectroradiometer (MISR) give information directly related to PM, such as aerosol optical depth (AOD) and other light scattering properties, and continue to be invaluable. Several upcoming missions promise to continue the records of MODIS and MISR. Upcoming geosynchronous satellite instruments (e.g., on GOES-S and GOES-T, and Tropospheric Emissions: Monitoring of Pollution [TEMPO]), including the current GOES-16 Advanced Baseline Imager (ABI) and Himawari-8/9 Advanced Himawari Imagers (AHI), are viewed as filling the potential void left by the limited remaining lifetimes of MISR and MODIS, but they do not or will not provide more comprehensive information on PM properties. The upcoming Flexible Combined Imager (FCI) onboard the European Meteosat Third Generation (MTG) satellite will present a global constellation of satellites with high spatial and temporal resolution aerosol observations. The polar-orbiting Multi-Angle Imager for Aerosols (MAIA) mission is still in the formulation stage and will provide enhanced information on PM properties for health applications. However, it will have a lifetime of about 2 years. The planned deployment of the polar-orbiting MetOp-SG Multi-Viewing Multi-Channel Multi-Polarization Imaging (3MI) instrument, a 2D wide field of view radiometer, will provide AOD and may provide more global information on aerosol characteristics, but will lack the temporal coverage (i.e., not geostationary Earth orbit [GEO]) desired for health and atmospheric chemistry studies. Planning would need to commence immediately to launch instruments with capabilities similar to, but beyond, MODIS and MISR to ensure long-term and stable continuation of their records. However, neither MODIS nor MISR provide the specific PM properties of most interest—for example, concentration (ground-level or elevated) and composition—but this critical need could be met with an expansion of in situ networks.

Spaceborne instruments that use ultraviolet through visible wavelengths of light, such as the Ozone Monitoring Instrument (OMI) and the recently launched, polar-orbiting instrument Tropospheric Monitoring Instrument (TROPOMI), provide atmospheric O_3 and NO_2 columns, which have very little information on the vertical distribution of O_3 within the troposphere. The upcoming geosynchronous TEMPO instrument is designed to observe the temporal evolution of pollutants throughout the day and may have somewhat more sensitivity to lower tropospheric O_3 (Zoogman et al., 2017) but will not give surface-level concentrations required for most applications. Therefore, surface and aircraft observations of O_3 remain indispensable, and an expansion of these observational networks would benefit health and ecosystem applications.

Global, or near-global coverage of pollutants (e.g., PM, O_3, and NO_2) with diurnal variation is important to link air quality to health and ecosystem damages and to identify source impacts on air quality. Several upcoming missions will provide partial coverage of the northern hemisphere midlatitudes. The TEMPO mission will observe much of North America, and its sister missions will observe East Asia (GEMS) and Europe (Sentinel). However, this planned network covers regions where air quality is largely improving. It does not cover much of South Asia, Africa, and the tropics, where population growth is rapid and over two billion additional people are expected by 2050. Monitoring the spatial and temporal evolution of air pollution over these developing regions will be a critical priority in the next few decades for issues of global human and ecosystems health and climate. For more detail on possible observing strategies for these important regions, see the Consolidated Science and Applications Traceability Matrix in Appendix B.

Connections and Linkages to Other Panels

Air pollution distributions strongly depend on meteorological processes, so this science question/objective connects to other science questions/objectives, such as Question W-1, within the Weather and Air Quality Panel. In addition, it has connections to the Ecosystems Panel, as air pollution degrades forest health and reduces crop yields, and to the Climate subpanel, as PM and O_3 are climate forcers.

W-6: Air Pollution Processes and Trends

Question W-6. What processes determine the long-term variations and trends in air pollution and their subsequent long-term recurring and cumulative impacts on human health, agriculture, and ecosystems?

Long-term, consistent, multi-instrument/multiplatform data records for a wide variety of pollutants are critical for robust quantitative determination in a range of health, air quality, and atmospheric composition applications. They have proven very powerful in assessing sources of emissions and for epidemiologic analyses, and their power will increase as the record lengthens. Increasing the range of species being characterized will enhance the use of the observations (e.g., to assess the health impacts of PM species).

This science question/objective was categorized as Important by the Weather and Air Quality Panel.

Objective W-6a. Characterize long-term trends and variations in global, vertically resolved speciated particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2) trends (within 20 percent per year), which are necessary for the determination of controlling processes and estimation of health effects and impacts on agriculture and ecosystems.

The goal is to create a comprehensive and long-term air quality observing network of satellite and complementary in situ observations. The fidelity of these long-term satellite data records depends on careful interconsistent calibration of the various individual data sets. Long-term and comprehensive data from in situ networks are a necessity for the determination of the credibility of these multidecadal satellite data records.

Measurement Objectives

Air pollutant observations should capture the changes in both the pollutants of most concern (e.g., PM and O_3) and also important chemical intermediates (e.g., NO_2 and volatile/semivolatile organic compounds), with sufficient spatial and temporal resolution to both test atmospheric models as well as to be directly used in specific applications, such as emission trend, ecosystem impact, and health analyses. Long-term trend analysis, when used along with similar long-term ground-based observations and modeling, suggests an accuracy of 20 percent for pollutant concentrations.

Measurement Approaches

The underlying technologies used in the current POR satellite are viable in this application, although increasing spatial resolution and chemical characterization are important to extending how those observations are being used and will be used in the future.

Connections and Linkages to Other Panels

As air pollution variations and trends strongly depend on variations and trends in meteorology, so this science question/objective connects to other science questions/objectives, such as Question W-1, within the Weather and Air Quality Panel. In addition, it has connections to the Ecosystems subpanel, as air pollution degrades ecosystems viability and reduces crop yields, and to the Climate subpanel, as PM and O_3 are climate forcers.

W-7: Tropospheric Ozone Processes and Trends

Question W-7. What processes determine observed tropospheric ozone (O_3) variations and trends, and what are the concomitant impacts of these changes on atmospheric composition/chemistry and climate?

Observing the 3D structure of tropospheric ozone (O_3) and how it evolves over time is central to understanding many aspects of the chemistry and dynamics of the troposphere and lower stratosphere. O_3 is important as a key oxidant and as a more readily observable precursor to the tropospheric hydroxyl radical (OH), the atmosphere's primary oxidant responsible for cleansing the atmosphere of, as well as creating, other pollutants, including some greenhouse gases (GHGs). Therefore, O_3 is central to tropospheric trace gas chemistry. In addition, tropospheric O_3 is also an important GHG, and its radiative forcing is highly dependent on altitude and latitude (Myhre et al., 2013). At Earth's surface, it is an important air pollutant, harming both humans and plants.

The Weather and Air Quality Panel categorized this science question/objective as Important.

Objective W-7a. Characterize tropospheric O_3 variations, including stratospheric-tropospheric exchange of O_3 and impacts on surface air quality and background levels.

Despite decades of study there are still shortcomings in our ability to accurately predict O_3 and OH levels through the United States and around the globe, and this adversely affects our ability to simulate tropospheric chemistry. Underlying questions to be answered include: What are the main factors leading to the errors in today's modeling capabilities? Are there missing related emissions sources? Are other processes more important? Determining the causes of observed tropospheric O_3 variations, from hourly to seasonal to interannual time scales, and km to global spatial scales, is necessary for enhancing predictive capability of today's atmospheric chemistry models that are used for health, air quality, ecosystem, climate, and agricultural management.

Measurement Objectives

The objective is to determine the anthropogenic and natural sources of tropospheric O_3 and its spatiotemporal variations. This requires fine horizontal resolutions (e.g., 5 × 5 km^2 or better) and fine vertical resolution (e.g., <500 m) from the surface through the lower stratosphere. Daily observations are optimal, such as for tracking tropospheric pollutant plumes and stratospheric intrusions.

Measurement Approaches

Observing the vertical distributions of tropospheric O_3 requires a combination of continuous observations from both in situ (e.g., ozonesondes) and satellite instruments. Ozonesondes have historically provided the best vertical resolution, although their global spatial and temporal coverage is sparse. Data collected on commercial aircraft (e.g., In-service Aircraft for a Global Observing System [IAGOS]) also give information on the vertical structure of O_3. Expansion of the ozonesonde and commercial airliner networks would provide better temporal and spatial coverage of in situ observations, including for the purpose of validation of satellite O_3 data.

Spaceborne instruments that use UV/VIS wavelengths of light, such as the Ozone Monitoring Instrument (OMI) and the recently launched Tropospheric Monitoring Instrument (TROPOMI), give atmospheric O_3 columns, which have very little information on the vertical distribution of O_3 within the troposphere. However, column data are useful because of global coverage and because various techniques allow the data to constrain the tropospheric column. The upcoming Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument may have more sensitivity to lower tropospheric O_3 (Zoogman et al., 2017).

The High Resolution Dynamics Limb Sounder (HIRDLS), a filter radiometer that measures IR wavelengths, was designed to provide unprecedented vertical gradient information (~1 km) for O_3, temperature, and several nitrogen-containing species in the upper troposphere and lower stratosphere (UT/LS), a dynamically active and important region for the exchange of O_3-rich stratospheric air to the troposphere. After launch activation of the HIRDLS instrument revealed that the optical path had become blocked, and only 20 percent of the aperture could view the Earth's atmosphere, requiring major algorithm development to account for the blockage and its other impacts. Nevertheless, the limited HIRDLS data demonstrated the utility of the instrument for UT/LS research relative to the Microwave Limb Sounder (MLS) and Michelson

Interferometer for Passive Atmospheric Sounding (MIPAS) instruments, which have coarser vertical resolutions (~3 km) in the UT/LS.

Ancillary observations of O_3 precursors will also help constrain the budget and distribution of tropospheric O_3. For instance, satellite data of lightning distributions and temporal variations will be useful to infer the middle and upper tropospheric NO_x lightning source, which is not currently reliably discerned in tropospheric column NO_2 data. This is important, as lightning NO_x is a major driver of tropospheric OH and also contributes to O_3 formation in the free troposphere, where O_3 is radiatively important. Other ancillary satellite observations that are useful include tropospheric columns of NO_2 and CO. Tropospheric OH and O_3 share many of the same drivers. Therefore, constraint of the concentrations and variations of O_3 and these drivers provides indirect constraints on tropospheric OH, which is not observable from space and is difficult to measure in situ, especially because of its large spatiotemporal variability.

Connections and Linkages to Other Panels

This science question has connections to the Climate subpanel, although there is no specific Climate science question/objective for tropospheric O_3.

W-8: Methane Source Trends and Processes

Question W-8. What processes determine observed atmospheric methane (CH_4) variations and trends, and what are the subsequent impacts of these changes on atmospheric composition/chemistry and climate?

Current observations of atmospheric methane (CH_4) do not adequately constrain its emission source strengths and their variations. CH_4 is a key contributor to rising background ozone (O_3) levels that contribute to urban and regional smog, as well as being responsible for a significant portion of global warming directly and through the increased O_3 levels (Ciais et al., 2013). It also impacts the atmospheric oxidizing capacity, the ability of the atmosphere to remove trace gases. Since preindustrial times, the atmospheric CH_4 burden has more than doubled because of anthropogenic emissions. Natural sources are expected to increase as well in response to a warming climate.

This science question/objective was categorized as Important by the Weather and Air Quality Panel.

Objective W-8a. Reduce uncertainty in tropospheric CH_4 concentrations and in CH_4 emissions, including uncertainties in the factors that affect natural fluxes.

In order to close the CH_4 budget, it is critical to constrain the strengths and distributions of the many types of natural and anthropogenic CH_4 sources and the primary sink, reaction with the hydroxyl radical (OH). However, available observational data of CH_4 and OH have proven inadequate to (1) constrain methane's global and regional source types and strengths, and (2) explain observed atmospheric trends and variation over the last few decades (Houweling et al., 2017; Rigby et al., 2017; Turner et al., 2017).

Measurement Objectives

Spatially resolved (e.g., 4 × 4 km^2) observations of CH_4 are necessary to separate CH_4 source types, which are often co-located or in close proximity, and to infer fluxes. Ancillary observations of carbon monoxide (CO), CH_4 isotopes, and ethane (C_2H_6) will help separate the various anthropogenic and natural CH_4 sources. Hourly CH_4 observations are desired, as, for example, fluxes from wetlands often vary substantially throughout the day. Desired precision is <1 percent with an accuracy of <5 ppbv.

Measurement Approaches

Closure of the CH_4 budget requires a combination of continuous observations, which will draw upon the strengths of surface networks and both passive and active spaceborne instruments. Such a comprehensive network will likely have sufficient coverage, sampling, and precision to constrain global, regional, and sectoral thermogenic and biogenic CH_4 emission sources. Our current understanding of CH_4 distributions and processes is founded mostly on sparse, but precise and accurate ground-based in situ measurements from global monitoring networks.

Passive satellite observations, such as from the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY, now defunct), the Greenhouse Gases Observing Satellite (GOSAT), the recently launched Tropospheric Monitoring Instrument (TROPOMI), and the upcoming Geostationary Carbon Cycle Observatory (GeoCARB) missions, lack spatial coverage over some large source regions, such as cloudy or low-light environments (e.g., Arctic, wetlands, monsoons). They also lack the required sensitivity to quantitatively derive regional CH_4 sources with critically low uncertainties.

Active (laser) remote sensing technology will likely be a key step in obtaining global measurements of atmospheric CH_4 that will complement data from in situ and passive sensors (Figure 7.6). Active sensors detect CH_4 in the absence of sunlight (i.e., at night and at high latitudes in all seasons), in the presence of scattered or optically thin clouds and aerosols, and over land and water surfaces. Though unproven from space, CH_4 lidar technology has been demonstrated on multiple aircraft platforms, and the key instrument components have a long heritage from previous space missions (e.g., Ice, Cloud, and Land Elevation Satellite [ICESat; 2003-2009], Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation [CALIPSO], and Cloud-Aerosol Transport System [CATS]). The joint Franco-German Methane Remote Sensing Lidar Mission (MERLIN) is scheduled for launch in 2020 and is the only active trace gas mission currently in

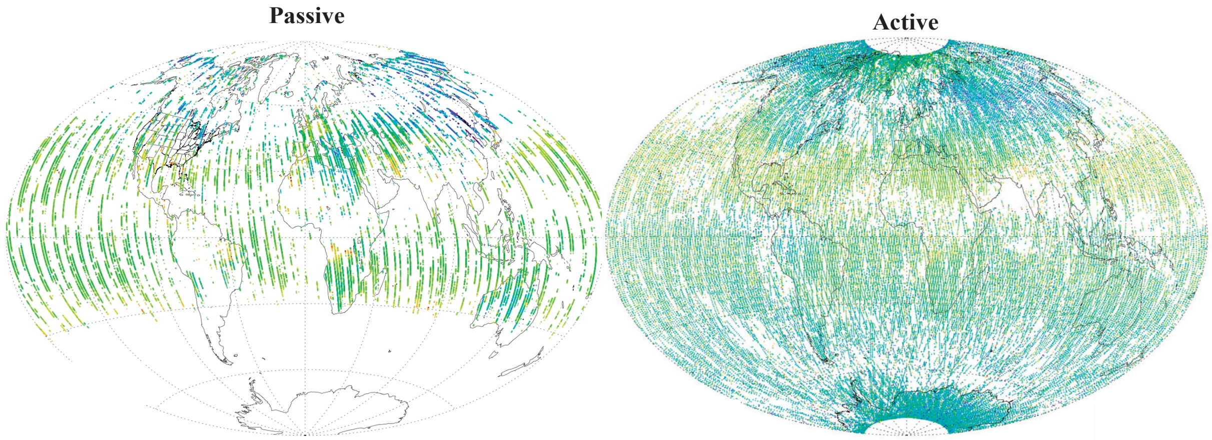

FIGURE 7.6 Spatial coverage of (left) passive and (right) active instruments in July 1-6, 2015. Reasons for gaps in passive coverage include low light (southern hemisphere in this image), high particulate matter levels and clouds (e.g., polar regions and areas experiencing monsoons). SOURCE: Image courtesy of Randy Kawa (NASA).

development (Kiemle et al., 2011; Stephan et al., 2011). Its target sensitivity is 8 to 36 ppb, with 50 km horizontal resolution. While it will serve as a proof-of-concept, its projected lifetime is only 3 years, and there will likely be significant biases associated with its two-wavelength technique. Innovative multiwavelength techniques in future lidar instruments may reduce these biases (Chen et al., 2012, 2014; Sun and Abshire, 2012; Abshire et al., 2013, 2014; Ramanathan et al., 2013, 2015).

Connections and Linkages to Other Panels

This science question has connections to the Climate subpanel, as CH_4 is a potent greenhouse gas, and the Ecosystems subpanel, as natural CH_4 emission sources include wetlands and thawing permafrost.

W-9: Role of Cloud Microphysical Processes

Question W-9. What processes determine cloud microphysical properties and their connections to aerosols and precipitation?

Precipitation forecasts cover different space and time scales, from what is happening outside someone's home to seasonal forecasts over a particular watershed for agriculture applications. While precipitation forecasts have improved over the last decade, more accurate forecasts of the location and intensity will help people as they plan their daily lives as well as assist businesses in their planning. An important step in better precipitation forecasts requires observations of the coupling between cloud water content, vertical mass fluxes, and precipitation yield; these are needed to develop new formulations for models operating at these fine spatial scales. As the computing power continues to increase, cloud resolving models now used in regional models will operate on global domains (Tao et al., 2017).

The scientific community has identified a coming challenge for an improved understanding of in-cloud microphysical processes (e.g., deposition, aggregation, riming, accretion, melting, entrainment, and evaporation) and the circulation patterns that lead to precipitation (Bony et al., 2015; WCRP, 2015). While our understanding largely comes from theoretical studies and explorations using appropriate cloud models and simulation, observations provide the constraints that guide these explorations and document the environmental factors that determine the roles of various in-cloud processes. Currently, these processes are crudely parameterized in most weather models even though they are critical to the storm precipitation. Models that explicitly represent these processes show extreme sensitivity to precipitation based on the choice of process rates. The set of observational constraints that have been possible with past and present observations have not proven sufficient to constrain the models, and new observations spanning all weather scales are needed to quantify these processes and their dependence on the storm environment.

This science question/objective was categorized as Important by the Weather and Air Quality Panel.

Objective W-9a. Characterize the microphysical processes and interactions of hydrometeors by measuring the hydrometeor distribution and precipitation rate to within 5 percent.

Achieving this objective requires observations of cloud microphysical property profiles (e.g., water content, particle size, and number concentration), precipitation, cloud-scale vertical and horizontal motions, profiles of aerosol properties that provide information on cloud condensation nuclei concentrations, and the environmental conditions around the storm. Current observations provide only limited insight into the highly uncertain relationships between air motions, aerosols, microphysical processes, and precipitation formation that models must accurately represent. Priority observations must characterize the microphysical processes and interactions of hydrometeors by measuring the hydrometeor distribution and precipitation rate to within 5 percent.

Measurement Objectives

Providing observational constraints on convective precipitation efficiency requires, at a minimum, accurate measurements of ice water path (IWP) and precipitation on cold-cloud-process-resolving scales. To further relate these to the vertical mass fluxes responsible for transporting ice mass to the upper troposphere requires corresponding estimates of hydrometeor fall speed and vertical air motions. Aerosols impact a cloud by influencing the initial droplet spectrum activated in an updraft near the cloud base. Observations of cloud vertical motions, precipitation, and aerosol geophysical properties can be used to constrain microphysical process rates. Characterizing the storm environment is also important, particularly wind, temperature, and moisture profiles and the boundary layer structure. The observations need to be made at a temporal and spatial resolution that enables interpretation of the environment and the life cycle of the storm. The weather satellite observations of record can provide the environmental conditions. Hyperspectral infrared observations on geostationary satellites (Li et al., 2011) can provide the needed profiles of temperature, moisture, and to a certain degree, winds at the required space and time scales in nonpolar regions.

Measurement Approaches

Observation of integrated ice mass, particle fall velocities, vertical air motions, and surface precipitation rates would satisfy a need to constrain precipitation efficiency, convective mass fluxes, and sedimentation rates in weather and global models. Accurately modeling the interactions of hydrometeors and precipitation rate at a minimum requires observations of the ratio of ice mass aloft to precipitation flux at the surface over the range of conditions encountered in nature. This will require a combination of passive and active measurement systems.

Radar reflectivity measurements at multiple frequencies provide a means to derive the mean particle diameter, along with estimates of terminal fall speed, density, and habit. Liquid and ice particles have significantly different backscatter and attenuation characteristics at different frequencies. Multifrequency active and passive observations can distinguish between these hydrometeor types. Wideband passive observations are sensitive to heavy rain (≦37 GHz), moderate and light rain (37-166 GHz) and ice scattering (≧89 GHz). Radar reflectivities supply additional constraints on vertical distribution of particles. The radar (e.g., TRMM, GPM, and CloudSat) missions provide heritage for the needed instruments and have demonstrated the utility of satellite-based Ku-, Ka-, and W-band (e.g., 14, 35, and 94 GHz) radar observations for profiling the full spectrum of condensed water throughout the atmosphere. The only planned international mission with Doppler capability is the ESA/JAXA EarthCARE mission (Sy et al., 2014). Doppler velocities at Ku-, Ka-, and W-band can now be measured to the desired accuracy at a horizontal resolution of at least 4 km for the full spectrum of precipitation.

Instantaneous IWP uncertainty has to be better than 50 percent for IWP in the range 3-1000 gm^{-2}. The uncertainty of mean particle size (e.g., mass-mean diameter, over the range 40-600 μm) should approach 25 percent for column-mean and 50 percent for vertically resolved measurements. A spatial resolution of 4 km is desirable in stratiform precipitation; 2 km resolution is required in the ice portions of convective cores. Submillimeter radiances provide sensitivity to integrated ice mass. Example approaches to submillimeter wavelength radiometry include the airborne Conical Scanning Submillimeter-wave Imaging Radiometer (CoSSIR; Evans et al., 2005). Radars have now flown in space with sufficient frequency diversity to sample the full spectrum of atmospheric ice with the added ability to retrieve the rainfall below (Stephens et al., 2008; Hou et al., 2015). The first spaceborne submillimeter radiometer, the Ice Cloud Imager (ICI), is planned to launch on the MetOp-SG satellites. It has been demonstrated that IWP can be inferred to accuracies better than 50 percent over a range from 2 to 1000 gm^{-2} from submillimeter radiances (Evans et al., 2002). This range of IWP could be expanded to cover the full spectrum of suspended and precipitating ice by coordinating the observations with an infrared radiometer and a lower frequency passive microwave in a constellation modeled after the highly successful A-Train (L'Ecuyer and Jiang, 2010).

Instantaneous surface precipitation rate (mm/hr) uncertainties are estimated at 50 percent. Multifrequency radar (Ku-/Ka-band in moderate precipitation; Ka-/W-band in light precipitation) need observations at 2 km spatial resolution, with 4 km resolution being more realistic in heavier precipitation, where Ku-band will be required.

Vertical velocity (m/s) with an accuracy of 0.2 m/s (stratiform); 0.5 m/s (convection) can be determined with Doppler velocity approach at one or more frequencies (depending on precipitation intensity and location in cloud). Recent literature suggests that substantial progress could be made with simultaneous measurements of vertical velocity and IWP to accuracies of 20 cm/s and 50 percent, respectively, on individual storm scales (Saleeby and van den Heever, 2013; Varble et al., 2014; Tao et al., 2017). Combined Doppler velocity with terminal fall speed estimates from mean particle size can be used to infer vertical air motions.

Aerosol loading of environment is determined from lidar observations of aerosol backscatter, extinction, and depolarization at 532 and 1064 nm, with a horizontal resolution of 100 m and a vertical resolution of approximately 50 m. Active lidars are likely not to provide a sampling of the entire storm environment. Coupling the lidar with the imaging systems can provide a more complete analysis of the aerosol loading of the environment. Total aerosol optical depth of the environment around the storms can also be retrieved with operational imagers on geostationary and polar orbiting satellites. Observations of cloud boundaries (e.g., cloud top and areal coverage) will also be needed and can largely be attained from POR visible and infrared imagers planned for operational geostationary and polar orbiting satellites.

Connections and Linkages to Other Panels

Observations are needed to constrain cloud microphysical properties, precipitation, and storm dynamics processes on various weather scales and quantify their dependence on the environment. Global climate models (GCMs) need appropriate observations that define the relationships between ice-phase precipitation processes, detrainment rates, and surface rainfall. The lack of global measurements of atmospheric ice water path, for example, has led to an order of magnitude uncertainty in GCMs, and recent evidence suggests that model improvement over time has been slow (Jiang et al., 2012; Su et al., 2013). Better precipitation forecasts also support the Hydrology Panel by better defining the amount of water that falls on the ground.

W-10: Clouds and Radiative Forcing

Question W-10. How do clouds affect the radiative forcing at the surface and contribute to predictability on time scales from minutes to subseasonal?

Clouds in Earth's atmosphere occur with widely varying spatial and temporal scales. Clouds have a first-order effect on the radiative balance at the surface, and the radiative heating/cooling within the planetary boundary layer and atmosphere. The radiative effect of clouds is fundamentally linked to cloud-aerosol processes.

Inadequate representation of clouds in numerical weather forecast models can lead to significant temperature biases and errors in subsequent forecasts of severe weather, transportation hazards, renewable energy, agriculture, and flooding hazards. Multiyear satellite- and aircraft-based studies (Rossow and Schiffer, 1999; Wood and Field, 2011) have shown that 15 percent of the global cloudiness is at or below a 10 km horizontal scale. Even high-resolution, convective-allowing models run at 3 km horizontal scale are unable to capture this significant fraction of cloudiness. Consequently, high-resolution weather forecast errors result from this inability to adequately represent these small-scale clouds and the subsequent effects on boundary-layer evolution. The proposed very high resolution global measurements of clouds are critical for weather forecasts from which widespread economic and safety-related decisions are made hourly. They are essential both for model improvement (especially, subgrid-scale cloud representation) and for effective all-sky radiance data assimilation to improve global and regional short-range weather forecasts. A similar challenge with representation of subgrid clouds (Bauer et al., 2015; Furtado, 2016) contributes to errors in coupled atmospheric-ocean models producing subseasonal (roughly 2 to 8 weeks) guidance.

This science question/objective was categorized as Importantby the Weather and Air Quality Panel.

Objective W-10a. Quantify the effects of clouds of all scales on radiative fluxes, including on the boundary layer evolution. Determine the structure, evolution, and physical/dynamical properties of clouds on all scales, including small-scale cumulus clouds.

The goal of this objective is to observe and understand the effects of clouds on the radiative balance at the surface. This emphasis on radiative forcing from clouds (and related aerosols) complements the focus on cloud microphysics processes (see section on Question W-9) and on deep convective clouds (see section on Question W-4). The science objectives related to surface properties (see section on Question W-3) also require these improved surface shortwave and longwave radiation fluxes and related cloud effects. Related measurements of aerosols and aerosol-cloud interaction are also necessary to improve accuracy of overall cloud and radiation effects on weather models.

Measurement Objectives

The relevant measurements are the three-dimensional distribution of water vapor and temperature, horizontal and vertical winds, hydrometeors and aerosols, the horizontal distribution of precipitation, and cloud information (e.g., cloud fraction, depth, and droplet size). These parameters affect the radiative fluxes at the surface and within the atmosphere. Global measurements, including the polar regions, are required, along with the ability to accurately discriminate between clouds and land-surface areas with similar thermal characteristics. The ability to determine the radiative properties of clouds and aerosols on all scales, including small-scale cumulus clouds, is required, along with the need to quantify the effects of cloud radiative fluxes of all scales. The global measurements of cloud information represent the new requirements relevant to this science question; the other geophysical variables overlap with many of the other Weather and Air Quality Panel priorities.

Measurement Approaches

Current space-based measurements include those from polar and geostationary VIS, IR, and MW sensors (e.g., MODIS and VIIRS, CERES, GOES-16, AVHRR, MeteoSat, and Himawari-8). Complementary ground-based systems include ceilometers (e.g., at airports in the United States) and very limited surface radiation networks (e.g., U.S. Surface Radiation Budget Network [SURFRAD]).

Additional required space-based observations include high-resolution VIS/IR imagers. Resolutions down to 200 m horizontal would be desirable, although 1 km horizontal would be acceptable. A higher-resolution Visible/Infrared Imaging Radiometer Suite (VIIRS)-like instrument, with the day-night band and an update frequency of 3 hours would be ideal, although a 6-hour frequency would be acceptable. Complementary ground-based observations, such as the globally distributed, higher density surface-based radiation stations and the U.S. DOE/ARM sites are also needed.

Connections and Linkages to Other Panels

The measurements required for this science question/objective are closely linked to those of the Climate Panel. Both emphasize the combination of spaceborne, airborne, and ground-based measurements to measure fluxes and the impact of clouds. Both emphasize cloud physical properties and radiative fluxes, and both recognize the importance of aerosols to cloud formation and properties and those impacts on the radiative fluxes.

RESULTING SOCIETAL BENEFIT

The state of our atmosphere exerts a strong influence on human activities. A goal of this chapter is to determine the appropriate questions that will eventually lead to forecasting capabilities that minimize the adverse impacts on people and maximize the positive socioeconomic consequences. Attaining these goals will require new observations combined with operational satellite observations and improved capabilities in data assimilation and numerical simulations. The maximum benefit can be achieved only by also identifying the most adversely affected populations and the most impacted economic sectors, and through the knowledge and flexibility of decision makers who will make use of the improved predictions. This section is restricted to the valuation of improved weather and air quality forecasts and its benefits. To be of value, these predictions must be timely, accurate, and relevant. The science questions and objectives laid out in the preceding section need to be answered to achieve more accurate weather forecasts and air quality simulations in the coming decade.

Improvements in current forecast models along with the incorporation of observations within the data assimilation systems have been useful in providing appropriate weather guidance to decision makers. However, forecasting heavy precipitation remains a challenge, and without understanding the microphysical processes involved in convective growth, the simulation of the physics of a convective storm at a scale of 1-3 km is not possible. The limitations of the convective resolving models are impacting the ability to identify and predict strong winds and heavy rainfall with sufficient lead time for people and organizations to react. New instruments and technologies to measure the interactions between storm updraft, cloud water, and ice with the ensuing formation of precipitation will provide constraints on physical representations in storm models. There will be significant societal benefits in preparing for heavy rains if it can be determined exactly when and where heavy precipitations occurs. One example is the September 2016 flood in Ellicott City, Maryland, that resulted from a combination of unprecedented rainfall, unfavorable topography, and past land use and infrastructure decisions based on historic climate norms for the area. While a heavy rain event was forecasted 5 days in advance, it was more extreme than predicted and was a very rare event that resulted in flash flooding (NOAA NWS, 2016). Advances in precipitation forecasts along with improved hydrology models are believed to be a key factor for improving the outcome of such an event in the future.

Not currently observing the time evolution of the PBL's vertical structure on a national scale limits our ability to most accurately forecast the PBL's collapse, the initiation of convection, the outbreak of severe weather, and the location and intensity of tornados, hail, and damaging straight-line winds. As of mid-

May, the tornado death toll for 2017 has risen to 34.[5] By providing NOAA/NWS forecasters with better information, it would be possible to provide more reliable information to the public earlier, warning on the forecasts rather than the actual observations of the severe weather itself. High temporal resolution ("minute-scale") temperature and moisture soundings over the continental United States could be an effective tool in addressing this requirement.

Accurate operational subseasonal forecast systems directly support decision making, and the potential impact of useful subseasonal forecasts is extensive. Examples of expected use include (1) agriculture and fisheries at a local/regional level as well as for food security concerns at national and international levels; (2) water availability and management at local/regional levels as well as for security concerns at national and international levels; (3) hazard preparation and response, including for floods, tropical cyclones, and other severe storms; (4) health considerations, including those related to air and water quality, vector-borne diseases, and severe heat and cold conditions; (5) energy production and generation (e.g., wind, hydroelectric) for demand related to anomalous temperature conditions; (6) transportation, including ship routing and guidance for potential Arctic passages; and (7) military planning and security concerns related to many of the preceding items. While the potential of subseasonal prediction to yield actionable information in these areas is evident, bringing this promise to fruition still requires considerable advances in research and operations, both of which depend critically on specific types of observations. Hurricanes Harvey, Irma, and Maria in the late summer and fall of 2017 resulted in an unprecedented damage for the United States (states and territories) from both extraordinary precipitation and wind damage. Improved 2-week prediction on the potential for extreme weather events such as tropical cyclones or severe convective storms (e.g., Brunet et al., 2010; Vitart et al., 2017; Vitart and Robertson, 2017) enabled by improved global observations, data assimilation, and Earth system prediction models will be critical for these longer range decision-making areas for the United States (NASEM, 2017).

Satellites collect data on pollutant concentrations that are not captured by traditional networks—for example, over the ocean and above the surface. The information from satellites is particularly powerful when linked with the long-term ground-based observational air quality measurement networks, research and commercial aircraft measurements, and increasingly refined models. Satellite observations provide information that can be assimilated to better predict where pollutant levels will be high and to determine where to target emission reductions to most effectively reduce adverse impacts. The benefit to society is that satellite data of fire locations and pollutant concentrations are being used by health and air quality managers to support decision-making activities. Wildfires throughout North America, such as during the summer of 2017, can expose residents in rural and urban areas to unhealthy and often hazardous levels of particulate matter for weeks at a time. Satellite data and air quality models are used to inform fire management efforts to minimize the exposure of the population to severe haze and also to issue air quality alerts so that people may take action to limit their exposure.

Since Hurricanes Andrew (1992) and Katrina (2005), there has been significant progress in providing useful information to the public that must prepare for the hurricane landfall. With the improvement in the meteorological knowledge of the atmospheric physics, the technology of the observations from satellites and the ground, and the operational implementation of both, the associated forecasts (e.g., timing, location, and intensity of hurricane landfall, predicted winds, flooding, storm surge, etc.) have achieved increased public confidence and enabled civil and emergency managers to understand and prepare for likely outcomes days to over a week in advance. The National Weather Service now can work closely and effectively with the emergency management community at the federal, state, and local levels—a successful cooperation that likely saved many lives in Texas, Louisiana, Florida, Puerto Rico, and the U.S. Virgin Islands

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[5] C. Dolce and L. Lam, 2017, "2017 U.S. Tornado Deaths Near Three Dozen, and More Than Half Have Been in Mobile Homes," *Weather.com*, May 17, https://weather.com/storms/tornado/news/tornado-death-toll-may-2017.

this past hurricane season. Further improvement in the forecast skill, from more advanced observations of weather and air quality along with state-of-the-art assimilation into numerical models, will enable earlier and more accurate predictions (of potential fire as well as severe weather). When effectively communicated to the public, these forecasts will lead to increased probabilities of reduced risk to the public and better outcomes from disastrous circumstances for the millions that are directly affected. This means leveraging the maturing science of observing and predicting severe weather, water, and climate-related events into comprehensive, reliable, and optimal management of societal preparation, response, and recovery.

Society will always be sensitive to weather and air quality, and thus the importance of better predictions for the protection of lives and property and continued economic growth will remain an ongoing challenge. The global suite of international operational geostationary satellites provide valuable imagery at spectral resolutions that can complement low Earth orbit NASA research missions by providing the spatial and temporal context of the scene being observed. The next decade provides a unique opportunity for NASA, NOAA, and USGS to work collaboratively to gather new measurements that make improved prediction a reality.

REFERENCES

Abshire, J.B., A. Ramanathan, H. Riris, J. Mao, G.R. Allan, W.E. Hasselbrack, C.J.Weaver, and E.V. Browell. 2014. Airborne measurements of CO_2 column concentration and range using a pulsed direct-detection IPDA lidar. *Remote Sensing* 6:443-469.

Abshire, J.B., H. Riris, C. Weaver, J. Mao, G. Allan, W. Hasselbrack, and E. Browell. 2013. Airborne measurements of CO_2 column absorption and range using a pulsed direct-detection integrated path differential absorption lidar. *Applied Optics* 52:4446-4461.

Andrews, T., P.M. Forster, O. Boucher, N. Bellouin, and A. Jones. 2010. Precipitation, radiative forcing and global temperature change. *Geophysical Research Letters* 37:L14701.

Arakelyan, A.K., M.L. Grigoryan, A.K. Hambaryan, and A.A. Arakelyan. 2009. Ka-band, short-pulse, combined scatterometer-radiometer system and the results of its preliminary application for snow, bare, and vegetated soil remote sensing from low altitude measuring platforms. In *SPIE Proceedings Vol. 7308: Radar Sensor Technology XIII*. SPIE Defense, Security, and Sensing, Orlando, FL.

Ardanuy, P. 2011. All Aboard the J-Train. *Space News*. October 5. http://spacenews.com/all-aboard-j-train/.

Armstrong, R.L., and M.J. Brodzik. 2001. Recent Northern Hemisphere snow extent: A comparison of data derived from visible and microwave satellite sensors. *Geophysical Research Letters* 28(19):3673-3676.

Avila, L.A., and J. Cangialosi. 2012. *Tropical Cyclone Report: Hurricane Irene*. National Hurricane Center. https://www.nhc.noaa.gov/data/tcr/AL092011_Irene.pdf.

Avnery, S., D.L. Mauzerall, J. Liu, and L.W. Horowitz. 2011. Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. *Atmospheric Environment* 45(13):2284-2296.

Baker, W.E., R. Atlas, C. Cardinali, A. Clement, G.D. Emmitt, B.M. Gentry, R.M. Hardesty, et al. 2014. Lidar—measured wind profiles: The missing link in the global observing system. *Bulletin of the American Meteorological Society* 95:543-564.

Banta, R.M., C.J. Senff, R.J. Alvarez, A.O. Langford, D.D. Parrish, M.K. Trainer, L.S. Darby, et al. 2011. Dependence of daily peak O_3 concentrations near Houston, Texas on environmental factors: Wind speed, temperature, and boundary-layer depth. *Atmospheric Environment* 45:162-173.

Banta, R.M., C.J. Senff, J. Nielsen-Gammon, L.S. Darby, T.B. Ryerson, R.J. Alvarez, S.R. Sandberg, E.J. Williams, and M. Trainer. 2005. A bad air day in Houston. *Bulletin of the American Meteorological Society* 86(5):657-669.

Barnston, A.G., S. Li, S.J. Mason, D.G. DeWitt, L. Goddard, and X. Gong. 2009. Verification of the first 11 years of IRI's seasonal climate forecasts. *Journal of Applied Meteorology and Climatology* 49(3):493-520.

Bauer, P., A. Thorpe, and G. Brunet. 2015. The quiet revolution of numerical weather prediction. *Nature* 525:47-55.

Belward, A., M. Bourassa, M. Dowell, S. Briggs, H. Dolman, K. Holmlund, R. Husband, et al. 2016. *The Global Observing System for Climate: Implementation needs*. GCOS-200. https://unfccc.int/files/science/workstreams/systematic_observation/application/pdf/gcos_ip_10oct2016.pdf.

Bony, S., B. Stevens, D.M.W. Frierson, C. Jakob, M. Kageyama, R. Pincus, T.G. Shepherd, et al. 2015. Clouds, circulation, and climate sensitivity. *Nature Geoscience* 8:261-268.

Bormann, N., and J.N. Thépaut. 2004. Impact of MODIS polar winds in ECMWF's 4DVAR data assimilation system. *Monthly Weather Review* 132:706-718.

Bourassa, M.A., H. Bonekamp, P. Chang, D. Chelton, J. Courtney, R. Edson, J. Figa, et al. 2010. Remotely sensed winds and wind stresses for marine forecasting and ocean modeling. In *Proceedings of the OceanObs'09: Sustained Ocean Observations and Information for Society Conference Volume 2*, Venice, Italy, September 21-25, 2009.

Bourassa, M.A., S. Gille, D.L. Jackson, B.J. Roberts, and G.A. Wick. 2010. Ocean winds and turbulent air-sea fluxes inferred from remote sensing. *Oceanography* 23:36-51.

Bourassa, M.A., and K. McBeth-Ford. 2010. Uncertainty in scatterometer-derived vorticity. *Journal of Atmospheric and Oceanic Technology* 27:594-603.

Brauer, M., G. Freedman, J. Frostad, A. van Donkelaar, R.V. Martin, F. Dentener, R. van Dingenen, et al. 2016. Ambient air pollution exposure estimation for the global burden of disease 2013. *Environmental Science and Technology* 50(1):79-88.

Brocca, L., S. Hasenauer, T. Lacava, F. Melone, T. Moramarco, W. Wagner, W. Dorigo, et al. 2011. Soil moisture estimation through ASCAT and AMSR-E sensors: An intercomparison and validation study across Europe. *Remote Sensing of Environment* 115(12):3390-3408.

Brunet, G., M. Shapiro, B. Hoskins, M. Moncrieff, R. Dole, G.N. Kiladis, B. Kirtman, et al. 2010. Collaboration of the weather and climate communities to advance subseasonal-to-seasonal prediction. *Bulletin of the American Meteorological Society* 91(10):1397-1406.

Buizza, R., and M. Leutbecher. 2015. The forecast skill horizon. *Quarterly Journal of the Royal Meteorological Society* 141:3366-3382.

Burney, J., and V. Ramanathan. 2014. Recent climate and air pollution impacts on Indian agriculture. *Proceedings of the National Academy of Sciences* 111(46):16319-16324.

Cardinali, C. 2009. Monitoring the observation impact on the short-range forecast. *Quarterly Journal of the Royal Meteorological Society* 135:239-250.

Cardone, V.J., A.T. Cox, K.A. Lisaeter, and D. Szabo. 2004. “Hindcasts of Winds, Waves and Currents in Northern Gulf of Mexico in Hurricane Lili (2002).” Paper OTC 16821. Presentation at the Offshore Technology Conference, Houston.

Chelton, D.B., J.C. Ries, B.J. Haines, L.L. Fu, and P.S. Callahan. 2001. Satellite altimetry. *International Geophysics* 69:1-2.

Chen, J.R., K. Numata, and S.T. Wu. 2012. Error reduction methods for integrated-path differential-absorption lidar measurements. *Optics Express* 20(14):15589-15609.

Chen, J.R., K. Numata, and S.T. Wu. 2014. Error reduction in retrievals of atmospheric species from symmetrically measured lidar sounding absorption spectra. *Optics Express* 22(21):26055-26075.

Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, et al. 2013. Carbon and other biogeochemical cycles. In *Climate Change 2013: The Physical Science Basis* (T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, eds.). Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Cohen, A.J., M. Brauer, R. Burnett, H.R. Anderson, J. Frostad, K. Estep, K. Balakrishnan, et al. 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the Global Burden of Diseases Study 2015. *Lancet* 389(10082):1907-1918.

Collard, A., and S. Healy. 2003. The combined impact of future space-based atmospheric sounding instruments on numerical weather prediction analysis fields: Assimilation study. *Quarterly Journal of the Royal Meteorological Society* 129: 2741-2760.

Comiso, J.C. 2002. A rapidly declining perennial sea ice cover in the Arctic. *Geophysical Research Letters* 29(20):1956.

Curlander, J., B. Holt, and K. Hussey. 1985. Determination of sea ice motion using digital SAR imagery. *IEEE Journal of Oceanic Engineering* 10(4):358-367.

de Sherbinin, A., M.A. Levy, E. Zell, S. Weber, and M. Jaiteh. 2014. Using satellite data to develop environmental indicators. *Environmental Research Letters* 9: 084013.

Duncan, B.N., L.N. Lamsal, A.M. Thompson, Y. Yoshida, Z. Lu, D.G. Streets, M.M. Hurwitz, and K.E. Pickering. 2016. A space-based, high-resolution view of notable changes in urban NOx pollution around the world (2005-2014). *Journal of Geophysical Research* 121:976-996.

ECMWF (European Centre for Medium-Range Weather Forecasts). 2016. “New Satellite Wind Data Expected to Boost Forecast Performance.” https://www.ecmwf.int/en/about/media-centre/news/2016/new-satellite-wind-data-expected-boost-forecast-performance.

Evans, K.F., S.J. Walter, A.J. Heymsfield, and G.M. McFarquhar. 2002. The Submillimeter-wave cloud ice radiometer: Simulations of retrieval algorithm performance. *Journal of Geophysical Research* 107(D3):AAC2-1-AAC2-21.

Evans, K.F., J.R. Wang, P. Racette, G. Heymsfield, and L. Li. 2005. Ice cloud retrievals and analysis with data from the Compact Scanning Submillimeter Imaging Radiometer and the Cloud Radar System during CRYSTAL-FACE. *Journal of Applied Meteorology* 44:839-859.

Fan, J., Y.C. Liu, K.M. Xu, K. North, S. Collis, X.D. Guang, J. Zhang, Q. Chen, P. Kollias, and S.J. Ghan. 2015. Improving representation of convective transport for scalećaware parameterization: 1. Convection and cloud properties simulated with spectral bin and bulk microphysics. *Journal of Geophysical Research: Atmospheres* 120(8):3485-3509.

Fishman, J., J.K. Creilson, P.A. Parker, E.A. Ainsworth, G.G. Vining, J. Szarka, F.L. Booker, and X. Xu. 2010. An investigation of widespread ozone damage to the soybean crop in the upper Midwest determined from ground-based and satellite measurements. *Atmospheric Environment* 44(18):2248-2256.

Freeland, H.J., D. Roemmich, S.L. Garzoli, P.Y. LeTraon, M. Ravichandran, S. Riser, V. Thierry, et al. 2010. Argo—A decade of progress, remotely sensed winds and wind stresses for marine forecasting and ocean modeling. In *Proceedings of the OceanObs’09: Sustained Ocean Observations and Information for Society Conference Volume 2*, Venice, Italy, September 21-25, 2009.

Furtado, K., P.R. Field, I.A. Boutle, C.J. Morcrette, and J.M. Wilkinson. 2016. A physically-based, subgrid parameterization for the production and maintenance of mixed-phase clouds in a general circulation model. *Journal of the Atmospheric Sciences* 73(1):279-291.

Geddes, J.A., R.V. Martin, B.L. Boys, and A. van Donkelaar. 2016. Long-term trends worldwide in ambient NO_2 concentrations inferred from satellite observations. *Environmental Health Perspectives* 124(3):281-289.

Gelaro, R., and Y. Zhu. 2009. Examination of observation impacts derived from observing system experiments (OSEs) and adjoint models. *Tellus A* 61A:179-193.

Gottschalck, J., M. Wheeler, K. Weickmann, F. Vitart, N. Savage, H. Lin, H. Hendon, et al. 2010. A framework for assessing operational Madden-Julian Oscillation Forecasts: A CLIVAR MJO Working Group project. *Bulletin of the American Meteorological Society* 91(9):1247-1258.

Grell, G.A., and S.R. Freitas. 2014. A scale and aerosol aware stochastic convective parameterization for weather and air quality modeling. *Atmospheric Chemistry and Physics* 14:5233-5250.

Haddad, Z.S., W.-K. Tao, T.N. Krishnamurti, G. Tripoli, R.A. Houze, S. Van den Heever, A.D. Del Genio, et al. 2016. "Direct Observations of the Dynamics of Tropical Convection." White paper provided to the 2017 ESAS Decadal Survey.

Hagos, S., Z. Feng, C.D. Burleyson, K.S.S. Lim, C.N. Long, D. Wu, and G. Thompson. 2014. Evaluation of convection-permitting model simulations of cloud populations associated with the Madden-Julian Oscillation using data collected during the AMIE/DYNAMO field campaign. *Journal of Geophysical Research: Atmospheres* 119:12052-12068.

Hemer, M.A., J.A. Church, and J.R. Hunter. 2010. Variability and trends in the directional wave climate of the Southern Hemisphere. *International Journal of Climatology* 30:475-491.

Holdren, J.P., and S. Donovan. 2016. *National Strategic Computing Initiative Plan*. National Strategic Computing Initiative Executive Council. https://www.whitehouse.gov/sites/whitehouse.gov/files/images/NSCI%20Strategic%20Plan.pdf.

Hou, A.R., K. Kakar, S. Neeck, A.A. Azarbarzin, C.D. Kummerow, M. Kojima, R. Oki, K. Nakamura, and T. Iguchi. 2015. The Global Precipitation Measurement Mission. *Bulletin of the American Meteorological Society* 96:701-722.

Hou, A.Y., S.Q. Zhang, and O. Reale. 2004. Variational continuous assimilation of TMI and SSM/ I rain rates: Impact on GEOS-3 hurricane analyses and forecasts. *Monthly Weather Review* 132:2094-2109.

Houweling, S., P. Bergamaschi, F. Chevallier, M. Heimann, T. Kaminski, M. Krol, A.M. Michalak, and P. Patra. 2017. Global inverse modeling of CH_4 sources and sinks: an overview of methods. *Atmospheric Chemistry and Physics* 17:235-256.

IPCC (Intergovernmental Panel on Climate Change). 2015. *Ocean Observations*. IPCC AR5 report. Geneva, Switzerland: Intergovernmental Panel on Climate Change.

Irene Recovery Office. 2011. "Irene: Reflections on Weathering the Storm." http://www.vermontdisasterrecovery.com/sites/www.vermontdisasterrecovery.com/themes/vdr/uploads/pdfs/2013-IRO-final-report.pdf.

Jackson, D.L., and G.A. Wick. 2010. Near-surface air temperature retrieval derived from AMSU-A and sea surface temperature observations. *Journal of Atmospheric and Oceanic Technology* 27:1769-1776.

Jackson, G.S., G. Mace, A. da Silva, S. van den Heever, S. Tanelli, et al. 2016. A*ddressing Major Earth Science Challenges in Cloud and Precipitation Process Modeling*. White paper provided to the 2017 ESAS Decadal Survey.

Jackson, T.J., M.H. Cosh, R. Bindlish, P.J. Starks, D.D. Bosch, M. Seyfried, D.C. Goodrich, M.S. Moran, and J.Y. Du. 2010. Validation of advanced microwave scanning radiometer soil moisture products. *IEEE Transactions on Geoscience and Remote Sensing* 48(12):4256-4272.

Jiang, J.H., H. Su, C. Zhai, V. Perun, A.D. Del Genio, L.S. Nazarenko, L.J. Donner, et al. 2012. Evaluation of cloud and water vapor simulations in CMIP5 climate models using NASA "A-Train" satellite observations. *Journal of Geophysical Research* 117(D14):D14105.

Kendon, E.J., N.M. Roberts, H.J. Fowler, M.J. Roberts, S.C. Chan, and C.A. Senior. 2014. Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change* 4:570-576.

Kiemle, C., M. Quatrevalet, G. Ehret, A. Amediek, A. Fix, and M. Wirth. 2011. Sensitivity studies for a space-based methane lidar mission. *Atmospheric Measurement Techniques Discussion* 4:3545-3592.

Kilpatrick, T., N. Schneider, and B. Qiu. 2016. Atmospheric response to a midlatitude SST Front: Along front winds. *Journal of the Atmospheric Sciences* 73(9): 3489-3509.

Kilpatrick, T.J., and S.P. Xie. 2015. ASCAT observations of downdrafts from mesoscale convective systems. *Geophysical Research Letters* 42(6):1951-1958.

Kirtman, B.P., D. Min, J.M. Infanti, J.L. Kinter, D.A. Paolino, Q. Zhang, H. van den Dool, et al. 2013. The North American Multimodel Ensemble: Phase-1 seasonal-to-interannual prediction; Phase-2 toward developing intraseasonal prediction. *Bulletin of the American Meteorological Society* 95(4):585-601.

Koplitz, S.N., L.J. Mickley, M.E. Marlier, J.J. Buonocore, P.S. Kim, T. Liu, M.P. Sulprizio, et al. 2016. Public health impacts of the severe haze in Equatorial Asia in September-October 2015: Demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure. *Environmental Research Letters* 11:094023.

Krotkov, N.A., C.A. McLinden, C. Li, L.N. Lamsal, E.A. Celarier, S.V. Marchenko, W.H. Swartz, et al. 2016. Aura OMI observations of regional SO_2 and NO_2 pollution changes from 2005 to 2015. *Atmospheric Chemistry and Physics* 16:4605-4629.

Kumar, G., and R.A. Bauer. 2016. *2016 Annual Report of the NASA Earth Science Technology Office*. https://esto.nasa.gov/files/AnnualReports/2016AR.pdf.

Kwok, R., A. Schweiger, D.A. Rothrock, S. Pang, and C. Kottmeier. 1998. Sea ice motion from satellite passive microwave imagery assessed with ERS SAR and buoy motions. *Journal of Geophysical Research: Oceans* 103(C4):8191-8214.

Langland, R.H., and N.L. Baker. 2004. Estimation of observation impact using the NRL atmospheric variational data assimilation adjoint system. *Tellus* 56A:189-201.

Laxon, S., N. Peacock, and D. Smith. 2003. High interannual variability of sea ice thickness in the Arctic region. *Nature* 425(6961): 947-950.

Lebo, Z., B. Shipway, J. Fan, I. Geresdi, A. Hill, A. Miltenberger, H. Morrison, P. Rosenberg, A. Varble, and L. Xue. 2017. Challenges for cloud modeling in the context of aerosol-cloud-precipitation interactions. *Bulletin of the American Meteorological Society* August:1749-1752.

L'Ecuyer, T.S., and J.H. Jiang. 2010. Touring the atmosphere aboard the A-Train. *Physics Today* 63(7):36-41.

Li, J., J. Li, J. Otkin, T.J. Schmit, and C.Y. Liu. 2011. Recent innovations in deriving tropospheric winds from meteorological satellites: Warning information in a preconvection environment from the Geostationary Advanced Infrared Sounding System—A simulation study using the IHOP case. *Journal Applied Meteorology and Climatology* 50(3):776-783.

Li, J., C.Y. Liu, P. Zhang, and T.J. Schmit. 2012. Applications of full spatial resolution space-based advanced infrared soundings in the preconvection environment. *Weather and Forecasting* 27:515-524.

Li, J.L., D.E. Waliser, G. Stephens, S. Lee, T. L'Ecuyer, S. Kato, and N. Loeb. 2013. Characterizing and understanding radiation budget and cloud water biases in CMIP3/CMIP5 GCMs, contemporary GCMs and reanalyses. *Journal of Geophysical Research* 118(15):8166-8184.

Li, Z.L., J.L. Li, J. Otkin, T.J. Schmit, and C.Y. Liu. 2013. Land surface emissivity retrieval from satellite data. *International Journal of Remote Sensing* 34(9-10):3084-3127.

Lien, G.Y., T. Miyoshi, and E. Kalnay. 2016. Assimilation of TRMM multisatellite precipitation analysis with a low-resolution NCEP global forecast system. *Monthly Weather Review* 144:643-661.

Lillo, S., and D. Parsons. 2017. Investigating the dynamics of error growth in ECMWF medium-range forecast busts. *Quarterly Journal of the Royal Meteorological Society* 143(704):1211-1226.

Lim, S.S., T. Vos, A.D. Flaxman, G. Danaei, K. Shibuya, H. Adair-Rohani, M.A. AlMazroa, et al. 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: A systematic analysis for the Global Burden of Disease Study 2010. *Lancet* 380(9859):2224-2260.

Lin, H., G. Brunet, and R.P. Mo. 2010. Impact of the Madden-Julian Oscillation on wintertime precipitation in Canada. *Monthly Weather Review* 138(10):3822-3839.

Lorenc, A.C., and R.T. Marriott. 2014. Forecast sensitivity to observations in the Met Office Global numerical weather prediction system. *Quarterly Journal of the Royal Meteorological Society* 140(678):209-224.

Loughner, C.P., M. Tzortziou, M. Follette-Cook, K.E. Pickering, D. Goldberg, C. Satam, A. Weinheimer, et al. 2014. Impact of bay-breeze circulations on surface air quality and boundary layer export. *Journal of Applied Meteorology and Climatology* 53(7):1697-1713.

Lyons, W.A., and H.S. Cole. 1976. Photochemical oxidant transport: mesoscale lake breeze and synoptic-scale aspects. *Journal of Applied Meteorology* 15:733-743.

Ma, Z., X. Hu, A.M. Sayer, R. Levy, Q. Zhang, Y. Xue, S. Tong, J. Bi, L. Huang, and Y. Liu. 2016. Satellite-based spatiotemporal trends in PM2.5 concentrations: China, 2004-2013. *Environmental Health Perspectives* 124:184-192.

Marshall, A.G., D. Hudson, M. Wheeler, O. Alves, H.H. Hendon, M.J. Pook, and J.S. Risbey. 2014. Intra-seasonal drivers of extreme heat over Australia in observations and POAMA-2. *Climate Dynamics* 43:1915-1937.

Marshall, A.G., D. Hudson, M.C. Wheeler, H.H. Hendon, and O. Alves. 2011. Assessing the simulation and prediction of rainfall associated with the MJO in the POAMA seasonal forecast system. *Climate Dynamics* 37(11-12):2129-2141.

Masters, D., R.S. Nerem, C. Choe, E. Leuliette, B. Beckley, N. White, and M. Ablain. 2012. Comparison of global mean sea level time series from TOPEX/Poseidon, Jason-1, and Jason-2. *Journal of Marine Geodesy* 35:20-41.

Matus, A.V., T.S. L'Ecuyer, J.E. Kay, C. Hannay, and J.F. Lamarque. 2015. The role of clouds in modulating global aerosol direct radiative effects in spaceborne active observations and the Community Earth System Model. *Journal of Climate* 28:2986-3003.

Mitrescu, C., S. Miller, J. Hawkins, T. L'Ecuyer, J. Turk, P. Partain, and G. Stephens. 2008. Near-real-time applications of CloudSat data. *Journal of Applied Meteorology and Climatology* 47(7):1982-1994.

Mo, K.C., and B. Lyon. 2015. Global meteorological drought prediction using the North American Multi-Model Ensemble. *Journal of Hydrometeorology* 16(3):1409-1424.

Myhre, G., D. Shindell, F.M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, et al. 2013. Anthropogenic and natural radiative forcing. In *Climate Change 2013: The Physical Science Basis* (eds. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley). Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

NASA (National Aeronautics and Space Administration). 2015. *Earth Science Senior Review*. https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/2015_ESDSeniorReviewReport_FINAL.pdf.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2016a. *Achieving Science with CubeSats: Thinking Inside the Box*. Washington, DC: The National Academies Press.

NASEM. 2016b. *Attribution of Extreme Weather Events in the Context of Climate Change*. Washington, DC: The National Academies Press.

NASEM. 2016c. *Next Generation Earth System Prediction: Strategies for Subseasonal to Seasonal Forecasts*. Washington, DC: The National Academies Press.

Neena, J.M., J.Y. Lee, D. Waliser, B. Wang, and X. Jiang. 2014. Predictability of the Madden-Julian Oscillation in the Intraseasonal Variability Hindcast Experiment (ISVHE). *Journal of Climate* 27:4531-4543.

Nesbitt, S.W., and E.J. Zipser. 2003. The diurnal cycle of rainfall and convective intensity according to three years of TRMM measurements. *Journal of Climate* 16:1456-1475.

NHC (National Hurricane Center). 2016. *2016 Verification Report*. http://www.nhc.noaa.gov/verification/verify5.shtml.

NOAA (National Oceanic and Atmospheric Administration). 1999. *Operational Requirements Document for the Evolution of Future NOAA Operational Geostationary Satellites*. Washington, DC: U.S. Department of Commerce.

NOAA NCEI (NOAA National Centers for Environmental Information). 2017. "U.S. Billion-Dollar Weather and Climate Disasters." https://www.ncdc.noaa.gov/billions/.

NOAA NWS (NOAA National Weather Service). 2016. "Ellicott City Historic Rain and Flash Flood—July 30, 2016." http://www.weather.gov/lwx/EllicottCityFlood2016.

OECD (Organisation for Economic Co-operation and Development). 2016. *The Economic Consequences of Outdoor Air Pollution*. Paris: OECD Publishing.

Powell, M.D., and S.D. Aberson. 2001. Accuracy of United States tropical cyclone landfall forecasts in the Atlantic Basin (1976-2000). *Bulletin of the American Meteorological Society* 82:2749-2767.

Ramanathan, A., J. Mao, G.R. Allan, H. Riris, C.J. Weaver, W.E. Hasselbrack, E.V. Browell, and J.B. Abshire. 2013. Spectroscopic measurements of a CO_2 absorption line in an open vertical path using an airborne lidar. *Applied Physics Letters* 103:214102.

Ramanathan, A.K., J. Mao, J.B. Abshire, and G.R. Allan. 2015. Remote sensing measurements of the CO_2 mixing ratio in the planetary boundary layer using cloud slicing with airborne lidar. *Geophysical Research Letters* 42(6):2055-2062.

Reitebuch, O. 2012. The space-borne wind lidar mission ADM-Aeolus. Pp. 815-827 in *Atmospheric Physics—Background, Methods, Trends* (ed. U. Schumann). Berlin Heidelberg: Springer-Verlag.

Revercomb, H. 2012. "Update on GEO Hyperspectral Sounders: GIFTS and GeoMetWatch 'Storm.'" WMO Commission for Atmospheric Sciences. Thorpex ICSC, DAOS Working Group 5th Meeting, UW-Madison, Union South, September 19-20.

Ricciardulli, L., T. Meissner, and F. Wentz. 2012. Towards a climate data record of satellite ocean vector winds. Pp. 2067-2069 in *Proceedings of the 2012 IEEE International Geoscience and Remote Sensing Symposium*.

Rigby, M., S.A. Montzka, R.G. Prinn, J.W.C. White, D. Young, S. O'Doherty, M.F. Lunt, et al. 2017. Role of atmospheric oxidation in recent methane growth. *Proceedings of the National Academy of Sciences* 114(21):5373-5377.

Roberts, J.B., C.A. Clayson, F.R. Robertson, and D.L. Jackson. 2010. Predicting near-surface characteristics from SSM/I using neural networks with a first guess approach. *Journal of Geophysical Research* 115:D19113.

Rossow, W.B., and R.A. Schiffer. 1999. Advances in understanding clouds from ISCCP. *Bulletin of the American Meteorological Society* 80:2261-2288.

Rouault, M.J., A. Mouche, F. Collard, J.A. Johannessen, and B. Chapron. 2010. Mapping the Agulhas Current from space: An assessment of ASAR surface current velocities. *Journal of Geophysical Research* 115:C10026.

Saatchi, S., S. Asefi-Najafabady, Y. Malhi, L.E.O.C. Aragao, L.O. Anderson, R.B. Myneni, and R. Nemani. 2013. Persistent effects of a severe drought on Amazonian forest canopy. *Proceedings of the National Academy of Sciences* 110(2):565-570.

Saleeby, S.M., and S.C. van den Heever. 2013. Developments in the CSU-RAMS Aerosol Model: Emissions, nucleation, regeneration, deposition, and radiation. *Journal of Applied Meteorology and Climatology* 52:2601-2622.

Scaife, A.A., A. Arribas, E. Blockley, A. Brookshaw, R.T. Clark, N. Dunstone, R. Eade, et al. 2014. Skillful long-range prediction of European and North American winters. *Geophysical Research Letters* 41(7):2514-2519.

Sieglaff, J.M., T.J. Schmit, W.P. Menzel, and S.A. Ackerman. 2009. Inferring convective weather characteristics with geostationary high spectral resolution IR window measurements: A look into the future. *Journal of Atmospheric and Oceanic Technology* 26:1527-1541.

Simmons, A., R. Armstrong, A. Becker, A. Belward, B. Biskaborn, A. Bombelli, M. Bourassa, et al. 2015. *Status of the Global Observing System for Climate*. GCOS-195. Geneva: World Meteorological Organization.

Smith, S.R., M.A. Bourassa, and D.L. Jackson. 2012. Supporting satellite research with data collected by vessels. *Sea Technology,* June.

Song, Q., D.B. Chelton, S.K. Esbensen, N. Thum, and L.W. O'Neill. 2009. Coupling between sea-surface temperature and low-level winds in mesoscale numerical models. *Journal of Climate* 22(1):146-164.

State of Vermont Agency of Administration. 2012. *Vermont Recovering Stronger: Irene Recovery Status Report*. http://www.vpr.net/uploads/files/vt_recovering_stronger_rpt_june_2012.pdf.

Steele-Dunne, S.C., J. Friesen, and N. van de Giesen. 2012. Using diurnal variation in backscatter to detect vegetation water stress. *IEEE Transactions on Geoscience and Remote Sensing* 50(7):2618-2629.

Steffen, J. 2014. "The Effects of Sea Surface Temperature Gradients on Surface Turbulent Fluxes." Master's thesis. Tallahassee: Florida State University.

Stephan, C., M. Alpers, B. Millet, G. Ehret, P. Flamant, and C. Deniel. 2011. MERLIN: A space-based methane monitor: Lidar remote sensing for environmental monitoring XII. *Proceedings of the SPIE* 8159:815908-815915.

Stephens, G.L., T. L'Ecuyer, R. Forbes, A. Gettleman, C. Golaz, K. Suzuki, P. Gabriel, and J. Haynes. 2010. The dreary state of precipitation in global models. *Journal of Geophysical Research* 115:D24211.

Stephens, G.L., J. Li, M. Wild, C. Clayson, N. Loeb, S. Kato, T. L'Ecuyer, P. Stackhous, M. Lebsock, and T. Andrews. 2012. An update on Earth's energy balance in light of the latest global observations. *Nature Geoscience* 5:691-696.

Stephens, G.L., D.G. Vane, S. Tanelli, E. Im, S. Durden, M. Rokey, D. Reinke, et al. 2008. The CloudSat Mission: Performance and early science after the first year of operation. *Journal of Geophysical Research* 113(D8).

Stevens, B., and A. Seifert. 2008. Understanding macrophysical outcomes of microphysical choices in simulations of shallow cumulus convection. *Journal of the Meteorological Society of Japan* 86A:143-162.

Stroeve, J., J.E. Box, F. Gao, S.L. Liang, A. Nolin, and C. Schaaf. 2005. Accuracy assessment of the MODIS 16-day albedo product for snow: comparisons with Greenland in situ measurements. *Remote Sensing of Environment* 94(1):46-60.

Stull, R.B. 1988. *An Introduction to Boundary Layer Meteorology*. Netherlands: Springer.

Su, H., J.H. Jiang, C. Zhai, V. Perun, J.T. Shen, A.D. Del Genio, L.S. Nazarenko, et al. 2013. Diagnosis of regime-dependent cloud simulation errors in CMIP5 models using "A-Train" satellite observations and reanalysis data. *Journal of Geophysical Research: Atmospheres* 118(7):2762-2780.

Sun, X., and J.B. Abshire. 2012. Comparison of IPDA lidar receiver sensitivity for coherent detection and for direct detection using sine-wave and pulsed modulation. *Optics Express* 20(19):21291-21304.

Sun, Y., S. Solomon, A. Dai, and R.W. Portmann. 2007. How often does it rain? *Journal of Climate* 19:916-934.

Sy, O.O., S. Tanelli, P. Kollias, and Y. Ohno. 2014b. Application of matched statistical filters for EarthCARE cloud Doppler products. *IEEE Transactions on Geoscience and Remote Sensing* 52:7297-7316.

Sy, O.O., S. Tanelli, N. Takahashi, Y. Ohno, H. Horie, and P. Kollias. 2014a. Simulation of EarthCARE spaceborne Doppler radar products using ground-based and airborne data: Effects of aliasing and nonuniform beam-filling. *IEEE Transactions on Geoscience and Remote Sensing* 52:1463-1479.

Tao, W.K., and J. Chern. 2017. The impact of mesoscale convective systems on global precipitation: A modeling study. *Journal of Advances in Modeling Earth Systems* 9:790-809.

Travis, K.R., D.J. Jacob, J.A. Fisher, P.S. Kim, E.A. Marais, L. Zhu, K. Yu, et al. 2016. Why do models overestimate surface ozone in the Southeastern United States? *Atmospheric Chemistry and Physics* 16:13561-13577.

Turner, A.J., C. Frankenberg, P.O. Wennberg, and D.J. Jacob. 2017. Ambiguity in the causes for decadal trends in atmospheric methane and hydroxyl. *Proceedings of the National Academy of Sciences* 114(21):5367-5372.

Uccellini, L.W. 2017. Small tornadoes skew the statistics for warning times. *Washington Post*. April 28.

U.S. EPA (U.S. Environmental Protection Agency). 2011. *The Benefits and Costs of the Clean Air Act from 1990 to 2020, Final Report—Rev. A*. Washington, DC: U.S. EPA, Office of Air and Radiation. April. https://www.epa.gov/sites/production/files/2015-07/documents/fullreport_rev_a.pdf.

U.S. EPA. 2016. *Our Nation's Air: Status and Trends Through 2015*. https://gispub.epa.gov/air/trendsreport/2016/.

Van Dingenen, R., F.J. Detener, F. Raes, M.C. Krol, L. Emberson, and J. Cofala. 2009. The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment* 43(3):604-618.

Varble, A., E.J. Zipser, A.M. Fridlind, P. Zhu, A.S. Ackerman, J.P. Chaboureau, S. Collis, J. Fan, A. Hill, and B. Shipway. 2014. Evaluation of cloud-resolving and limited area model intercomparison simulations using TWPdCE observations: 1. Deep convective updraft properties. *Journal of Geophysical Research: Atmospheres* 119(24):13891-13918.

Velden, C.S., and K.M. Bedka. 2009. Identifying the uncertainty in determining satellite-derived atmospheric motion vector height attribution. *Journal of Applied Meteorology and Climatology* 48:450-463.

Vitart, F. 2017. Madden-Julian Oscillation prediction and teleconnections in the S2S database. *Quarterly Journal of the Royal Meteorological Society* 143:2210-2220.

Vitart, F., C. Ardilouze, A. Bonet, A. Brookshaw, M. Chen, C. Codorean, M. Deque, et al. 2017. The Sub-seasonal to Seasonal Prediction (S2S) Project Database. *Bulletin of the American Meteorological Society* 98(1):163-173.

Vitart, F., G. Balsamo, R. Buizza, L. Ferranti, S. Keeley, L. Magnusson, F. Molteni, and A. Weisheimer. 2014. *Sub-Seasonal Predictions, ECMWF Research Department Technical Memorandum 738*. Reading, UK: ECMWF.

Vitart, F., A. Leroy, and M.C. Wheeler. 2010. A Comparison of dynamical and statistical predictions of weekly tropical cyclone activity in the Southern Hemisphere. *Monthly Weather Review* 138(9):3671-3682.

Vitart, F., and A. Robertson. 2017. The Sub-seasonal to seasonal prediction project (S2S) and the prediction of extreme events. Accepted in *npj Climate and Atmospheric Science*.

Vitart, F., A.W. Robertson, and D.T. Anderson. 2012. Subseasonal to seasonal prediction project: Bridging the gap between weather and climate. *WMO Bulletin* 61:23-28.

Wagner, W., S. Hahn, R. Kidd, T. Melzer, Z. Bartalis, S. Hasenauer, J. Figa-Saldana, et al. 2013. The ASCAT soil moisture product: A review of its specifications, validation results, and emerging applications. *Meteorologische Zeitschrift* 22(1):5-33.

Waliser, D.E. 2011. Predictability and forecasting. P. 613 in *Intraseasonal Variability of the Atmosphere-Ocean Climate System, 2nd Edition* (eds. W.K.M. Lau and D.E. Waliser). Heidelberg: Springer.

Warner, J.X., R.R. Dickerson, Z. Wei, L.L. Strow, Y. Wang, and Q. Liang. 2017. Increased atmospheric ammonia over the world's major agricultural areas detected from space. *Geophysical Research Letters* 44:2875-2884.

WCRP (World Climate Research Programme). 2015. "WCRP Grand Challenges." http://wcrp-climate.org/grand-challenges.

Weisz, E., N. Smith, and W.L. Smith, Sr. 2015. The use of hyperspectral sounding information to monitor atmospheric tendencies leading to severe local storms. *Earth and Space Science* 2:369-377.

Wentz, F., L. Ricciardulli, E. Rodriguez, B. Stiles, M. Bourassa, D. Long, R. Hoffman, et al. 2017. Evaluating and extending the Ocean Winds Data Climate Record. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 99:1-21.

Wentz, F.J., L. Ricciardulli, C. Gentemann, T. Meissner, K.A. Hilburn, J. Scott. 2013. "Remote Sensing Systems Coriolis WindSat." http://www.remss.com/missions/windsat.

Wentz, F.J., L. Ricciardulli, E. Rodriguez, B. Stiles, M. Bourassa, D. Long, R. Hoffman, et al. 2016. Evaluating and extending the Ocean Wind Climate Data Record. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 10(3):2165-2185.

Wheeler, M.C., and H.H. Hendon. 2004. An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Monthly Weather Review* 132:1917-1932.

WHO (World Health Organization). 2016. *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease*. http://apps.who.int/iris/bitstream/10665/250141/1/9789241511353-eng.pdf?ua=1.

Wigbels, L., G.R. Faith, and V. Sabathier. 2008. *Earth Observations and Global Change: Why? Where Are We? What Next?* Washington, DC: Center for Strategic and International Studies.

Wilczak, J.M., and J.W. Glendening. 1988. Observations and mixed-layer modeling of a terrain-induced mesoscale gyre: The Denver Cyclone. *Monthly Weather Review* 116:2688-2711.

WMO (World Meteorological Organization). 2012. *WIGOS: WMO Integrated Global Observing System*. Final Report of the Fifth WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction. Technical Report 2012-1. Geneva.

WMO. 2017. "WMO Observing Systems Capability Analysis and Review." https://www.wmo-sat.info/oscar/.

Wood, R., and P. Field. 2011. The distribution of cloud horizontal sizes. *Journal of Climate* 25:4800-4816.

World Bank and the Institute for Health Metrics and Evaluation. 2016. *The Cost of Air Pollution: Strengthening the Economic Case for Action*. Washington, DC: World Bank.

Young, I.R., S. Zieger, and A.V. Babanin. 2011. Global trends in wind speed and wave height. *Science* 332(6028):451-455.

Zhang, B., W. Perrie, P.W. Vachon, X.F. Li, W.G. Pichel, J. Guo, and Y.J. He. 2012. Ocean vector winds retrieval from C-band fully polarimetric SAR measurements. *IEEE Transactions on Geoscience and Remote Sensing* 50(11):4252-4261.

Zhang, C. 2013. Madden-Julian Oscillation: Bridging weather and climate. *Bulletin of the American Meteorological Society* 94:1849-1870.

Zhang, F., and G. Zhou. 2015. Estimation of canopy water content by means of hyperspectral indices based on drought stress gradient experiments of maize in the North Plain China. *Remote Sensing* 7:15203-15223.

Zhao, Y., A.K. Liu, and D.G. Long. 2002. Validation of sea ice motion from QuikSCAT with those from SSM/I and buoy. *IEEE Transactions on Geoscience and Remote Sensing* 40(6):1241-1246.

Zhu Y., and R. Gelaro. 2008. Observation sensitivity calculations using the adjoint of the gridpoint statistical interpolation (GSI) analysis system. *Monthly Weather Review* 136: 335-351.

Zoogman, P., X. Liu, R.M. Suleiman, W.F. Pennington, D.E. Flittner, J.A. Al-Saadi, B.B. Hilton, et al. 2017. Tropospheric emissions: Monitoring of pollution (TEMPO). *Journal of Quantitative Spectroscopy and Radiative Transfer* 186:17-39.

8

Marine and Terrestrial Ecosystems and Natural Resources Management

INPUT SUMMARY

Ecosystems deliver essential benefits to humans through the resources and services that they provide. Understanding the structure and function of ecosystems, as well as the fluxes and storage of carbon, water, nutrients, and energy within them, is critical. Remote sensing affords a unique opportunity to observe key ecosystem components globally. Combining remote sensing, other observations, and numerical models, supports increased understanding of ecosystem processes. Ecosystem processes can also be inferred from time series of remote observations. The Panel on Marine and Terrestrial Ecosystems and Natural Resource Management articulates the continued need for remote sensing of ecology, biodiversity, and biogeochemical cycles.

In the past, satellite measurement systems such as the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR); the Sea-viewing Wide Field Sensor (SeaWiFS); the Earth Observing System (EOS)—in particular, the Moderate-Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua platforms; and most recently, the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (S-NPP) mission have provided information on global distributions of sea-surface temperature, clouds, terrestrial and marine vegetation, land surface-atmosphere interactions, and aerosols as well as many other global Earth science properties. Moderate resolution (250 m to ~1 km), multispectral imaging systems have enabled the first consistent, global determinations of primary production for land and ocean ecosystems and its variations on seasonal to interannual time scales. These data have documented the response of the terrestrial environment to extreme weather, including heat waves, droughts, and floods; highlighted the probability of coral bleaching; and tracked vegetation photosynthetic capacity and phenology, which were used to estimate the fluxes of carbon and water locally and globally. These data have also improved the management capacity for a wide range of food and natural resource applications.

NOTE: This chapter was written by members of the Panel on Marine and Terrestrial Ecosystems and Natural Resource Management and is provided for reference only. Any study finding or consensus recommendation will appear in Chapters 1-5, the report from the survey steering committee.

Many other satellite measurement systems have made important contributions to understanding global ecosystems as well. For example, high-resolution (~30 m) multispectral imagery from the Landsat Thematic Mapper has been available since 1982. Landsat-8 and the Sentinel-2 series of imagers have enabled accurate global maps of land cover, vegetation disturbance and recovery, phenology, and photosynthetic capacity of vegetation to be made on unprecedented spatial scales (~30 m). These data have also enabled the creation of maps and health indices for coral reefs as well as a range of other aquatic and marine systems. Information on aquatic health helps document ecosystem resilience and vulnerability to extinctions or cascading effects due to trophic interactions. As another example, space-based lidars (e.g., Cloud-Aerosol Lidar with Orthogonal Polarization [CALIOP]) can extend measurements of phytoplankton carbon biomass (and Net Primary Production [NPP] based on carbon biomass) throughout the entire year in high-latitude subpolar and ice-free polar regions beyond what is possible with radiometry owing to low sun angles and perpetual darkness in the winter months.

Remote sensing of ecosystem components will continue to be a key to furthering our understanding of Earth systems and of life on Earth. This panel report identifies five overarching science questions (Table 8.1)

TABLE 8.1 Summary of Science and Application Questions and Their Priorities

	Science and Applications Questions	**Highest Priority Measurement Objectives (MI=Most Important, VI=Very Important)**
E-1	**Ecosystem Structure, Function, and Biodiversity.** What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space? ("Structure" is the spatial distribution of plants and their components on land, and of aquatic biomass. "Function" is the physiology and underpinning of biophysical and biogeochemical properties of terrestrial vegetation and shallow aquatic vegetation.)	**(VI) E-1a.** Quantify the distribution of the functional traits, functional types, and composition of terrestrial and shallow aquatic vegetation and marine biomass, spatially and over time. **(MI) E-1b.** Quantify the three-dimensional (3D) structure of terrestrial vegetation and 3D distribution of marine biomass within the euphotic zone, spatially and over time. **(MI) E-1c.** Quantify the physiological dynamics of terrestrial and aquatic primary producers. Two additional objectives associated with this question were ranked Important.
E-2	**Fluxes Between Ecosystems, Atmosphere, Oceans, and Solid Earth.** What are the fluxes (of carbon, water, nutrients, and energy) *between* ecosystems and the atmosphere, the ocean, and the solid Earth, and how and why are they changing?	**(MI) E-2a.** Quantify the fluxes of CO_2 and CH_4 globally at spatial scales of 100-500 km and monthly temporal resolution with uncertainty <25% between land ecosystems and atmosphere and between ocean ecosystems and atmosphere. Two additional objectives associated with this question were ranked Important.
E-3	**Fluxes Within Ecosystems.** What are the fluxes (of carbon, water, nutrients, and energy) *within* ecosystems, and how and why are they changing?	**(MI) E-3a.** Quantify the flows of energy, carbon, water, nutrients, and so on sustaining the life cycle of terrestrial and marine ecosystems and partitioning into functional types. One additional objective associated with this question was ranked Important.
E-4	**Carbon Accounting.** How is carbon accounted for through carbon storage, turnover, and accumulated biomass? Have all of the major carbon sinks been quantified, and how are they changing in time?	Two objectives associated with this question were ranked Important.
E-5	**Carbon Sinks.** Are carbon sinks stable, are they changing, and why?	Three objectives associated with this question were ranked Important.

NOTE: Important (I) measurement objectives are not shown here.

within three primary topic areas that remote sensing can contribute to in the coming decade. Those broad topic areas are (1) structure, function, and biodiversity; (2) fluxes of carbon, water, nutrients, and energy; and (3) carbon accounting, monitoring, and management.

Understanding the composition, structure, and functioning of ecosystems is essential to understanding the services they provide and how they are changing. The functional traits of terrestrial plants (structure, physiology, phenology, reproduction, and biochemistry) determine the patterns of energy, carbon, water, and nutrient fluxes for terrestrial ecosystems, and they provide a direct, mechanistic link to biological diversity. The same holds true for coastal and shallow aquatic ecosystems. The structure of marine ecosystems affects the efficiency of energy transfer through food webs, ultimately determining fish production and the flux of organic matter into deeper ocean waters.

Fluxes of carbon, water, nutrients, and energy occur both between and within ecosystems. Understanding the fluxes that link ecosystems with the rest of the Earth system is critical for understanding how these systems are related and for predicting how these connections will change over time. Key fluxes within ecosystems are mediated by the composition and functional traits of the organisms present. Imaging spectroscopy is a tool for determining global terrestrial and marine plant functional traits and functional types and, in some cases, provides taxonomic composition. Traits, types, and taxonomic composition, as well as their variability and how they are changing, are poorly understood globally. Nor is there a comprehensive understanding of how they feed back to the climate system via altered biogeochemical fluxes.

The strength of land and ocean carbon sinks is critically important to mitigating increasing atmospheric concentrations of greenhouse gases, but the physical and physiological processes governing these sinks remain uncertain. In turn these uncertainties lead to large uncertainties in predicting the impacts of climate change and reduce ability to manage mitigation efforts effectively. For example, what happens to stored carbon in biomass or soils during periods of drought or extreme temperatures?

For each of these science questions, the panel further identified several measurement objectives, highlighting those that were Very Important (VI) and Most Important (MI). (See Table 8.1.) In considering the measurement approaches needed to address the identified objectives, the panel assumes that operational systems, as well as those in the Program of Record (POR), will continue and will provide several key measurements. Assumptions of particular note are the continuation of the Joint Polar Satellite System (JPSS) weather satellites flying the VIIRS instrument through 2035; the continuation of Landsat-8 (followed by Landsat-9 through Landsat-11) complemented by the European Sentinel-2 and Sentinel-3 satellites; the launch of the Orbiting Carbon Observatory-3 (OCO-3); and the Ecosystem Spaceborne Thermal Radiometer Experiment on the Space Station (ECOSTRESS), the Global Ecosystem Dynamics Investigation (GEDI) and the Hyperspectral Imager Suite (HISUI) on the International Space Station (ISS), which will bring an unprecedented suite of new high spatial resolution diurnal data sets, with new synergies arising from operating these instruments together; as well as the launching of the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission. For oceans the PACE mission will enable significant advancements in our ability to quantify seawater components and understand how their distributions change and respond to the physics and chemistry of the ocean. It is also important to note that the degradation of the MODIS Terra sensor leaves a large gap in moderate-resolution AM observations, which will restrict a number of applications that currently rely on the combination of AM and PM information, and that nadir-viewing Sun synchronous satellites such as Sentinel-2 will exhibit significant glint for ocean targets if “tilt” capability is not included in the sensor design, highlighting the need for coordination between sustained land imaging and aquatic systems groups when designing future multiuse satellites.

To complement the measurement approaches that are assumed to be continuing or commencing in the near future, the panel identified additional measurement approaches necessary for addressing the priority objectives. The terrestrial, coastal ocean, and inland waters research community identifies a Sun synchronous polar orbit for a high-fidelity imaging spectrometer with 30 m pixel resolution for accurate measurements of plant traits, biochemical concentrations, and conditions (potentially with commonality to an implementation of TO-18 in Appendix C, the Surface Biology and Geology Targeted Observable). The time and space characteristics of PACE measurements in the POR are most relevant to open ocean and adjacent waters of the mid- to outer continental shelves (ca. 80 to 90 percent of ocean area), whereas effective imaging of coastal areas and inland waters require additional space-based measurements with higher pixel resolution. Characterizing the different habitats of the complex coastal ecotone (e.g., in waters shallower than 50 m or within one km of the coast) requires high-fidelity sampling in four different categories: spatial resolution, spectral resolution, radiometric quality, and temporal resolution. The high-fidelity imaging spectrometer instrument would be the first of its kind to routinely measure the entire global landmass and coastal waters at high spatial resolution.

Another challenge is to determine the vertical distribution of the ocean primary producers that is not possible from passive Ocean Color Radiometry (OCR). Lidars are able to profile light attenuation and particle backscattering optical properties within the upper ocean (Churnside, 2014; Behrenfeld et al., 2016). Lidars are active remote sensing tools and can determine ocean carbon biomass through moderate cloud and aerosol layers, at night or even during the winter darkness of high-latitude subpolar or ice-free polar regions when OCR is not possible. Measurements of the three-dimensional (3D) physical structure of terrestrial vegetation from lidars is a high priority, because canopy height profiles and aboveground biomass, particularly in forested ecosystems of the world, have a wide range of practical applications in addition to more fundamental understanding of the global carbon and water cycles.

Understanding the flux of carbon between terrestrial and marine ecosystems and the atmosphere requires high-accuracy, global CO_2 and CH_4 observations. Although the current generation of near infrared (NIR) passive sensors has provided atmospheric greenhouse gas data on unprecedented scales, additional space-based measurements are needed to constrain flux processes in vulnerable tropical and high-latitude ecosystems. Flux estimation requires an observing system with near-surface sensitivity, reduced levels of systematic error, and global coverage in all seasons. This capability provides critical information needed to better understand the processes driving regional scale carbon budgets and carbon-climate feedbacks.

There is also the need for a 300 km swath-width thermal imager with 30 to 60 m spatial resolution with at least three bands: 3.5-4.0 μm, 10.5-11.5 μm, and 11.5-12.5 μm. This imager would complement the Sustainable Land Imaging (SLI) capability of existing and planned multispectral missions and would also be a candidate for a thermal capability for the Sentinel-2a, -2b, -2c, and -2d visible (VIS), NIR, and shortwave infrared (SWIR) imagers, which lack thermal imaging capability (Fisher et al., 2017). The 10 to 30 m imagers on Landsat-10 and Landsat-11 are expected to have a swath width of 300 km. Two 300 km swath width Landsats and two Sentinel-2 imagers in orbit at the same time would provide an equatorial revisit frequency of 2.5 days, potentially enabling many MODIS and VIIRS data and products to be projected from nominally 500 m to 30-60 m (Li and Roy, 2017).

New measurements and observations will be needed to address the science objectives identified by this panel. In Table 8.2, the highest priority science and application objectives are mapped to the Targeted Observables that will strongly contribute to addressing those objectives.[1]

Achieving this panel's stated objectives would have both direct and indirect benefits. The direct benefits include more precise and comparable measurements of the structure, composition, and dynamics of terrestrial and marine biomass as well as the fluxes and flows of carbon and energy between ecosystems and the atmosphere. These direct observations provide evidence-based decision support to inform several economically important applications concerning the sustainable management of terrestrial landscapes,

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[1] Not mapped here are cases where the Targeted Observables may provide a narrow or an indirect benefit to the objective, although such connections may be cited elsewhere in this report.

TABLE 8.2 Priority Targeted Observables Mapped to the Science and Applications Objectives That Were Ranked as Most Important (MI) or Very Important (VI)

Priority Targeted Observables	Science and Applications Objectives
Aerosol Properties	E-2a
Atmospheric Winds	E-2a
Greenhouse Gases	E-2a, E-3a
Surface Biology and Geology	E-1a, E-1b, E-1c, E-2a, E-3a
Terrestrial Ecosystem Structure	E-1b, E-3a
Ocean Ecosystem Structure	E-1b
Aquatic-Coastal Biogeochemistry	E-1a, E-1b, E-1c, E-2a, E-3a
Soil Moisture	E-1c, E-3a
Ocean Surface Winds and Currents	E-1b, E-2a
Vegetation, Snow, and Surface Energy Balance	E-1c, E-3a
Surface Topography and Vegetation	E-1b, E-3a

coastal environments, and open-ocean ecosystems. Example applications include sustainable forest management for greenhouse gas accounting and precision agriculture.

Earth observation data products and synthesis information derived from meeting the stated objectives will also support a number of national and international agreements and objectives. These include international agreements on sustainable use of the oceans, trade in endangered species, economic and trade agreements related to timber and agriculture, reducing emissions from deforestation and forest degradation, and the UN Sustainable Development Goals. For example, remote sensing products enable evaluation of the distribution and status of habitats. Observations here also support national laws and polices such as the Soil and Water Conservation Act, National Environmental Policy Act, Endangered Species Act, Magnuson-Stevens Fishery Conservation and Management Act, and a variety of other standing societal mandates.

INTRODUCTION AND VISION

Motivation

Ecosystems are critical life-support systems for the planet. They deliver essential benefits to humans and provide stability and resilience after disturbance events through the resources and services that they provide. The Millennium Ecosystem Assessment (MEA, 2005) and several National Research Council (NRC) reports have considered ecosystem services in four categories:

1. Provisioning services (e.g., food, feed, fuel, and fiber);
2. Regulating services (e.g., climate regulation, flood control, and water purification);
3. Cultural services (e.g., recreation, spiritual services, and aesthetic services); and
4. Supporting services (e.g., nutrient cycling and soil formation).

The MEA (2005) noted that in the latter half of the twentieth century, humans altered ecosystems more dramatically than at any other time in Earth's history, and humans consume 20 percent of terrestrial NPP every year (Imhoff et al., 2004). That assessment provides many specific examples, including land conversion to cropland, damming of rivers and streams, inputs of nitrogen and phosphorous through excessive fertilizer use, and emissions of carbon dioxide and other greenhouse gases. Marine fisheries are also threatened by overfishing and climate change. Human activities including eutrophication of coastal waters and coastal development also threaten coastal ecosystems. While these ecosystem changes have helped accommodate a growing population and increased quality of life for many, they have also contributed to the degradation of other ecosystem services and a net loss in biodiversity (MEA, 2005). Maintenance of ecosystems and ecosystem services is vital from an economic perspective as well. For example, in 2013 in the United States, the agriculture industry contributed as much as $230 billion to the economy.[2] The 2015 drought in California cost an estimated $2.7 billion, as well as over 20,000 jobs (Howitt et al., 2015). Coastal wetlands are credited with having prevented $625 million in damages during Hurricane Sandy alone (Narayan et al., 2016).

Understanding the structure and function of ecosystems, as well as the fluxes and storage of carbon, water, nutrients, and energy within ecosystems, is critical to preserving ecosystems and ensuring the sustainability of ecosystem services. Some changes may be rapid, while others will require decades to distinguish between real trends and interannual variability (Henson, 2014). Remote sensing measurements and analysis of ecosystems affords a unique opportunity to observe key ecosystem components and ecosystem changes over various spatial and time scales. This panel articulates the need for new remote sensing technologies for ecology, biodiversity, and biogeochemical cycles, and the objectives and observations identified by this panel have relevance to those identified by other panels as well.

Ecology, Biodiversity, and Biogeochemical Cycles

Vascular plants are key structural elements of terrestrial ecosystems and the basis of all terrestrial food webs (Barthlott and Placke, 1996; Mutke and Barthlott, 2005). Similarly, marine phytoplankton are responsible for most of the primary productivity in the ocean and are the base of most marine food webs. High plant diversity is associated with high biodiversity in co-located animal and microbial groups. The geographic patterns of species distributions are central to terrestrial ecology (Gaston, 2000; Ricklefs, 2004; Wiens and Donoghue, 2004; Field et al., 2009). Marine habitats are also highly diverse, with taxa that represent all existing phyla on Earth today.

At the global scale a remarkably strong association has been shown between climate and species richness. On land temperature controls species richness at higher latitudes, while other climatological and geological factors affecting nutrient availability are driving biodiversity in the tropics (Currie, 1991; Wright et al., 1993; Hawkins et al., 2003; Kreft and Jetz, 2007; Jimenez et al., 2009). Temperature, nutrients, and light also affect species composition of ocean phytoplankton, whose distribution of functional types differs significantly between warm, stratified waters and cooler, nutrient-rich waters owing to upwelling or vertical mixing.

Together, climate and ecology help to determine biodiversity. This coupling, through biogeochemistry and the carbon cycle, affects greenhouse gas concentrations in the atmosphere, which in turn control ocean and land temperatures and affect essential vertical mixing in the ocean. Carbon moves through terrestrial ecosystems and oceans, exists in the atmosphere as gases including carbon dioxide (CO_2) and methane (CH_4), and exists in ocean water as inorganic carbon, in plankton, and in marine sediments (Figure 8.1). Since 1900 the atmospheric CO_2 concentration has increased from 300 ppm to >400 ppm and continues to increase at the rate of approximately 2 ppm/year due to fossil fuel combustion and land use change. Global, budget-based analyses demonstrate that atmospheric CO_2 concentrations would be further elevated if not for significant carbon uptake by terrestrial vegetation and the oceans, which together absorb nearly half of CO_2 emissions (Khatiwala et al., 2009; Le Quéré et al., 2014).

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[2] See The World Bank, "World Development Indicators (2017). Agriculture, Value Added (Current US$)." https://data.worldbank.org/indicator/NV.AGR.TOTL.CN?end=2015&locations=US&start=1997&view=chart.

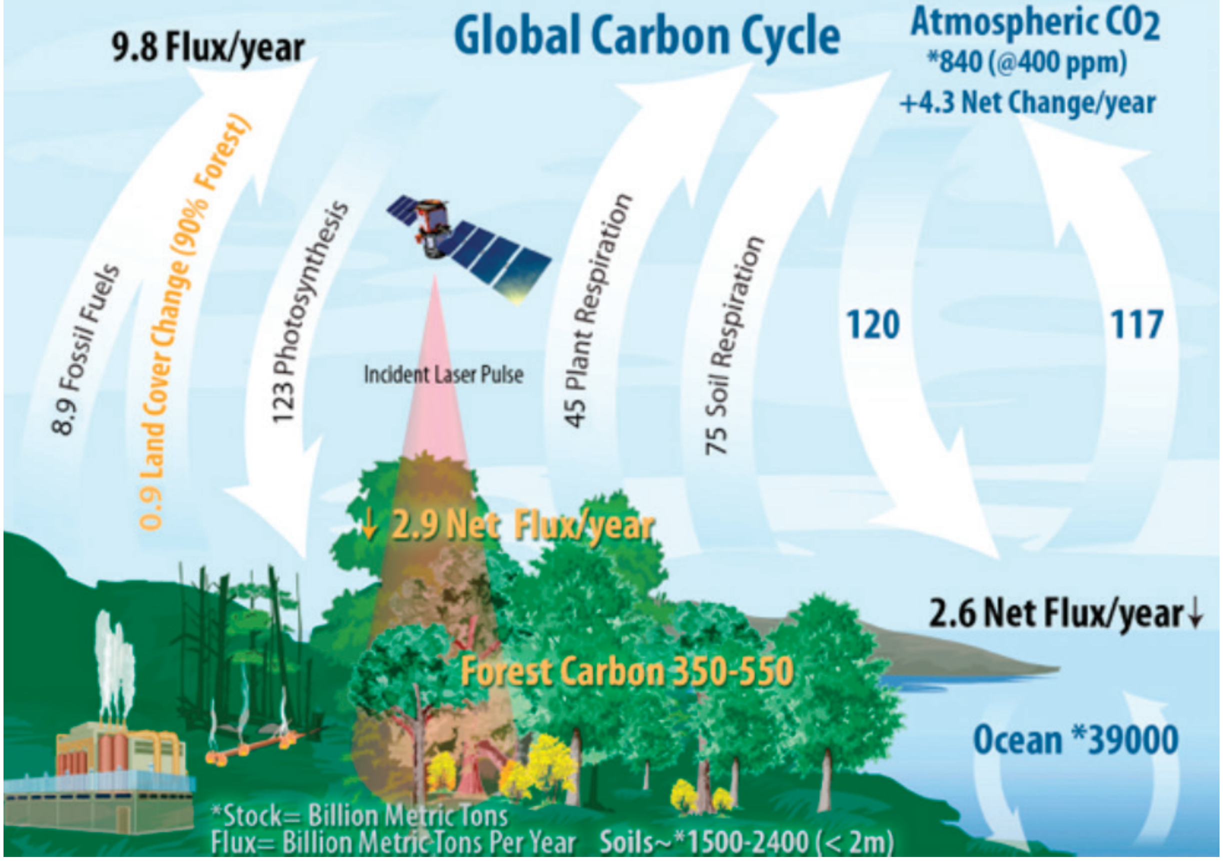

FIGURE 8.1 Depiction of the carbon cycle, showing reservoirs, fluxes or transfers between reservoirs, and the processes responsible. The atmospheric CO_2 concentration is a principal determinant of Earth's temperature and thus climate. Units are in billion metric tons for carbon stocks and billion metric tons/year for fluxes. The Carbon Dioxide Information Analysis Center advises that 1 ppm of atmospheric CO_2 is equivalent to 2.13 gigatons of carbon. NOTE: This figure is updated from IPCC AR5 (2013), with respiration data from Schlesinger (2015), ocean fluxes from Westberry and Behrenfeld (2013), and land photosynthesis from Beer et al. (2010). SOURCE: NASA Goddard Space Flight Center.

The concentrations of greenhouse gases control temperature, and in turn, directly affect ecosystem health, biodiversity, and the processes that influence carbon cycling. The deep ocean has also played an important role as a heat reservoir, mitigating the impact on lower atmosphere, land, and upper ocean temperatures (Rhein et al., 2013; Drijfhout et al., 2014). These fundamental linkages couple biogeochemistry, ecology, and biodiversity and will determine how climate and biodiversity change together in the future (Sommer et al., 2010; Harrison and Noss, 2017).

Intrinsic connections between ecosystems and the physical climate system also demonstrate the vulnerability of these key resources. For example, soil respiration increases with temperature, resulting in greater releases of CO_2 during warm periods. Thawing of permafrost soils may release large amounts of CO_2 and CH_4 to the atmosphere. Changing patterns of upper ocean stratification due to warming and changing patterns of rainfall alter nutrient fluxes to the upper ocean, leading to changes in both concentration and ratios of essential nutrients that lead to shifts in community composition (Falkowski et al., 1998; Lomas et al., 2014). Many of the benefits that society derives from ecosystems are related to the abundance and variety of life, but a deeper understanding of the processes governing ecosystem health is necessary. How will ecosystem diversity and productivity change with climate and with increased human demands for food? How will these changes affect the ecology and biogeochemistry of terrestrial, coastal, and open ocean habitats? What strategies can be implemented for the effective conservation and sustainable use of resources, including commercial fisheries and agriculture? Will land and ocean carbon reservoirs continue to absorb half of human CO_2 emissions? And if not, what are the consequences for climate?

Satellite and in situ observations are fundamental to understanding the complex linkages between carbon, energy fluxes, and biodiversity. Only satellite-borne sensors can provide simultaneous global carbon cycle observations needed for quantifying large-scale carbon cycle processes that control the land's forest and vegetation biomass stocks, and only satellite-borne sensors provide the necessary spatial and temporal observations to understand the role of the oceans in carbon fluxes and storage. Using data from these sensors with models now enables researchers to track carbon through the land, ocean, and atmosphere. As an observing system, satellites allow us to measure atmospheric CO_2 and CH_4, and estimate sources and sinks; measure land and ocean photosynthesis; measure the reservoir of carbon in plants on land and how this reservoir changes in space and time; and measure the extent and impact of fires and land use change.

In situ observations are necessary complements to satellite observations for confirming satellite-measured CO_2 concentrations and determining soil and vegetation carbon quantities. In situ observations are also required to confirm the relationships between components of ocean ecosystems and ocean biogeochemistry, as well as the relationships between ocean carbon concentrations and observations derived from satellite radiances, and to provide critical vertical information. Atmospheric in situ observations of greenhouse gases are used to calibrate and validate satellite measurements and to refine atmospheric transport models, and provide critical multidecadal context needed to interpret observed variability.

A major challenge in addressing the dominant influence of temperature on ecosystems is capturing the movement of carbon, and hence feedbacks, between the multiple reservoirs—the atmosphere, terrestrial vegetation, soils, freshwater, oceans, and geological sediments—that collectively form the carbon cycle. Doing so requires that individual component fluxes be known to comparable levels of uncertainty (see Figure 8.1; Table 8.3). Consequently, a number of geophysical parameters are necessary for understanding the carbon cycle, and must be observed simultaneously: atmospheric CO_2 and CH_4 concentrations, land and ocean photosynthesis, land respiration and decomposition, and air-sea exchange. Also necessary are continuous measurements of processes that change at time scales of annual to decadal periods such as vegetation biomass, disturbance, and recovery, biomass burning, and carbon flux to the deep ocean.

Challenges, Opportunities, and Benefits of Prior Efforts

Challenges

Scaling

Ecosystems are complex, with species interacting at different trophic levels and different food webs that define the functional, structural, and biotic attributes of the system. Over different time scales disturbance forces create both rapid and slow changes, which cause significant and profound changes in ecosystem composition and function. Consequently, ecosystems have processes and functions that operate over different spatial and temporal scales and respond differently to different parts of the electromagnetic spectrum, depending on the conditions of the environment and the composition of the biosphere. The spatial resolution of an observation of an ecosystem is one of the important scales to understand to correctly interpret the spectral information. This problem is challenging when applied to ecosystems and biodiversity, as

TABLE 8.3 Current Flux Uncertainty Levels for the Land Carbon Cycle

Carbon Cycle Component	Flux Uncertainty Now (Pg C and Atmospheric ppm CO_2 Equivalent)	Reference
Atmospheric CO_2 concentrations	±0.1 Pg C or ±0.05 ppm CO_2	Tans and Thoning (2008)
Land gross primary productivity	±8 Pg C or ±3.8 CO_2	Beer et al. (2010)
Vegetation disturbance and recovery	±1 Pg C or ±0.5 ppm CO_2	Le Quéré et al. (2015)
Biomass burning	±0.4 Pg C or ±0.2 ppm CO_2	van der Werf (2010)
Plant respiration	±9 Pg C or ±4 ppm CO_2	Schlesinger and Bernhardt (2013)
Soil (roots, mycorrhizae, etc.) respiration-decomposition	±15 Pg C or ±7 ppm CO_2	Schlesinger and Bernhardt (2013)

NOTE: All fluxes are per year (see Figure 8.1). The current global land carbon sink is 2.9 Pg C/year with a land cover change flux of 0.9 Pg/C year.
SOURCE: Data are from Tans and Thoning (2008); Le Quéré et al. (2015); Schlesinger and Bernhardt (2013); Beer et al. (2010); and van der Werf et al. (2013).

remote sensing technologies operate at specific scales. If the object is significantly smaller than the pixel or the process occurs at scales smaller than a pixel, it introduces uncertainty into the measurement. There are several approaches to addressing this problem: higher spatial resolution data can be used to train a classifier or validate results in coarser spatial data; statistical methods such as spectral mixture analysis can estimate the subpixel fraction of each component (endmember); and new computational statistical methods based on data analytics and machine learning can be used to solve subpixel composition.

Satellites with coarse resolution imagers include weather satellites having Geostationary Operational Environmental Satellite (GOES) or Polar Operational Environmental Satellites (POES) resolution at approximately 250 m to 1 km pixels—examples in the POR are VIIRS, NOAA-16, and PACE when it is launched. Moderate-resolution satellite imagers are generally in a polar orbit except for those on the ISS, which is in a 51-degree inclination orbit, allowing them to view the part of Earth under the satellite at different times of the day on different orbits. Moderate-resolution Landsat class satellites have pixel sizes that range from 10 m to 100 m. Examples are Landsat-7 and -8, Sentinel-2 and SPOT-4 and -5, and the proposed Earth observing satellites in the POR that are under construction, such as Environmental Mapping and Analysis Program (EnMAP), and for deployment on the ISS, such as ECOSTRESS and HISUI. Last, high spatial resolution polar-orbiting satellites that have smaller than 5 m pixel size are in the domain of commercial vendors. These are polar-orbiting multispectral satellites with very high spatial resolution, such as WorldView-1, -2, -3, and -4, Quickbird, GeoEye, and others. The company Planet is proposing to provide daily 5 m visible and near-infrared imagery from a large number of 3 Unit (3U) CubeSats. Still, the relative resolution (high, moderate, or coarse) may vary by application.

Improving Coverage in Key Regions

Understanding the function of ecosystems in high-latitude and tropical regions is critical for understanding the response of the Earth system to natural and human-induced changes. Northern hemisphere high latitudes have experienced the most warming during the past century resulting in an increase in growing season length and vegetation photosynthetic capacity. The impacts of increasing fire frequency, thawing of carbon-rich permafrost soils, melting sea ice, and changes in Southern Ocean circulation on ecosystems and carbon balance are unknown. Tropical ecosystems support the greatest biodiversity and largest carbon stocks on the planet, but these dense and sparsely inhabited areas are critically undersampled by in situ networks. Both high-latitude and tropical ecosystems are challenging to observe by satellite because of persistent cloudiness and a lack of ground-based calibration/validation resources. However, improvements over current generation satellites are possible through the expanded use of lidar and Synthetic Aperture Radar (SAR)—for example, the European Space Agency (ESA) Sentinel-1a and -1b missions—technologies, increased sampling frequency by combining information from multiple sensors, and expanded airborne and ground-based sampling. An excellent example of this is the harmonization of Landsat-8, Sentinel-2a, and Sentinel-2b 30 m multispectral data with an equatorial revisit frequency of 3.7 days.

Data Services

Increasing spatial and temporal resolution of satellite data products, including those from the commercial sector, enables significant advances in ecosystem science, but poses a challenge for both data providers and users. Advanced visualization, data subsetting, and remote access tools can aid users, especially those without science or computational backgrounds, but require sustained support by funding agencies.

Opportunities

Leveraging Sustained Land Imaging

International investments in sustained land imaging now provide global 30 m multispectral imagery at an equatorial repeat frequency of 3.7 days, with an increase in sampling frequency to 3 days anticipated in 2020 with the launch of Landsat-9. This capability will lead to improving observation-based estimates of gross primary production (GPP) and other carbon fluxes that have previously used MODIS data at 1 km resolution (Badgley et al., 2017). Continuity of these critical long-term data sets provides a crucial context for new measurements that will enable a deeper understanding of ecosystem function and structure. These data could be enhanced by the addition of hyperspectral data that can provide additional information on ecosystem functioning.

Transitioning Mature Airborne Technology to Space

Following the 2007 Earth Science Decadal Survey, NASA made substantial technology investments in airborne hyperspectral imaging of vegetation and ocean color, and lidar observations of vegetation structure, greenhouse gases, and ocean profiles of particulate carbon. These technologies have been demonstrated by aircraft, supporting more rapid development and deployment of such missions.

Synergy with Commercial Satellite Data

The commercial sector is actively developing small satellite systems for Earth imaging. For example, Planet uses off-the-shelf electronics to build highly capable small satellites launched into constellations that will have the capability to image Earth daily. Capella Space is developing small satellites to provide SAR imagery from constellations of small satellites. The potential for measuring the OCR of coastal waters from small satellites will be evaluated by SeaHawk,[3] a proof-of-concept mission supported by the Moore Foundation. Small satellites have significant potential to cut launch and other costs, although their capability to meet science community objectives needs to be demonstrated. The panel also notes that to meet these objectives, small satellites are reliant on the calibration and mapping integrity provided by Landsat and other medium-resolution satellites.

Benefits of Prior Efforts

Satellite observations over the past several decades have enabled routine monitoring of global ecosystems and a better understanding of their interaction with climate and human-induced change (NRC, 2008). Quantifying primary production for both terrestrial and marine ecosystems has been a central concern of carbon cycle research and is now integrated into earth system models.

Accurate estimates of leaf area index (LAI) are critical to correctly scaling carbon, water, and energy fluxes to estimate rates of photosynthesis, evapotranspiration, and respiration on land surfaces. Today, MODIS and VIIRS provide accurate estimates of LAI that inform global estimates of terrestrial GPP and NPP, and, combined with the AVHRR/2 time series (in operation since 1981), provide a multidecadal record of how ecosystems have changed. Recent work has shown that satellite observations of solar-induced fluorescence (SIF) from atmospheric composition satellites (OCO-2, GOSAT, GOME-2) can identify periods when vegetative productivity is low (e.g., Frankenberg et al., 2011; Joiner et al., 2011) and have been combined with MODIS multispectral imagery to produce GPP estimates entirely from observations (Badgley et al., 2017).

Satellite ocean color measurements have proven to be essential for supporting the science and applications related to ocean ecosystems and biogeochemistry. These and other ancillary measurements (e.g., incident solar irradiance) are used to calculate the mean and fluctuating components of ocean NPP at regional to global scales. Additional spectral bands of NASA's MODIS and ESA's medium-spectral resolution imaging spectrometer (MERIS) were also used to estimate ecological parameters such as phytoplankton size and taxonomic composition, both of which affect the efficiency of carbon flow from phytoplankton to higher trophic levels, including fish, and to the long-term sequestration of exported carbon in the ocean interior. For MODIS additional narrow-band measurements around the chlorophyll-a fluorescence peak at 685 nm added the potential for estimating the physiological state of phytoplankton and its growth potential. The PACE mission will enable a significant leap forward in our ability to quantify seawater components and how their distributions change and respond to the physics and chemistry of the ocean.

Satellite data have also revolutionized our understanding of how humans use and change the landscape, which has implications for the structure and functioning of ecosystems, and their exchanges of energy, water, and nutrients. Obtaining global land cover maps has been a goal of terrestrial remote sensing from the beginning of Landsat; however, only since the EOS era have direct measurements of land cover been produced at an appropriate global scale (DeFries and Townshend, 1999). Landsat data with its 30 m spatial resolution and consistent, long-term sampling provides an excellent data set that has been used to assess changes in global forests (e.g., Hansen et al., 2013) and climatic shifts in high-latitude ecosystems (e.g., Ju and Masek, 2016). These data sets have also supported widespread monitoring of agricultural production. The use of Landsat, MODIS, and VIIRS satellite data is central to global projects including the Famine Early Warning System Network established by the U.S. Agency for International Development (USAID) in 1985 and the U.S. Department of Agriculture's (USDA's) global agricultural production estimates released monthly (USDA, 2017). As extensive observational data from Landsat, Sentinel-2, and commercial

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[3] See University of North Carolina, Wilmington, "SOCON: Sustained Ocean Color Observations with Nanosatellites: SeaHawk CubeSat Satellite Bus," http://uncwweb.uncw.edu/socon/seahawk.html.

satellites become increasingly available, along with ancillary data in relational geospatial databases, they support informatics approaches that aid farmers in optimizing yields (Liu et al., 2010; Zheng et al., 2013; Verrelst et al., 2014; Guan et al., 2017; Veloso et al., 2017).

The same data sets have also provided the best global source of information regarding the impact of fires on ecosystems. For example, early studies with AVHRR showed that most fires in the tropics are of anthropogenic origin, while in the boreal forests, large wildfires were generally caused by lightning (Verbesselt et al., 2012). More recently, analysis of MODIS and VIIRS data provided refined estimates of burned area and of emissions of trace gases and aerosols from fires (e.g., van der Werf et al., 2006, 2010; Schroeder et al., 2014).

Airborne observations have been used to document wildfire temperatures by measuring the enhanced radiance in the hyperspectral SWIR bands (e.g., Dennison et al., 2006) and have documented the progressive drought stress in California's forest ecosystems in 2012-2015 using NIR water absorption bands (Asner et al., 2016b). Hyperspectral imagery is expected to improve understanding of the physiological responses of vegetation to these and other environmental disturbances (Khanna et al., 2013; Kefauver et al., 2014; Sanches et al., 2014). However, this potential has been poorly documented given the lack of satellite-based observations other than Hyperion, a one-year demonstration project launched in 2000, which lacked adequate signal-to-noise ratios for use in aquatic systems and many terrestrial applications. Despite its limitations Hyperion has demonstrated the potential for hyperspectral data compared to multispectral systems (Marshall and Thenkaball, 2015), and provides the basis for algorithms applicable to next-generation sensors such as EnMAP and Hyperspectral Infrared Imager (HyspIRI; e.g., Christian et al., 2015; Zhang et al., 2016).

Satellite and aircraft remote sensing observations have also greatly improved our understanding of coastal, wetland, estuarine, coral reef, and inland aquatic ecosystems. For example, airborne hyperspectral observations can be used to classify coral reef cover types (Hochberg and Atkinson, 2000) and estimate primary production rates and distributions (Hochberg and Atkinson, 2008). Landsat-5 imagery was used to construct a 30+ year time series of giant kelp canopy biomass on a 30 m basis over the entire California coastal waters and was used to diagnose the controls on kelp canopy changes in space and time (e.g., Bell et al., 2015a). Hyperspectral Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) airborne observations have extended this remote analysis of kelp forests by enabling the retrieval of kelp canopy chlorophyll concentrations independently from carbon biomass, providing robust proxies of the photo-physiological state of the kelp forests (Bell et al., 2015b). Last, high-resolution airborne imagery was used to assess seagrass cover and water depth of the Bahamas Banks (Dierssen et al., 2003). The airborne results cited here demonstrate the capabilities that hyperspectral remote sensing brings to understanding terrestrial, coastal, and aquatic ecosystems. While Hyperion was not widely used for aquatic systems, the Hyperspectral Imager for the Coastal Ocean (HICO) sensor aboard the International Space Station provides another example of how hyperspectral information would improve understanding of aquatic systems compared to multispectral systems (Ryan et al., 2011; Figure 8.2).

PRIORITIZED SCIENCE OBJECTIVES AND ENABLING MEASUREMENTS

This panel identified five overarching science questions within three primary topic areas that remote sensing can contribute to in the coming decade. Those broad topic areas are (1) structure, function, and biodiversity; (2) fluxes of carbon, water, nutrients, and energy; and (3) carbon accounting. For each of the science questions, the panel further identified several objectives. The five questions are enumerated in the following sections with the associated objectives described in detail. The panel recognized all objectives as being important, but notes those that are Very Important (Objective E-1a) and Most Important (Objectives E-1b, E-1c, E-2a, and E-3a).

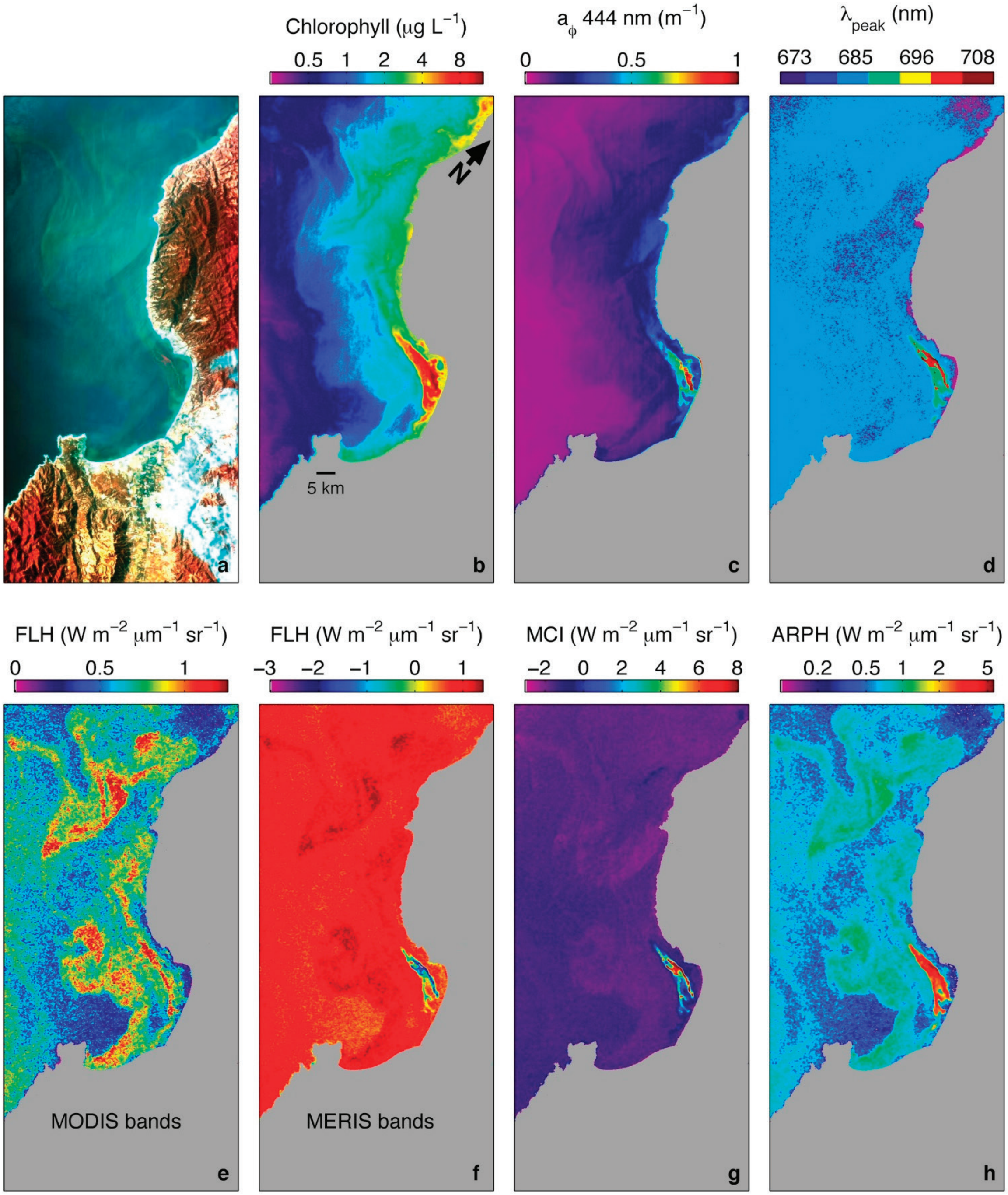

FIGURE 8.2 Phytoplankton characterization from a suite of algorithms using a HICO hyperspectral image acquired on November 6, 2012, over Monterey Bay, California. The enhanced color image (panel A) used bands centered at the 466 nm (blue), 554 nm (green), and 708 nm (near infrared, to emphasize signal of a red tide). Hyperspectral data allow various band combinations to be used to optimize the imagery compared to multispectral sensors. SOURCE: Ryan et al. (2011).

E-1: Ecosystem Structure, Function, and Biodiversity

Question E-1. What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space? ("Structure" is the spatial distribution of plants and their components on land, and of aquatic biomass. "Function" is the physiology and underpinning of biophysical and biogeochemical properties of terrestrial vegetation and shallow aquatic vegetation.)

Objective E-1a

Objective E-1a. Quantify the distribution of the functional traits, functional types, and composition of terrestrial and shallow aquatic vegetation and marine biomass, spatially and over time.

Motivation

Characterization of the functional traits, functional types, and composition of terrestrial vegetation was identified by the Ecosystems Panel as a Very Important measurement based on the need to better understand the relationships between the composition of the biosphere and other Earth system processes, including climate. Multiple properties of plants (biochemistry, structure, phenology, reproduction) determine their ecological role in the biosphere. The collection of these plant properties embodies the taxonomic composition, abundance, and biomass, and their variations in space and over time defines their role in both terrestrial and marine ecosystems. These plant properties determine the patterns of energy, carbon, water, and nutrient fluxes for these systems (Lavorel et al., 2002; Diaz et al., 2004; Kattge et al., 2011; Asner et al., 2016a). It is now feasible, given hyperspectral imaging instrumentation, to map the distribution and concentrations of many terrestrial canopy biochemical and structural properties from space, which will provide new opportunities to monitor and quantify ecosystem composition and function (Schimel et al., 2013; Jetz et al., 2016; Asner et al., 2017). Hyperspectral imaging affords the most accurate community structure mapping in shallow marine systems, such as coral reefs (Hochberg et al., 2003; Hedley, 2013). Identifying taxonomic composition does not necessarily imply a specific rank like genus and species, as it can also apply to the family level or the conifer clade within the gymnosperms. This panel does not advocate for a requirement to identify and map all 300,000 or so terrestrial and aquatic plant species but instead notes that newer hyperspectral technologies can increase our understanding of the most abundant or dominant species in Earth's ecosystems as measured from space at a Landsat-class spatial resolution. For example, consider a gradient in water availability across a deciduous hardwood forest that may be observed in the field as a change in the distribution of deciduous hardwood species across the gradient, but this compositional change would not be detected from orbit with existing technology, as there would be no change in the "functional type" of the ecosystem as currently mapped. Mapping at the taxonomic level using imaging spectrometry has advanced rapidly in all types of environments in the past two decades, from Roberts et al. (1998) and Underwood et al. (2003) to Ferreira et al. (2016), Laurin et al. (2016), and Roth et al. (2016), but the level of species resolution depends on the traits that distinguish one species (or genera, family, or clade) relative to others in their surroundings. There are a growing number of papers that show relationships between plant biodiversity (and its relation to heterotrophic biodiversity) and spectral characteristics. In some cases species, subspecies, or subgenera are defined (Cavender-Bares et al., 2016); in others, emphasis is on alpha, beta, or gamma diversity without specifying species composition (Punalekar et al, 2016; Wang et al. 2016a, 2016b). Expanding our knowledge of the composition of terrestrial ecosystems is also important for modeling habitat suitability for all species including animals, many of which have critical land and water conservation monitoring needs. Doing so also forms a bridge between species (and their functioning) and the rest of the Earth system.

Similar to terrestrial systems, understanding biodiversity in aquatic ecosystems in relation to biogeochemical cycles requires quantification of the functional composition and changes over appropriate temporal and spatial scales. Appropriate scales are question-dependent, but for coastal aquatic systems, a commonly cited requirement is to achieve subtidal (hours) temporal revisit rates, with spatial resolutions between 10-200 m (Devred et al., 2013; Mouw et al., 2015; Moses et al., 2016). Aquatic ecosystems have many important roles in the global system. For example, the oceans support highly productive and diverse ecosystems that have important roles in the global cycling of carbon and the sequestration of CO_2 on monthly to millennial time scales. Coastal ocean, brackish water, and freshwater ecosystems provide a wide range of ecosystem services to society, from critical habitats for endangered species, to coastal protection, to fisheries. For planktonic ecosystems, functional types can be defined in terms of the cell size and biogeochemical roles of the phytoplankton populations, as a function of food quality for higher trophic levels, and as beneficial versus harmful algal bloom (HAB) groups.

For many marine faunal species, population characteristics are defined by habitat suitability mapping, which in turn, often requires continuous mapping of NPP and other parameters. Faunal suitability mapping is particularly important for conservation and fisheries applications. Hence, the characterization of oceanic, coastal, and freshwater aquatic ecosystems requires a taxonomic or functional characterization of the composition of these systems obtained from satellite observations. This is important, because ecosystem structure affects the efficiency of energy transfer through marine food webs, ultimately determining fish production and the flux of organic matter into deeper ocean waters. High spectral resolution measurements from PACE (1 km) and from a future high spatial resolution (30 m) imaging spectrometer for coastal and inland waters will determine signatures of phytoplankton taxonomic diversity and particle size distributions, enabling us for the first time to quantify global ocean ecosystem structure and biodiversity metrics from space. Space-based high-resolution imaging spectroscopy will also enable for the first time global characterization of the nearshore coastal zone and shallow aquatic ecosystems.

The wide array and inherent accuracy of the observables will provide critically needed support for developing and validating numerical models linking biology and physics to forecast future ocean ecosystem structure and the ocean carbon cycling they regulate.

Measurement Objectives

The suite of land plant properties observable by satellite sensors are those that absorb and reflect energy in the wavelengths between the visible and shortwave infrared region of the solar spectrum (400-2500 nm). Because these measurements relate to observations of photosynthetic pigments, water content, carbon concentrations, nutrients, and other biochemicals that are related to plant productivity, structure, and defense, they provide direct information about ecosystem function. Measurements and use of such traits to infer functional processes has a long history in the plant biology and ecological literature and more recently in the development of large plant trait databases, such as the TRY database (Kattge et al., 2011). Imaging spectrometer measurements and analysis from NASA's AVIRIS and numerous other imaging spectrometers have been widely published throughout the remote sensing literature. While there are no "standard products" for AVIRIS because it is a research instrument, the HyspIRI Airborne Preparatory Project developed a set of georectified and atmospherically corrected radiance products to simulate data flow from an operational hyperspectral satellite. Case studies and products enabled by next-generation remote sensing were highlighted in a recent special issue.[4]

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[4] See *Remote Sensing of Environment*, 2015, "Special Issue on the Hyperspectral Infrared Imager (HyspIRI): Emerging Science in Terrestrial and Aquatic Ecology, Radiation Balance and Hazards," Volume 167, https://doi.org/10.1016/j.rse.2015.06.011.

In 10 years of mapping the functional diversity of tropical and temperate forest canopy species, a large literature has developed on the use of imaging spectroscopy to map plant functional types, tree species diversity, and their biochemical traits (Kokaly, 2001; Kokaly et al., 2009; Clevers et al., 2011; Asner et al., 2014; Cheng et al., 2014; Féret and Asner, 2014, 2015; Sebrin et al., 2014; Asner and Martin, 2016; Meerdink et al., 2016).

There is a recognized need to improve estimates of photosynthetic and respiratory responses to light and temperature to increase accuracy of estimates of GPP, NPP, and Net Ecosystem Productivity (NEP). In particular, improving parameters related to nitrogen content, SIF, V_{cmax}, and J_{max}, are important to improving today's Earth system models (Rogers et al., 2017). This is an active area of photosynthetic research, and there are recent papers that support the relationship between leaf nitrogen concentration and V_{cmax} and J_{max} (Dechant et al., 2017; Kattge et al., 2009; Quebbeman and Ramirez, 2016). Quebbeman and Ramirez (2016) approached modeling from a mechanistic optimization perspective and tested it with data from the TRY database (Kattge et al., 2011), while Dechant et al. (2017) empirically found relationships through canopy measurements. Numerous papers (e.g., Kokaly et al., 2009; Clevers et al., 2011; Serbin et al., 2014; Meerdink et al., 2016) show good quantitative predictions of leaf nitrogen from leaf, canopy, and imaging reflectance levels. Given the significance of these measurements of photosynthetic performance, this research could yield significant advances from imaging spectroscopy that would increase our ability to better measure GPP, including measurements of SIF. The scientific and applications benefits of measuring GPP from space using solar-induced fluorescence would also advance our understanding of the carbon cycle (Badgley et al., 2017).

Spaceborne imaging spectrometer data are needed over large areas to measure ecosystem composition and plant functional properties of land vegetation. Airborne imaging spectroscopy in the visible to shortwave infrared (VSWIR) spectral region has demonstrated the ability to acquire this critical information over large spatial domains (meters to thousands of kilometers), while SLI provides phenology observations every 4 days (Richardson et al., 2012). The capacity to monitor and follow changes in functional traits and functional types and observe vegetation phenology at a 30 m spatial resolution from Earth orbit will transform our ability to understand and predict future changes in ecosystems that result from land use, disturbance, severe weather, and climate changes. While imaging spectroscopy is the *only* technology that can provide the detailed spectral data to allow identification and quantification of major biochemical and structural components of plant canopies, the combination of hyperspectral imagery with multispectral time series data will achieve improved understanding of ecosystem function and early detection of changes in these processes. In support of such a mission, NASA has invested in numerous pre-HyspIRI airborne, modeling, and field program activities, with numerous publications and government documentation, to further advance and mature the coupled science and technology for a future orbital spaceborne imaging spectrometer mission. NASA, the U.S. Geological Survey (USGS), and ESA are now merging or harmonizing Landsat-8, Sentinel-2a, and Sentinel-2b 30 m multispectral imagery with an equatorial repeat frequency of 3.7 days.

Within aquatic systems a suite of biogeochemical traits can also be inferred from spectral radiometry based on a combination of structure (cell size and particulate inorganic and organic carbon), pigments (to identify functional groups of algae), and discrete fluorescence bands to assess physiology (e.g., Devred et al., 2013; Mouw et al., 2015; Moses et al., 2016). Analogous to terrestrial remote sensing, this information can be used to identify harmful algal blooms and partition total biomass into size classes, providing information about trophic transfer and export flux (e.g., Uitz et al., 2010; Siegel et al., 2014; Mouw et al., 2015). In some cases remote sensing observations can be used to infer physiological status—for example, by estimating the carbon:chlorophyll ratio of phytoplankton populations (Behrenfeld et al., 2005) and giant kelp forest canopies (Bell et al., 2015b). As with terrestrial remote sensing, the capacity to track changes in these processes has the potential to transform our ability to understand and predict future changes in ecosystems resulting from resource management, disturbance, annual to decadal oscillations (e.g., El Niño), and climate change. While some of these traits could be obtained from multispectral imagery, a targeted coastal imaging sensor is necessary to achieve all of the goals, and is complementary with similar efforts for the open ocean using PACE and consistent with suggestions for a terrestrial hyperspectral imaging sensor.

For shallow seafloor systems, such as coral reefs, current aspirations are more modest. Ecosystem structural and functional features are more similar to those of terrestrial systems than to those of the open ocean, but strong absorption of red and NIR wavelengths by water largely precludes direct sensing of detailed biochemical and physiological parameters. Pigmentation has been demonstrated to be retrievable via hyperspectral measurements at the level of the coral colony (Hochberg et al., 2006), but it is unknown how such observations might scale to larger remote sensing pixels, although progress has been made in that direction for giant kelp (Bell et al., 2015b). In general though, the main objective is identification and quantification of basic benthic community structure—for example, for coral reefs, the proportional cover of coral, algae, and sand (Hochberg, 2011). Owing to the complexity of light interactions in these environments, high to moderate spatial resolution imaging spectroscopy has been demonstrated to provide greater retrieval accuracy than multispectral sensors (e.g., Botha et al., 2013; Phinn et al., 2013).

Measurement Approaches

Three measurement systems are required to quantify the composition of terrestrial vegetation and marine biomass. First, a moderate spatial resolution (30-45 m Ground Sample Distance [GSD]), hyperspectral resolution (10 nm; 400-2500 nm), high fidelity (Signal to Noise Ratio [SNR] = 400:1 Visible and Near Infrared [VNIR]/250:1 Short-wave Infrared [SWIR]) imaging spectrometer is needed for characterizing land, inland aquatic, coastal zone, and shallow coral reef ecosystems (possibly with commonality to an implementation of TO-18 in Appendix C, the Surface Biology and Geology Targeted Observable; this corresponds to the region in Figure 8.3 referred to as HyspIRI).

Second, a global ocean color mission (GSD = 0.25-1.0 km; revisit ≤ 2 days) is required to properly assess open ocean planktonic ecosystems. Its sensor should be hyperspectral ocean (5 nm; 380-1050 nm) with high fidelity (SNR ≥ 1000:1 at Top of Atmosphere [TOA] clear sky ocean radiance) so that phytoplank-

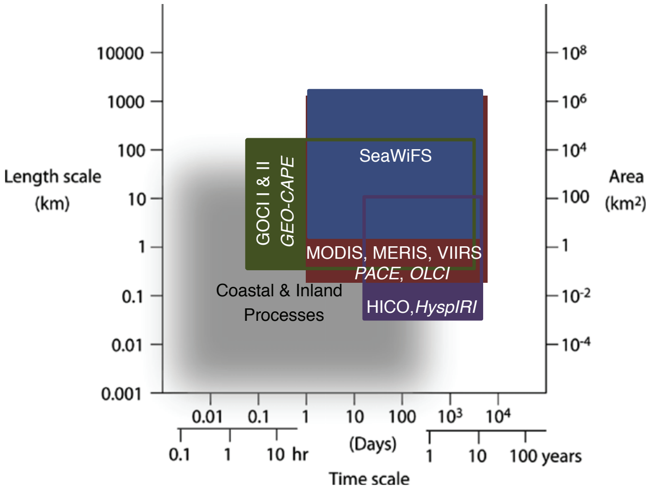

FIGURE 8.3 Coastal and inland processes are poorly characterized by most existing satellite sensors because of the high spatial and temporal resolution required to adequately document the physical biogeochemical processes of interest, including nearshore tidal currents, resuspension events, point-source delivery of nutrients, suspended sediments and colored dissolved organic matter (CDOM), and algal blooms. SOURCE: Mouw et al. (2015).

ton NPP processes and functional types can be quantified in challenging environments. The successful launch of the PACE mission in NASA's Program of Record would satisfy this need.

Last, there remains a need for moderate-spatial (~250 m), high-temporal (2-3 hour repeat), hyperspectral (5-10 nm; 380-1050 nm) observations for coastal and inland waters (Figure 8.3; TO-3 in Appendix C, the Aquatic-Coastal Biochemistry Targeted Observable), particularly for the western hemisphere (Corson et al., 2011; Fishman et al., 2012; Pahlevan et al., 2014; Arnone et al., 2016). This can be achieved via geostationary orbits or via a constellation of small satellites with orbits optimized to cover priority coastal waters (e.g., U.S. coastal waters). SeaHawk is a proof-of-concept mission based on a small satellite program and will provide the first operational test case for use of a constellation of small satellites targeting OCR. While the spectral resolution is limited (based on the legacy SeaWiFS sensor), the SeaHawk concept provides an important opportunity to evaluate the improved spatial coverage for coastal and inland waters.

Objective E-1b

Objective E-1b. Quantify the global three-dimensional (3D) structure of terrestrial vegetation and 3D distribution of marine planktonic biomass within the euphotic zone, spatially and over time.

Motivation

Quantifying the global 3D structure of terrestrial vegetation and marine planktonic biomass within the euphotic zone, spatially and over time, was identified as among a few objectives ranked as Most Important. Measurements of the 3D physical structure of vegetation are a priority, because canopy height profiles and aboveground biomass, particularly in forested ecosystems of the world, have a wide range of practical applications. Forest carbon stock estimates, based on calibration and validation of canopy structure metrics (profiles of canopy elements) with forest inventory measurements, provide robust "emission factor" data that, when coupled with "activity data" associated with changes in forest cover and extent, form the basis for emissions reporting, including uncertainties, using standard protocols (Tyukavina et al., 2015; Goetz et al., 2016).

Mapping forest structure and carbon stocks is widely used in forest management (Dubayah et al., 2010; Wulder et al., 2012) and highly relevant to safeguarding the livelihoods of communities dependent on forests for fuel, fiber, and food ("provisioning" ecosystem services). Most recently, lidar-derived forest structure measurements have helped to resolve long-standing debates about the influence of drought on tropical forest productivity and variability (Tang and Dubayah, 2017; see Figure 8.4). Forest structure metrics are also well-documented determinants of animal habitat properties, and thus community abundance and biological diversity, as well as habitat preferences and utilization (reviewed by Lefsky et al., 2002; Vierling et al., 2008; Bergen et al., 2009; Davies and Asner, 2014). The latter, in turn, is important for biodiversity conservation and adaptive management of threatened and endangered species (Goetz et al., 2010).

Quantification of the vertical dimension of marine biomass has long eluded satellite oceanographers. In order to measure global stocks of planktonic biomass, knowledge of the vertical dimension of biomass is required. Many studies assume that phytoplankton biomass levels are uniform throughout the euphotic zone (Behrenfeld et al., 2006, 2013; Siegel et al., 2014), although this clearly is not a valid assumption. Understanding the vertical profile of ocean biomass on global scales will greatly improve satellite retrievals of NPP rates as well as provide determinations of mixed layer euphotic zone depths. Recent results from NASA's Ship-Aircraft Bio-Optical Research (SABOR) field campaign showed substantial improvements in NPP estimates (up to 54 percent) when lidar-derived profiles of optical properties are used (Schulien et al., 2017). BioArgo floats will provide vertical profiles of ocean temperature and salinity, as well as biological parameters, dissolved oxygen, and backscatter much deeper into the water column than the lidar profiles.

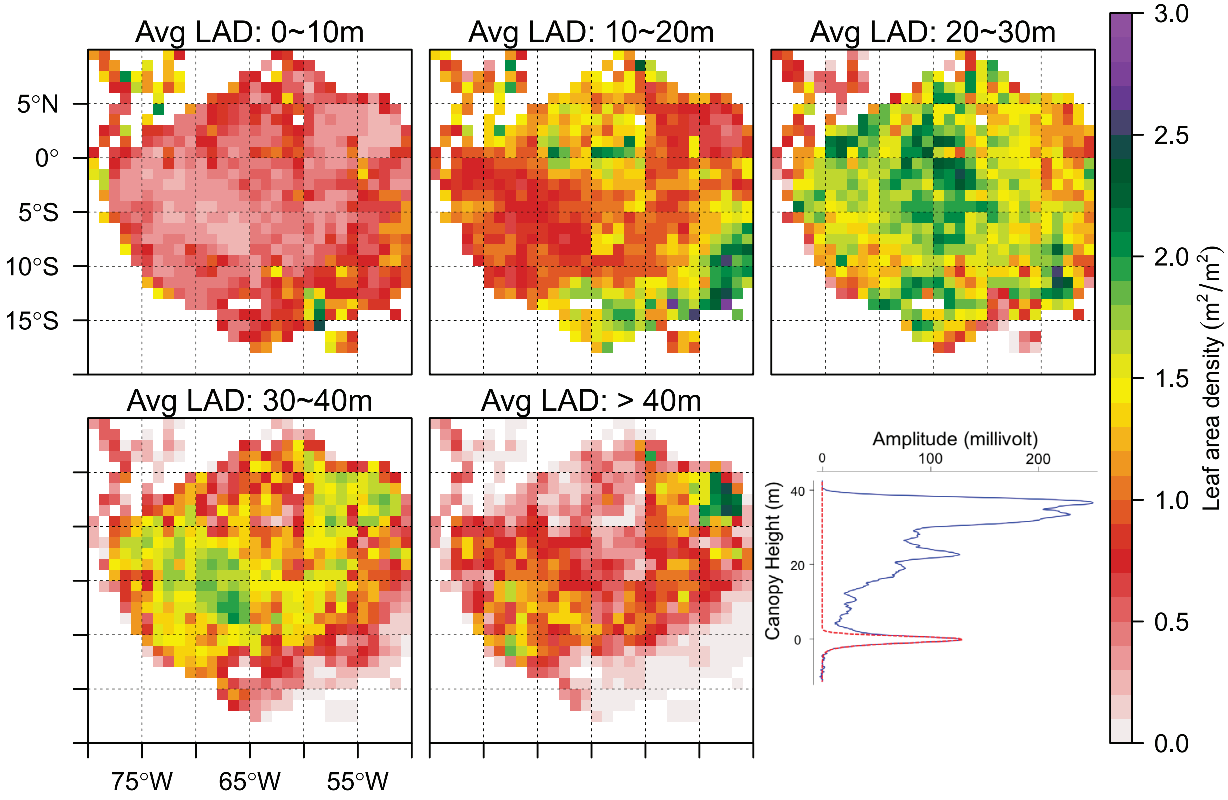

FIGURE 8.4 Maps of average vertical leaf area density (LAD) across the Amazon Basin within various height intervals, showing the vertical distribution of leaf area above the ground surface. LAD is derived as an integrated lidar-observed leaf area within height intervals (e.g., 0-10 m, 20-30 m). Data were derived from NASA's Ice, Cloud, and Land Elevation Satellite (ICESat) aggregated to 1-degree spatial resolution. The lower right panel shows an example of a footprint-level waveform with a Gaussian fit to the lidar height returns. ICESat emits a laser beam toward Earth's surface and measures the vertical distribution of energy reflected from vegetation (blue line) and the ground (red line). ICESat operated from 2003 to 2009. SOURCE: Modified fromTang and Dubayah (2017).

However, the upper ocean part of the BioArgo profile will overlap with the lidar measurements, and thus provide complementary measurements for comparisons and calibrations.

Unlike satellite ocean color imagers, active remote sensing with lidars can operate during darkness and can penetrate through moderate cloud and aerosol layers. This is critical for very high latitude oceans where the complete annual coverage of phytoplankton biomass is poorly known (Behrenfeld et al., 2017). The ability of advanced lidars to profile up to three optical depths also makes them useful for understanding ocean biological processes under perpetually cloudy conditions, such as the sub-Arctic North Pacific Ocean. Understanding ocean ecosystem processes in the Arctic Ocean and throughout the Southern Ocean is critical, as these ecosystems are changing rapidly due to warming and altered circulation patterns (Smetacek and Nicol, 2005; Schofield et al., 2010).

Measurement Objectives

A lidar satellite mission to provide 3D vegetation structure has long been a high priority of the terrestrial ecosystem science community, with a history dating back to the canceled Vegetation Canopy Lidar (VCL) mission in the mid-1990s; the Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission called for by the 2007 decadal survey but canceled as a result of budget shortfalls during the 2007-2009 financial crisis; and most recently the Global Ecosystem Dynamics Investigation (GEDI) lidar planned for a 2-year deployment on the International Space Station (ISS) by early 2019. Prior science definition teams of VCL, DESDynI-LiDAR, and GEDI-LiDAR have all specified measurement criteria that meet well-defined science needs. These have been extensively documented in NASA reports (DESDynI workshop report, 2007) and peer-reviewed publications.

GEDI-LiDAR, as the first space-based 1064 nm waveform lidar designed for ecosystem studies, will substantially advance mapping of forest canopy 3D structure and aboveground biomass for areas between ±52 degrees latitude. With full waveform sampling using multiple lasers that produce a 25 m footprint at the surface, GEDI is an appropriate model for next-decade ecosystem characterization with lidar. Desired sampling for ecosystem studies include 1 ha cells populated with 10-25 m footprint acquisitions, with global scale repeat sampling every 5 years.

Airborne and shipborne lidars generally measuring at 532 nm have long been used to quantify a variety of aquatic science problems, from the assessment of internal wave propagation on subsurface particle maxima to marine fish schooling (e.g., Churnside, 2014). The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) satellite mission enabled an average of relevant oceanographic optical properties through the upper ocean to depths of 10s of meters (Behrenfeld et al., 2017). Lidars are active, so they can be deployed at night and provide observations in regions with zero or very low sun elevations where passive ocean color sensors do not provide data. Advanced lidars, such as the High Spectral Resolution Lidar (HSRL; Piironen and Eloranta, 1994; Hair et al., 2008), determine vertical profiles of both aerosol and cloud particle backscattering coefficients as well as the lidar beam's vertical attenuation in the ocean over several optical depths. The HSRL system has been extensively demonstrated in the field from aircraft (Hair et al., 2008; Müller et al., 2014; Burton, 2015; Schulien et al., 2017).

Understanding the vertical profile of ocean biomass on global scales will greatly improve satellite-based calculations of NPP, as well as determinations of mixed layer and euphotic zone depths. The utility of such measurements was demonstrated recently for polar waters with the spaceborne CALIOP lidar (Behrenfeld et al., 2017). Of the global ocean, polar regions, particularly the Arctic, are seeing the most rapid warming and other changes such as loss of sea-ice cover. These have as yet unknown impacts on polar ecosystems. Data from lidars simultaneously profiling backscatter and beam attenuation at 355 nm and 532 nm can provide measurements that can be related to particulate carbon concentrations and dissolved organic matter absorption.

CALIOP was not designed to make in-ocean retrievals and cannot retrieve vertical profiles on oceanic scales (Lu et al., 2014), and an advanced lidar with oceanic profiling capability has not yet been flown in space. However, advanced lidars, such as the HSRL, enable multiple ocean property profile retrievals through about three optical depths, and this capability has been recently demonstrated in the field from HSRL airborne missions for several NASA oceanographic field campaigns (SABOR; North Atlantic Aerosols and Marine Ecosystem Study [NAAMES]; Azores; see Figure 8.5).

An advanced lidar instrument using the HSRL 532 nm channel would represent a substantial increase in the quality of the vertically resolved measurements for oceanic and most other applications. Vertical profiles of particle backscatter and vertical lidar path attenuation are created and are related to the total seawater absorption coefficient. To first order, passive ocean color observations provide measurement of

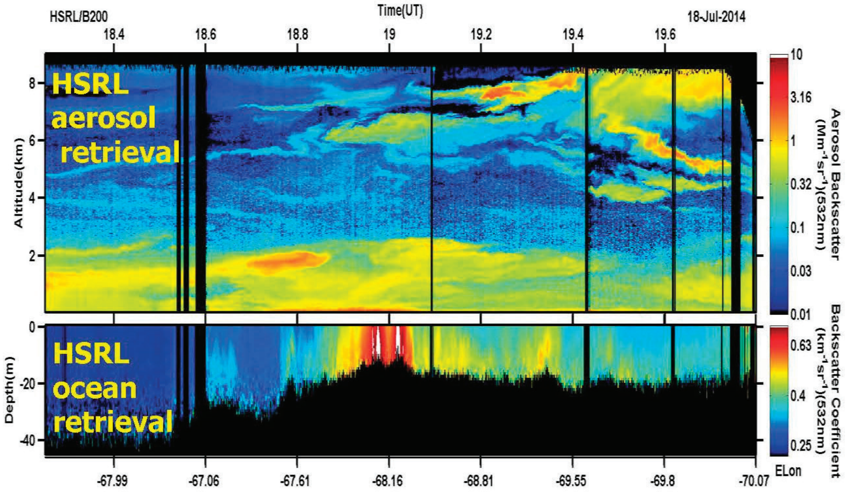

FIGURE 8.5 Backscatter from atmospheric aerosols and ocean particles as measured by an airborne 532 nm lidar along a transect line in the North Atlantic during a field program in 2014. Color codes indicate the intensity of scattering with red (high) and blue (low). SOURCE: Modified from Hair et al. (2016).

the ratio of the backscatter to absorption coefficients, whereas advanced lidar instruments provide these optical properties separately (which will be useful in integrated passive-active ocean retrievals) in the form of a vertical profile. With two advanced lidar channels at 355 and 532 nm, information can be obtained about ocean particle size distributions and separation of phytoplankton from colored dissolved organic matter absorption coefficients (Bruneau et al., 2015).

Measurement Approaches

Terrestrial Vegetation Lidar

The measurement approach for this objective would consist of imaging waveform acquired in swaths, with desired sampling of 1 ha cells with 10-25 m footprint size and global sampling every 5 years at 1064 nm.

Synergistic uses of spaceborne lidar with other missions in the POR, as well as new missions, are multifold. The GEDI is a lidar for sampling canopy structure and biomass that will be hosted on the ISS in 2019 and will operate for 2 years. ICESat-2, although not ideal for land vegetation because its wavelength is 532 nm, will be launched in 2020. Other examples include synergy with the NASA-ISRO Synthetic Aperture Radar (NISAR) radar mission, which launches circa 2022, as well as with the ESA P-band BIOMASS mission (launch in 2021), providing opportunity to spatially extend the lidar sampling to map 3D structure more extensively and contemporaneously. This panel notes that the ESA P-band BIOMASS mission is not permitted to operate over some parts of the world (including the United States) because of the operation of comparable frequency radars for tracking objects in space. Synergy with a new imaging spectrometer would also confer significant advances in assessments of the carbon cycle (Schimel et al., 2015) and biodiversity conservation (Asner et al., 2017) in combination with sustained land imaging. Lidar would be also synergistic with the other ISS instruments (OCO-3, ECOSTRESS, and HISUI) and with the

Landsat-8, Landsat-9, Sentinel-2a, and Sentinel-2b satellite fleet that could incorporate structure metrics, including biomass, in assessments of forest disturbance and recovery change.

While past efforts have demonstrated this capability using ICESat-1 Geoscience Laser Altimeter System (GLAS) waveform lidar with MODIS imagery (Baccini et al., 2012; Saatchi et al., 2011), synergy with the ICESat-2 photon-counting lidar to launch in 2020 provides opportunities to extend GEDI 3D structure to higher latitudes. This will compensate for the ICESat-2 lidar 532 nm penetration limitations for retrieving structure information in moderate to higher biomass forested regions. Last, synergy of waveform lidar with digital surface models derived from high-resolution commercial satellite stereo imagery can be used to generate canopy structure maps, when calibrated with 3D structure measurements from GEDI and ICESat-2 lidars to derive maps of surface topography beneath the canopy. These synergies have benefits across the research priorities of the decadal survey panels.

Ocean Plankton Biomass Profiling Lidar

Profiling ocean-aerosol-cloud lidar like a multispectral HSRL-2 will have the capability to make profiles of ocean biospheric properties on global scales. The instrument should have ~2 m vertical resolution and the ability to determine profiles of particle backscatter and diffuse attenuation spectra through the upper three optical depths of the ocean. The profiling lidar should have ~1 km footprint and sampling along track with near nadir viewing. It would be best if the ocean lidar system was flown in a Sun synchronous orbit to enable rapid global coverage and synergies with passive ocean color instruments. Optimally, the ocean profiling lidar would have three laser wavelengths—1064, 532, and 355 nm—so that spectral properties of both particle backscatter and diffuse attenuation can be diagnosed. This would enable the determination of the shape of particle number size spectra from the spectral information and a partitioning of phytoplankton absorption properties from colored dissolved organic matter (CDOM) absorption. The 355 nm channel makes the partitioning of phytoplankton from CDOM absorption possible. The ocean profiling lidar will revolutionize satellite remote sensing of the global ocean even without the 355 nm channel. The ocean profiling lidar builds on the successes of retrieving ocean properties from the CALIOP lidar (e.g., Behrenfeld et al., 2017). A similar profiling lidar was included in the ACE mission concept from the last decadal survey. Further NASA development and implementation of airborne HSRL-2 lidar systems are presently used in several NASA field campaigns.

Objective E-1c

Objective E-1c. Quantify the physiological dynamics of terrestrial and aquatic primary producers.

Motivation

The panel identified quantification of the physiological dynamics of primary producers as another Most Important priority.

A key to understanding the biogeochemical cycles and fluxes discussed in Questions E-2 and E-3, their sensitivity to climate change, and their feedbacks to climate are predictions of future conditions of the biosphere and the climate system. The biochemical properties of terrestrial vegetation, aquatic biomass, and soils provide quantitative or qualitative measurements that are used to determine the physiological dynamics of primary producers and soil processes. Determining the full range of physiological dynamics by quantifying canopy chemistry related to these processes also contributes to determining the functional types and traits of terrestrial ecosystems (Objective E-1a) and to determining vegetative biodiversity (see Objective E-1e).

Ocean color radiometry can determine important characteristics of phytoplankton physiology, providing a better understanding of bulk marine NPP estimates. For example, Bell et al. (2015b) demonstrate that giant kelp (macroalgae) physiological status can be assessed by directly estimating the carbon to chlorophyll ratio, and that it may be possible to estimate subtle changes in pigment ratios indicative of shifting environmental stressors and conditions. On a larger scale Behrenfeld et al. (2009) show that incorporation of fluorescence quantum yield characterizes nutrient (particularly iron) stress globally, while McGaraghan et al. (2011) demonstrate an ability to identify trends of iron bioavailability at high spatial and temporal resolution in the coastal ocean. These tools can identify shifts in physiological capacity that ultimately impact NPP, and therefore biogeochemical cycling. Quantification with an imaging spectrometer will also allow assessment of emergent properties related to the physiological dynamics of primary producers. For example, AVIRIS-Classic was used in San Francisco Bay to relate phytoplankton functional types to food quality, demonstrating that total biomass, or even growth rates, are inadequate for understanding how phytoplankton composition affects ecosystem function through trophic transfer (Kudela et al., 2016).

Measurement Objectives

The biochemical properties of terrestrial vegetation, aquatic (including ocean) biomass, and soils provide quantitative or qualitative measurements that are used to determine the physiological dynamics of primary producers and soil processes. Pigment composition can be used in both terrestrial and aquatic environments to quantify functional diversity.

For aquatic applications PACE in the POR for the open ocean and a high spatial resolution (30 m) hyperspectral sensor for coastal and inland waters will provide critical information on phytoplankton physiology and ecosystem health. The key to these observations is to complement higher spectral resolution observations in the blue to yellow wavelengths with very sensitive bands to measure solar stimulated fluorescence in the red. These fluorescence bands help to distinguish phytoplankton blooms from river plumes in coastal zones and shelf environments, and are useful for determining the efficiency of photosynthesis.

In the ocean and large lakes photosynthesis is conducted primarily by phytoplankton, composed of a broad suite of microbes, from cyanobacteria to eukaryotes. Quantification of algal pigment concentration per unit biomass provides quantification of physiological dynamics and a path for estimating algal growth rates and assessments of NPP. Elucidation of pigment composition also provides information about phytoplankton functional types (Objective E-1a). Phytoplankton fluorescence can provide an estimate of biomass that is not confounded by other (nonalgal) optical constituents such as sediments and colored dissolved organic matter. Fluorescence has also been used effectively to directly assess physiological status, and, in combination with estimates of particulate organic carbon, can be used to quantify changes in photosynthetic capacity independent of biomass (e.g., Behrenfeld et al., 2009). Macroalgae, marine plants, and corals fall somewhere between terrestrial and phytoplankton targets. Unlike plankton these organisms are stationary, and therefore amenable to benthic habitat mapping, enabling the characterization of the cover, condition, productivity, and diversity and roles that multiple stressors, such as water temperature, sediment inputs, and physical disturbance, may play.

More information is needed to understand the seasonal biochemical and physiological dynamics of terrestrial and aquatic primary productivity (Henson et al., 2013; Xia et al., 2015). Data are needed over vast regions to decompose the reflectance signal into measures of ecosystem composition and biochemically based trait characteristics. Airborne imaging spectroscopy, as described elsewhere in this report, has demonstrated the ability to acquire this critical information over large spatial scales (meters to thousands of kilometers). Developing the capacity to monitor functional types and traits of ecosystems from satellite views has the potential to transform our ability to understand and predict future changes in ecosystems that result from land use, disturbance, severe weather, and climate changes. Imaging spectroscopy is the only technology that can provide the detailed spectral data to allow identification and quantification of major biochemical and structural components of canopies at 30 m spatial resolution (Schaaf et al., 2013; Roth et al., 2015b; Singh et al., 2015) and for soils (Kruse et al., 2011). These data are needed to achieve improved understanding of ecosystem functionality and early detection of changes in these processes. These data, in combination with SLI 30 m multispectral data, will combine increased spectral information with 30 m multispectral time series data to exploit multitemporal information extraction.

For land plants concentrations of pigments can be identified and quantified (Ustin et al., 2009) to produce more accurate retrievals of photosynthetic capacity and rates, carbon assimilation, and plant functioning. For example, knowledge of the relative proportions of the xanthophyll pigments provides evidence for photoprotection during periods of excess light (Gamon et al., 2016). Estimates of the flux of carbon from pigment measurements will be significantly enhanced when they are combined with estimates of canopy fluorescence (Garbulsky et al., 2015) to better characterize downscaling of photosynthetic capacity during periods of environmental stresses (Joiner et al., 2013, 2014). Quantification of cell wall biochemicals, especially concentrations of cellulose and lignin (Kokaly et al., 2009), measurements of leaf mass per area (Asner et al., 2011; Cheng et al., 2014), and foliar nitrogen concentrations (Smith et al., 2002; Ollinger and Smith, 2005) provide information about important components of ecosystem productivity and functionality. For example, low leaf mass area is strongly correlated with high productivity potential across a wide range of plant species (e.g., in the TRY database [Kattge et al., 2011]), while the opposite is correlated with low productivity potential. Based on the extensive literature, retrievals of these biochemicals are robust across diverse ecosystems (e.g. Kokaly, 2001; Kokaly et al., 2009; Kokaly and Skidmore, 2015; Chen et al., 2014; Serbin et al., 2015; Meerdink et al., 2016), as are retrievals of soil surface biochemicals (Palacios-Orueta et al., 1999; Ben-Dor et al., 2009; Swayze et al., 2009). Retrievals of plant and soil biochemical have been demonstrated at pixels sizes of 30 m to 60 m resolution (Kruse et al., 2011; Schaaf et al., 2013; Roth et al., 2015).

Quantifying concentrations of soil surface biochemicals in terms of texture (sand, silt, and clay), organic matter, iron oxides, carbonates, and types of clay minerals (e.g., montmorillonite, illite, and kaolinite) provides better estimates of soil health, fertility status, and weathering (Nocita et al., 2015; Ben-Dor and Dematte, 2016). Additional soil chemicals related to nutritional status are desired to be measured, including potassium and magnesium (Demattê et al., 2017). The amount of these primary soil elements and secondary elements can be measured by observations of vegetation, especially when the elements are at low levels. For example, the lack of nitrogen will cause the leaves to have low pigment concentrations responses (Carter et al., 2008).

Estimates of evapotranspiration (ET) can be improved by obtaining coincident measurements of canopy water content and canopy temperature in addition to canopy leaf area index (LAI) and weather measurements of net radiation, air temperature, and wind speed (Kustas and Anderson, 2009; Anderson et al., 2011). Estimates of stomatal conductance derived from net radiation, leaf temperatures, and leaf area index will lead to improved estimates of water fluxes and canopy water status and provide information to identify irrigation deficiencies, crop and ecosystem drought, and potential wildfire risk. Measurements of soil moisture in the root zone would contribute to more accurate estimates of evapotranspiration if radar systems could provide greater penetration into the soil root volume (González-Zamora et al., 2016). Quantifying the proportions of live foliage and plant residues (dry leaves, stems) provides another indicator of plant stress and mortality that can be compared against the proportions under more favorable ecosystem conditions (Roberts et al., 2006).

Thermal infrared imaging can be used to quantify canopy temperatures, allowing estimates of environmental stresses, evapotranspiration, and plant stomatal closure by quantifying the difference between canopy and air temperature (Anderson et al., 2011). Net radiation is the primary driver of ET. Net radiation measurements are needed to estimate surface albedo, which changes with season and type of land cover.

To quantify ET, canopy LAI (leaf area per ground area) must also be measured. Measurement approaches that capture net radiation and LAI are described in the following subsection.

Thermal infrared measurements have broad utility for understanding environmental health and processes across a range of ecosystems. Surface temperatures provide information for assessing heat stress, while measurements of crop canopy temperatures provide information for yield prediction. For agriculture, knowledge of nighttime temperatures during the growing season is critical for anticipating insect and pathogen potential. Quantifying nighttime temperatures in winter provides information about freezing temperatures that could injure sensitive perennial crops like citrus. Surface temperatures of lakes and inland waters are used to infer habitat quality and eutrophication and can be used to provide estimates of macrophytes, algae, and cyanobacteria. Wetland temperatures also provide information about functioning of these ecologically sensitive systems, while temperatures of urban heat islands provide information essential to human health and well-being as well as key information on energy demands and management of utility systems and the energy grid.

Measurement Approaches

The remote quantification of physiological dynamics of the primary producers of Earth's ecosystems will require the synthesis of multiple satellite data sets, some of which have been introduced previously. These data should be collected in near coincident time. The measurements include (1) a moderate-spatial, moderate-hyperspectral-resolution imaging spectrometer to assess biochemistry and composition of terrestrial, aquatic, and coastal ecosystems; (2) a global hyperspectral ocean color imaging spectrometer to quantify open ocean planktonic ecosystems (similar to the PACE mission in the POR); as well as (3) high-spatial, high-temporal, hyperspectral observations of coastal and inland waters. These three measurement approaches were detailed in Objective E-1a. Further, both the profiling ocean lidar and the vegetation canopy imaging lidar detailed in Objective E-1b will help constrain NPP as a function of depth within the oceanic water column and within a vegetation canopy.

Additional measurements will help quantify the physiological dynamics of the primary producers in terrestrial environments. Measurements of SIF from land vegetation may constrain rates of vegetation GPP. SIF measurements are made within Fraunhofer lines that have a narrow bandwidth (≤1 Å) or in the oxygen A or B lines. Thus, very high spectral resolution observations (~0.3 nm bandwidth) are needed spanning 400 to 790 nm. SIF data are useful either globally from low Earth orbit (LEO) missions (with ~1 km^2 GSD) or on diurnal scales from geostationary Earth orbit (GEO; ~16 km^2 GSD). The POR includes the ESA's Sun synchronous LEO orbit Fluorescence Explorer (FLEX) mission for solar-induced fluorescence as well as NASA's Geostationary Carbon Cycle Observatory (GeoCARB) mission. SIF data can be combined with MODIS, VIIRS, and SLI multispectral data to determine terrestrial GPP using the method of Badgley et al. (2017).

Estimates of ET are needed to assess physiological stresses on terrestrial vegetation. This is done, in part, by quantifying the difference between canopy and air temperature. Canopy temperature can be assessed using multispectral thermal IR imaging (8-12 μm with cloud bands at 1.38 and 1.6 μm). These measurements need to be made at moderate resolution (~50 m GSD) with a revisit frequency of ≤15 days and with measurements made during the day and night. The thermal IR imager on Landsat-8 (and follow-ons) is in the POR. To quantify ET, canopy LAI must also be measured (from MODIS and VIIRS or Landsat/Sentinel-2 in the POR); therefore, it is desirable that thermal measurements are coincident with optical measurements of the canopy and acquired at similar spatial scale.

Furthermore, new imagers like the Advanced Baseline Imager (ABI) on the geostationary satellites in the GOES-16 series (and advanced international systems) provide high temporal (full disk every 15 minutes) and spatial resolution (0.5 km red, 1.0 km for VNIR and 2 km for TIR) data to accurately detect cloud cover and changes in cloud cover to produce an accurate daily estimate(s) of net radiation, the primary driver of ET.

Objective E-1d

Objective E-1d. Quantify the moisture status of soils.

Motivation

The panel determined that detecting and quantifying soil moisture status in the vadose zone, the area between the soil surface and groundwater, is an Important priority for understanding the terrestrial water cycle and energy budget, and for determining plant physiological condition and evapotranspiration of this decadal survey.

Water storage in the soil vadose zone is an important component of the terrestrial water cycle. Detecting spatial and temporal dynamics of water resources stored in the near-surface soil vadose zone by use of satellite sensors has important applications, including (1) better weather (1-14 days) and seasonal forecasting (14 days to 6 months) through improved initialization of weather and climate models; (2) improved data for decision support systems relating to drought mitigation; (3) improved hydrologic forecasts in support of advanced warning systems for flooding and landslide hazards; (4) improved crop yield forecasts that can provide data to decision support systems in assessing water requirements for crop growth; (5) aid in famine prediction and early warning; (6) improved prediction of heat stress, disease conditions, and associated insect vectors; (7) improved prediction of extreme weather; and (8) enabling quantitative determination of soil and plant respiration. NASA's Soil Moisture Active-Passive (SMAP) and ESA's Soil Moisture and Ocean Salinity (SMOS) missions use passive L-band microwave measurements to accurately measure soil moisture, but no enhanced replacement missions are planned once these missions end their useful life. The value of these measurements grows as the length of the data record grows. The monthly and season statistics on global soil moisture cannot be achieved without an extensive satellite data record.

Measurement Objectives

Active Satellite Resources

Of the various satellite resources involved in the International Soil Moisture Network, SMAP and SMOS missions are most capable, using L-band microwave technology for accurate soil moisture determination. A substantial contribution of soil moisture to NASA Earth Science Objectives (ESOs) requires a level of performance for L-band data not less than the current SMAP mission (2-3 day return frequency, 40 km spatial resolution, 0.04 m^3/m^3 accuracy). Additionally, long-term continuity of the data record is critical to meeting NASA ESO requirements. However, there are no known commitments from any space agency to continue passive L-band microwave missions to and beyond the year 2027.

Potential New Technology Investments

Relative to the current SMAP configuration, spatial resolution of passive L-band microwave retrieval can be improved by a factor of two (ca. 20 km) with current technology at the cost of a small increase in measurement error. This would involve resolution enhancement and image reconstruction techniques using the oversampling of microwave observations as well as a slightly larger antenna size. It would take considerable investment in new technology development to achieve a factor of 10 increase in spatial resolution as desired by some end users. Combining data from L-band radar and radiometer (the approach originally used on SMAP before failure of its active radar sensor) is another approach to solving the image resolution issue. Reaching a desired revisit interval of one day from low Earth orbit will likely require a constellation of at least two satellites. Improvement in the retrieval algorithms would permit an increased accuracy in retrieved soil moisture by more than 0.04 m^3/m^3.

Measurement Approaches

Remote sensing with L-band SAR instrumentation can detect water only in the top few centimeters of soil, which limits its ability for providing information on rooting zone water content. Root zone water data are highly important plant growth and survival information through droughts. Various modeling approaches have been implemented for estimating root zone soil moisture. These include use of watershed models (e.g., SWAT) or land-surface models (e.g., the Noah model) to estimate water balance with assimilation of remotely sensed thermal infrared or L-band observations as a means of filtering random errors in the water balance model (Crow et al., 2008; Bolten and Crow, 2012). Other recent work has indicated that simple data smoothing techniques using continuous L-band retrievals of surface soil moisture (5 cm) can create reliable estimates of root zone soil moisture (Qiu et al., 2014).

Direct detection of root zone soil moisture may be possible using P-band SAR. The advantages of P-band are that it theoretically samples the soil profile to a greater depth than L-band observations. The disadvantages are reduced spatial resolution and more sensitivity to vertical discontinuities unrelated to soil moisture such as clay lenses. Moreover, aboveground biomass can add complexity to the return signatures. Obtaining reliable retrievals of subsurface soil moisture using P-band SAR remains challenging.

Objective E-1e

Objective E-1e. Support targeted species detection and analysis (e.g., foundation species, invasive species, indicator species, etc.).

Motivation

The panel determined that targeted detection and analysis of foundation, invasive, and indicator species from satellite remote sensing observations is an Important priority to the application goals of this decadal survey, including the provisioning of food, fiber, and timber and availability of clean water.

The composition and diversity of global ecosystems are fundamentally and rapidly changing, through altered species and taxonomic composition, species introductions, and invasive species, and through losses of biodiversity and extinction (Folke et al., 2004; Han et al., 2014). Biodiversity contributes to provisioning ecosystem services, including food resources, fiber, and forage, but changes affect ecosystem processes in ways that are only partially understood, such as resilience to disturbance and recovery from disturbance, threshold responses and other nonlinear responses or alternative states from multiple drivers (Rockström et al., 2009). The significance of biological diversity in sustaining ecosystem functionality has been increasingly understood since the first Earth Summit in 1992. In recent years, biodiversity has been recognized as essential in the maintenance of ecosystem function, processes, and services (Folke et al., 2004; Rockstrom et al., 2009; Cardinale et al., 2012), and sustaining biodiversity is a significant focus of conservation efforts, for example, the Convention on Biological Diversity (Han et al., 2014). Biodiversity is defined by the number and diversity of species in an ecosystem, their combined interactions, and their interactions with the environment. The concept of biodiversity broadly includes the taxonomic and phylogenetic diversity of an ecosystem, including their genetic, morphological, and structural characteristics, as well as their ecological and functional traits. Declines in biodiversity have a major impact on the stability and resilience of ecosystems, possibly as a consequence of loss of functional traits associated with resource capture and decomposition (Folke et al., 2004). Loss of diversity also favors increases in invasive species as well as detrimental species such as harmful algal blooms in aquatic systems (e.g., Kononen, 2001). More subtle but equally damaging effects such as shifts in food quality within aquatic systems occur with decreased diversity (Galloway and Winder, 2015).

Measurement Objectives

How the taxonomic composition, abundance, and biomass vary in space and in time defines the functional traits and 3D structure of terrestrial and aquatic ecosystems. There is a recognized need to increase the knowledge of species abundances and distributions everywhere, but the greatest immediate need is to improve the knowledge of biodiversity in the tropics. Jetz et al. (2016) and Ritter et al. (2017) recommend imaging spectroscopy as an effective tool to map biodiversity.

Quantifying functional leaf and canopy traits like canopy chemistry and canopy structure contribute to identifying taxonomic composition, and the functional properties of terrestrial ecosystems, thus linking this objective with Objectives E-1a, E-1b, and E-1c. Because these properties determine the patterns of energy, carbon, water, and nutrient fluxes for these systems, it is desirable to identify and monitor composition of ecosystems and changes in composition.

Among the processes contributing to the loss of biodiversity are global changes to the climate and land use—both driven by human activities. The accelerating rate of climate change requires greatly enhanced knowledge about the distribution of species numbers, their compositions, and their interactions with ecosystem conditions. Measuring and monitoring global changes at the necessary scales requires remote sensing (Turner, 2014; Jetz et al., 2016; Ustin, 2016). Imaging spectroscopy from satellites and aircrafts provides observations at spatial, temporal, and spectral resolutions that facilitate these measurements and are complemented by expanding computational capacity and in situ monitoring systems. A growing literature has provided numerous examples of mapping individual species with imaging spectroscopy at scales from 20-60 m pixels (Roth et al., 2015) for forests (Kokaly et al., 2003; Kalacska et al., 2007; Asner et al., 2008; Somers et al., 2011; Féret and Asner, 2013, 2014; Baldeck et al., 2015), shrublands (Roberts et al., 1998; Drake et al., 1999; Held et al., 2003; Roth et al., 2012), and wetlands (Li et al., 2005; Hestir et al., 2008; Kamal and Phinn, 2011; Khanna et al., 2011; Santos et al., 2012). More recently, several studies have used spectroscopy to map phylogenetic structure (Cavender-Bares et al., 2016; Asner and Martin, 2016; McManus et al., 2016), and biodiversity measures like alpha and beta diversity and species richness have been successful (Féret and Asner, 2014; Wang et al., 2016a, 2016b). Identification of species is much more challenging in aquatic systems, but it is possible to identify phytoplankton functional types with next-generation sensors (Palacios et al., 2015; Hestir et al., 2015) and in some cases genera (Kudela et al., 2015), which can provide valuable information about water quality and biodiversity.

In some cases identifying the presence or absence of foundation species or other indicator species will provide insight into ecosystem functioning (e.g., Santos et al., 2016), the status of trophic layers within the ecosystem, the likely presence of species, and habitats that are associated with the community that the foundation species (or other indicator species) represents. Changes in the abundance and distribution of a foundation species or other indicator species can provide an early warning of ecosystem stresses. Many species can be identified from Landsat-class spatial resolution with pixels in the 30 m scale, such as agricultural species and others that are typically clustered or grow in near-monospecific patches. In other ecosystems, such as grasslands, species are always intermixed and individual species identification from spaceborne sensors is not possible; however, some studies have shown that the variance about the mean trait can be used to estimate species richness and even alpha and beta diversity (e.g., Wang et al., 2016a, 2016b). Some forest, shrub, and herb species are also detectable at this 30 m spatial scale (Underwood et al., 2007; Roth et al., 2015b; Stagakis et al., 2016). Monitoring crop health and development is essential to provide early famine warning and for agricultural security generally. Similarly, invasive plant species, often found in large patches, can make detection and mapping possible, as cited earlier. The invasion and spread of pest species cause deterioration in food security and the goods and services ecosystems provide, in addition to significant economic losses of tens to hundreds of billions of dollars per year at the country scale (Heikkilä, 2010) and an estimated $120 billion annually in the United States for invasive plant species alone (Pimentel et al., 2005). New measurement technologies, especially imaging spectroscopy and imaging lidar, provide opportunities to monitor species and biodiversity from space and allow assessment of efficacy of conservation and other land management actions and goals. Effective measurements for monitoring targeted species are consistent with measurements identified in Objective E-1a for identification of plant functional traits and plant functional types for both terrestrial species and freshwater aquatic and marine species (e.g., macrophytes, algae, and plankton).

Measurement Approaches

Identification of species that occur at scales approximating the Landsat pixel scale can be done with multiseasonal date imaging spectroscopy (Galvão et al., 2012) or in combination with available lidar. These data could provide information to improve assessments of food security and of the goods and services ecosystems provide. Similarly, invasive plant species or harmful algal blooms are often found in large patches, which makes their detection and mapping possible. New measurement technologies, especially imaging spectroscopy and imaging lidar, in combination with SLI multitemporal and multispectral 30 m data, provide opportunities to monitor species and biodiversity from space and allow assessment of efficacy of conservation and land and coastal management actions and goals. Effective measurements for monitoring targeted species are consistent with measurements identified in Objective E-1a for identification of plant functional traits and plant functional types for both terrestrial species and freshwater aquatic and marine species, including invasive macrophytes and harmful algae.

The POR includes polar orbiting moderate-resolution instruments (Landsat-8 with nine 30 m bands and two thermal IR bands, the Sentinel-2 series in the same orbit with 10 bands in visible to shortwave infrared). Global imagery from MODIS, VIIRS on the Suomi NPP, and its continuation in the JPSS program (as well as OLCI on the Sentinel-3 series) provide similar measurements at the km scale but with near daily global coverage. Polar orbiting satellites are insufficient to measure albedo, daily net radiation, and diurnal surface temperatures that can be produced from POR geostationary satellite data. For example, GOES-16 (and its follow-ons) will provide full disk radiances every 15 minutes, providing the best diurnal information to calculate net radiation and surface temperatures in the continental United States and Canada. The current global constellation of new geostationary sensors with improved spatial, spectral, and temporal resolutions and improved star trackers, includes the international investments from the Japanese (Himawari-8 and -9) and European Organisation for the Exploitation (EUMETSAT; Meteosat 10 and 11).

These multiband Landsat-class instruments provide the long time series for information about canopy photosynthetic capacity, providing essential information about gross and net primary productivity on land and vegetation phenology, but they do not provide more detailed information about plant, soil, and water chemistry—for example, pigments, water, and canopy and foliar structural and metabolic biochemicals that can assess actual physiological status and functioning. A hyperspectral imager is needed, but there is presently no global mission to provide these data.

The planned Environmental Mapping and Analysis Program (EnMAP) in the Copernicus series is in the POR for an imaging spectrometer mission with 30 m pixel resolution and 30 km swath.[5] It is in Phase D production for a 2018 launch by the German Aerospace Center (DLR) with a 5-year mission. However, it is power limited to 5000 linear km data acquisition daily. The Precursore Iperspettrale della Missione Applicativa (PRISMA) is a hyperspectral Italian Space Agency program with 30 m pixels, 30 km swath, and ~6700 km acquisition length per day with a 5-year life and a planned 2018 launch (Loizzo et al., 2016). The Japanese Hyperspectral Imager Suite (HISUI) will be deployed in a non-Sun-synchronous orbit aboard the International Space Station in the 2019 time frame. Although these missions provide opportunities for evaluating synergies among these instruments for mapping species, traits, and functional types, they do not meet the need for a global operational observation system. The HyspIRI mission from the 2007 decadal survey was designed to fill this need (and other global hyperspectral, moderate-resolution [~30 m] measurements identified here), but it is not currently scheduled for launch. Despite this, the ongoing HyspIRI Preparatory Airborne Campaign provides a rich suite of data for algorithm development in terrestrial, inland and coastal aquatic, and coral ecosystems that would be of immediate use if suggested imaging spectrometers were implemented. For the global coastal ocean, the PACE mission in the POR will more than adequately provide the data sets used to assess harmful algal blooms.

Hence, the targeted detection and analysis of foundation, invasive, and indicator species from satellite remote sensing observations will require the synthesis of many of the satellite measurements introduced previously. This includes (1) a moderate-spatial, moderate-hyperspectral-resolution imaging spectrometer needed to assess biomass and composition of terrestrial, aquatic, and coastal ecosystems; (2) a global hyperspectral ocean color mission to properly assess open ocean planktonic ecosystems (similar to the PACE mission in the POR); as well as (3) a high-spatial, high-temporal, hyperspectral mission for coastal and inland waters, particularly for the western hemisphere. These three measurement approaches were detailed in Objective E-1a. Further, both the profiling ocean lidar and the vegetation canopy imaging lidar detailed in Objective E-1b, will help to provide species identification and mapping as well.

Connections to Other Panels

Quantifying the composition of terrestrial vegetation and marine biomass and the physiological dynamics of Earth's primary producers are important to aspects of other decadal survey panel's science objectives, and their solutions require the measurement approaches that are identified here. For example, quantifying land cover, land cover changes, and rates of evapotranspiration contributes to addressing the science objectives of other panels, ranging from terrestrial water (Questions H-1, H-2, H-3, and H-4) and heat flux budgets (Questions W-3 and W-8) to hill slope dynamics (Question S-4 and S-5) and ocean water clarity. For example, the moderate-resolution, hyperspectral imaging spectrometer can be used to quantify rates of snow and ice melting and the thermal signatures associated with volcanic phenomena contributing to the Solid Earth Panel's objectives (Questions S-2 and S-4). Imaging spectrometer observations are also useful for assessing Earth surface albedos needed to constrain local to regional energy and water budgets. Sustained Land Imaging 30 m multispectral time series imagery also supports these science objectives with a very high revisit frequency.

The two lidar missions have many connections to the other panels. The terrestrial vegetation imaging lidar has important links to the Hydrology, Climate, and Weather Panels due to the roles of aboveground biomass on evapotranspiration patterns and to the water and energy cycles on local to regional scales (Questions H-1, H-2, W-3, and C-4). The vegetation imaging lidar also links to the Solid Earth Panel for

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[5] See the EnMAP website at http://www.enmap.org.

its ability to separate vegetation canopy from bare ground and its potential use in predicting geomorphic patterns (Question S-4). Ocean biomass profiling lidar is essentially the same lidar system that is proposed to measure cloud and aerosol optical and microphysical property profiles. Hence, there are strong and obvious synergies with the science discussed by the Climate and Weather panels (Questions W-5, W-6, W-9, and C-5). These measurements will be used to quantify important climatic processes such as cloud and aerosol radiative forcings and their interactions (the aerosol indirect effect), as well as increasing our understanding of the cloud microphysical processes leading to precipitation.

The Ecosystems Panel also has a strong connection to the Hydrology Panel with a mutual interest in mapping soil types and soil extent plus determining soil moisture (Questions H-1 to H-3). Soil moisture is of fundamental importance for GPP and for determining respiration on land, in combination with thermal measurements.

The measurements need to address Question E-1 will be needed for several of the other science objectives for this panel, particularly for long-term carbon storage (Question E-4).

E-2: Fluxes Between Ecosystems, Atmosphere, Oceans, and Solid Earth

Question E-2. What are the fluxes (of carbon, water, nutrients, and energy) between ecosystems and the atmosphere, the ocean, and the solid Earth, and how and why are they changing?

Objective E-2a

Objective E-2a. Quantify the fluxes of CO_2 and CH_4 globally at spatial scales of 100 to 500 km and monthly temporal resolution with uncertainty <25 percent between land ecosystems and atmosphere and between ocean ecosystems and atmosphere.

Motivation

The panel determined that quantifying the fluxes of CO_2 and CH_4, and other trace gases between land ecosystems and atmosphere and between ocean ecosystems and atmosphere is a Most Important priority.

Carbon dioxide (CO_2) is the most important greenhouse gas influenced by human activities (Rhein et al., 2013) and will be the primary driver of climate change over the coming century, by warming Earth's atmosphere, land, and oceans. Interactions between the atmosphere, ocean, and terrestrial biospheres have played a critical role in mitigating warming thus far by removing ~55 percent of anthropogenic CO_2 emissions from the atmosphere (Le Quéré et al., 2015). While budget-based estimates demonstrate the importance of the global land and ocean carbon sinks, quantification of the fundamental processes governing these sinks remain uncertain, leading to large uncertainties in projections of climate change over the coming century (Gregory et al., 2009; Arora et al., 2013; Hoffman et al., 2014). Although present at lower concentrations in the atmosphere, methane (CH_4), the second most important greenhouse gas (GHG), has a much stronger global warming potential than CO_2 over both decadal and century time scales (Rhein et al., 2013). Emissions of methane from agriculture, wetlands, and biomass burning represent more than half of recent emissions (Saunois et al., 2016), but the uncertainty of emissions from individual categories remains high, as do the response of emission processes to warming.

Improved understanding of the specific processes that control ecosystem-atmosphere fluxes of CO_2 and CH_4 are critical for improving model projections of climate change and for national and international efforts to establish emission reduction strategies. Global GHG fluxes are likely to be driven by changes in key regions that are poorly sampled by current satellites and in situ networks. Key science questions include the following:

- How will warming influence CO_2 and CH_4 emissions from Arctic-boreal ecosystems? What is the magnitude and speciation of emissions from permafrost? How will warming trends influence the carbon balance of high-latitude regions?
- What are the processes governing midlatitude and tropical land-atmosphere carbon exchange? How sustainable is the contemporary carbon sink? What are the responses of regional land carbon sinks to drought and heat stress?
- What are the relative roles of the solubility and biological pumps in controlling the marine CO_2 flux? How will climate change influence carbon uptake, particularly in the Southern Ocean? What are the relative roles of coastal and open ocean carbon flux?
- What processes are controlling recent increases in atmospheric CH_4? How is an increasing global population influencing agricultural emissions? How are wetland emissions responding to temperature and moisture changes?

Measurement Objectives

Quantifying the global fluxes of CO_2 and CH_4 between terrestrial and marine ecosystems and the atmosphere with a high level of accuracy sufficient to attribute changes on regional scales is critical for improved process-level understanding, which is needed to diagnose and predict changes in the Earth system. Regional fluxes are estimated by combining atmospheric measurements of carbon species with estimates of atmospheric transport to infer corrections needed to a prior estimate of net flux. Although typically used to estimate both land and ocean fluxes, such techniques provide a greater constraint on land fluxes, which have stronger seasonal variations and, as a result, a greater imprint on atmospheric mixing ratios.

Satellite-observed carbon concentrations play a critical and unique role in refining flux estimates, which can be directly measured only on very fine scales. For these reasons the Group on Earth Observations (GEO) Committee on Earth Observation Satellites (CEOS) Strategy for Carbon Observations from Space (CEOS, 2014) emphasized the need for satellite observations of atmospheric CO_2 and CH_4 to support monitoring, assessing, and attributing carbon sources and sinks. Flux estimates derived from current generation satellite measurements have provided new details on continental-scale tropical CO_2 fluxes that continue to be poorly constrained by in situ data. However, systematic measurement errors and a lack of coverage in key regions have limited the utility of current satellite observations for global flux estimation to date (Basu et al., 2013; Chevallier et al., 2014).

Quantification of global net CO_2 and CH_4 fluxes requires high-quality (random error <1 ppm for CO_2, 10 ppb for CH_4), spatially resolved ($<4 \times 4$ km^2), unbiased (systematic error < 0.2 ppm for CO_2, <0.5 ppb for CH_4) observations, with global coverage at monthly time scales. Coincident carbon monoxide (CO) measurements, which can support attribution of emissions to combustion and noncombustion sources, are recommended. Measurements used to estimate ocean and land primary production, biomass burning, and respiration are also critically needed to interpret net carbon fluxes and attribute to ecosystem processes. Those measurements are described in detail in the discussion of Objective E-3a, while atmospheric GHG measurements are discussed in more detail later.

Measurement Approaches

Space-based observations of CO_2 are currently made by the Orbiting Carbon Observatory-2 (OCO-2) and the Greenhouse Gas Observing Satellite (GOSAT), which also observes CH_4. Both missions retrieve GHG information from measurements of the near-infrared (NIR) absorption of reflected sunlight (1600 and 2060 nm for CO_2, 1670 nm for GOSAT CH_4). They also measure molecular oxygen (O_2) in the 765 nm A-band to compute the column-averaged dry air mole fraction of CO_2 (XCO_2) and CH_4 (XCH_4). Information from the O_2 A-band can also be used to estimate SIF, a quantity related to terrestrial gross primary production (Frankenberg et al., 2011; Joiner et al., 2011) and discussed in more detail in Objective E-3a. GOSAT footprints represent a 10.5 km diameter area, while OCO-2 observes a 10.5 km swath that includes 8 pixels representing smaller 3 km^2 areas, which results in a much greater data yield. OCO-2 and GOSAT both operate in Sun-synchronous orbits, measuring GHGs using two observation modes: in nadir mode, data are collected along the ground track of the satellite, and in glint, the spacecraft points toward the Sun "glint" spot to increase the ability to retrieve GHGs data over dark ocean surfaces.

Although the measurement technique is mature, having flown on multiple satellite missions, passive remote sensing of long-lived GHGs has several significant limitations. The need for sunlit conditions prevents measurements of high-latitude regions during polar night, which makes directly observing changes in these vulnerable ecosystems difficult. There are also indications that uneven seasonal coverage in the northern hemisphere mid- and high latitudes can negatively influence inverse flux estimates by allowing unreasonable fluxes to be inferred during months when observations are unavailable. Measurements are possible only under clear sky conditions, leading to poor coverage in persistently cloudy regions where large carbon stocks exist, like the Amazon and Southern Ocean, and urban areas with large aerosol loadings. In addition to limited coverage, small but spatially coherent biases in both the OCO-2 and GOSAT data sets have a strong impact on both the latitudinal distribution and the land/ocean partitioning of inferred global fluxes. Substantial investments in suborbital and expanded ground-based remote sensing networks could support more effective bias corrections and help to extend coverage into poorly observed low-light or cloudy regions, but this cost needs to be considered as a critical component of future passive missions.

An alternative approach to observing XCO_2 and XCH_4 using lidar technology has been demonstrated in a number of aircraft field campaigns to provide high-precision, low-bias measurements over a wide range of surface types, day and night, all seasons, and between scattered clouds (Jucks et al., 2015). Active measurements use the same NIR channels as current passive techniques, but provide their own illumination using a laser. This simplified viewing geometry limits errors due to scattering by clouds and aerosols, allowing a larger number of measurements to be collected in these environments, while the brighter illumination from the laser allows nadir observations to be taken over dark ocean surfaces, minimizing biases due to differing observation modes. Active instruments can also observe during both day and night, offering the ability to monitor critical Arctic-boreal ecosystems. For these reasons, the 2007 decadal survey recommended the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission, which has been since supported by NASA (currently pre-Phase A), but is not currently in the POR.

Challenges in transitioning active GHG remote sensing to space include scaling of telescope components from aircraft to space. The footprint of active, space-based measurements (~100 m) would also represent a much finer area than passive instruments, substantially reducing daily areal coverage. Active O_2 instruments that could be used to compute XCO_2 and XCH_4 are currently less mature than active CO_2 and CH_4 technology. This limitation could be addressed through the use of meteorological analysis information with the benefit of significant cost reduction, but advanced techniques would need to be developed to ensure that this approach does not introduce errors in the retrieval process. The first active GHG mission will be the Methane Remote Sensing Lidar Mission (MERLIN), a joint mission supported by the Centre National d'Études Spaciales (CNES) and DLR, currently scheduled for launch in 2021.

Measurements of CO that are co-located with column GHG measurements are highly desirable. Because CO is emitted by fossil fuel and biomass burning combustion, but not by ecosystem processes, the use of CO along with CO_2 and CH_4 may improve the ability to attribute fluxes to different processes (Wang et al., 2009). The reaction of CO with OH produces CO_2 as well as reduces the sink of CH_4, thus exerting an influence on the atmospheric distribution of both gases. Thermal infrared (TIR; 4.7 μm) measurements provide information about midtropospheric CO and are very mature, having first been included on the Measurements of Pollution in the Troposphere (MOPITT) instrument aboard Terra (since 2000) and subsequently by infrared sounders (Atmospheric Infrared Sounder [AIRS], Infrared Atmospheric Sounding Interferometer [IASI]). MOPITT also includes two shortwave infrared (SWIR) channels (2.3 and 4.6 μm), which provides additional information about near-surface CO.

Estimation of ocean-atmosphere fluxes is more challenging than estimation of land-atmosphere fluxes, but may be possible using a combination of satellite data, models, and in situ measurements. In addition to the inverse modeling techniques described earlier, measurements of air-sea fluxes of O_2 help constrain the CO_2 fluxes (Bopp et al., 2002; Resplandy et al., 2015). A common approach to determine air-sea CO_2 and O_2 fluxes is to use scatterometer measurements of surface roughness (surface winds) coupled with in situ measurements of trace gases from ship, BioArgo, or other sources to calculate fluxes (e.g., Gruber et al., 2009; Johnson et al., 2009). An alternative approach is to use empirical relations between sea-surface carbon dioxide fugacity, fCO(2)(sw), and sea-surface temperature (SST) and chlorophyll to calculate fCO(2)(sw) from remotely sensed SST and ocean color (e.g., Olsen et al., 2004; Hales et al., 2012).

SST radiometers and a scatterometer (RapidSCAT) are in the POR. The need for a future scatterometer to better understand ocean-surface winds and currents is noted by both the Climate and the Weather panels. Because the atmospheric signal of ocean fluxes is smaller than land fluxes, remote sensing approaches of column CO_2 and CH_4 (similar to OCO-2; see Schimel et al., RFI-2) or lidar profiles (see Kawa et al., RFI-2) have limited utility for directly measuring air-sea fluxes of these gases (McKinley et al., 2016). Continuation of in situ measurement programs and the measurements of flux components discussed in more detail under Objective E-3a are particularly critical for constraining ocean-atmosphere flux, and this challenging area will likely benefit from further technological development efforts.

Continuity versus New

Several planned missions will extend the record of passive GHG remote sensing, but all will face limitations in spatial coverage and bias that have been noted in current sensors. GOSAT-2, scheduled for launch in 2018, is expected to produce similar results to GOSAT. OCO-3, an instrument built from flight spares from OCO-2, is currently scheduled for deployment to the International Space Station (ISS) in 2018. The ISS orbit will not allow OCO-3 to observe regions outside of 52 degrees S to 52 degrees N latitude, leaving key Arctic and boreal ecosystems and the Southern Ocean unobserved. Both GOSAT-2 and OCO-3 include the addition of a refined pointing mechanism that will be used to collect denser observations over urban and other key areas of interest, but this is not expected to significantly improve understanding of atmosphere-ecosystem processes.

NASA recently announced the GeoCARB mission (2022 launch) as a hosted payload aboard a commercial communications satellite. This mission has been announced recently enough that at this time it is not yet in the Program of Record. When launched GeoCARB will be the first geostationary GHG remote sensing mission, allowing it to observe CO_2, CH_4, and CO over North, South, and Central America. Measurements will be obstructed by the presence of clouds or dense aerosols, but the goal is to increase data yield by scanning the Americas daily (and some key regions even more frequently) to increase the likelihood of encountering clear-sky conditions. The geostationary deployment will also prevent viewing of Arctic and boreal North America, while the lack of a glint observing mode will provide few if any usable soundings over ocean. Because GeoCARB does not observe globally, it does not address the science objective of improving global flux estimates, although it will likely help to inform regional carbon budgets over the Americas (Polonsky et al., 2014; Rayner et al., 2014).

The Tropospheric Monitoring Instrument (TROPOMI), launched in October 2017 aboard ESA's Sentinel-5 Precursor, will measure CO and CH_4 (SWIR, 2.3 μm) along with a suite of trace gases designed to better understand ozone photochemistry. Concentrations will be retrieved over moderate-size (7 × 7 km^2) footprints within a 2600 km wide swath, providing daily global coverage over a 7-year planned lifetime. CNES plans to launch MicroCarb in 2021, which will measure CO_2 at NIR wavelengths using a compact micro-satellite flying in a Sun-synchronous orbit. Although similar to the measurement technique used by OCO-2, MicroCarb will for the first time address the challenge of delivering science-quality CO_2 measurements from an instrument about one-third the size, weight, and cost of currently deployed technology. Similar to GeoCARB, MicroCarb is at a lower level of maturity than other missions and is not yet listed in the Program of Record. MERLIN, the first active CH_4 remote sensing mission, is scheduled for launch in 2021. MERLIN will use lidar technology to measure CH_4 absorption in the NIR. The use of a Sun-synchronous orbit will allow observations of CH_4 over all latitudes and during all seasons for the first time. Unlike passive satellite missions, MERLIN will not carry an O_2 measuring instrument, instead using analyzed meteorological information about surface pressure and water vapor to estimate XCH_4.

While planned passive missions demonstrate progress toward the carbon observing constellation outlined in the 2014 CEOS report, experience demonstrates that all such missions will leave key ecosystems underobserved and will be subject to substantial biases that limit their ability to improve ecosystem-atmosphere flux estimates. The need for active, space-based remote sensing of carbon gases, identified as a priority in the 2007 Decadal Survey, remains. The use of surface pressure and water vapor information from meteorological analyses can be used as an alternative to a direct measurement of O_2 to reduce cost, as discussed in ASCENDS (2015). Complementing planned missions with active remote sensing would provide a unique opportunity to improve bias correction of passive observations globally, improving the return on investment by NASA and international space agencies.

Objective E-2b

Objective E-2b. Quantify the fluxes from land ecosystems and between aquatic ecosystems.

Motivation

The panel determined that quantifying fluxes from land ecosystems and between aquatic ecosystems is an Important priority.

Although inland freshwater and brackish water ecosystems (e.g., lakes, rivers, reservoirs, estuaries, fjords, etc.) constitute a very small fraction of Earth's land surface, they provide many important ecosystem services, including water for irrigating crops, food for human consumption, and recycling of nutrients. The adjacency of aquatic ecosystems to the human population centers reflects both their importance to humankind as well as the potential threats to these ecosystems. Land use and climate changes are altering land ecosystems throughout the planet, and these changes propagate through rivers to marine ecosystems. For example, high nutrient loadings carried by rivers can increase marine primary production locally (e.g., Körtzinger, 2003; Regnier et al., 2013). On a global scale the movement of carbon between land and ocean is poorly constrained and has been identified as a key uncertainty that remains unrepresented in many models (Le Quéré et al., 2015). However, quantifying the fluxes from land surfaces to aquatic ecosystems and the transport of these materials from rivers and streams to the oceans on global scales is an intense challenge that spans a wide range of spatial scales and demands remote sensing measurements. Observations at wide-ranging spatial, temporal, and spectral resolutions can be achieved using instruments on aircrafts and satellites and are enhanced by expanding computational capacity and in situ monitoring systems.

Measurement Objectives

Answering the preceding science questions requires the measurement of (1) the dissolved and particulate constituents in aquatic ecosystems; (2) their transport downstream in riverine systems potentially into the coastal ocean; and (3) changes in aquatic ecosystem characteristics in response to changes in land use, land surface ecosystems, as well as climate and weather forcing. Remote measurement objectives for the measuring composition of aquatic ecosystems are identical to those for coastal ecosystems as detailed in Objective E-1a and will not be discussed further here.

The transport of water downstream and into the coastal ocean requires river discharge to be monitored or modeled over time, particularly given anticipated changes in discharge volume and timing with a change in climate. Water discharge along with dissolved and particulate concentrations will allow calculation of terrestrial fluxes to the ocean. Global river stage height measurements will be available from NASA's upcoming Surface Water and Ocean Topography (SWOT) mission.

Last, measurements to quantify changes in terrestrial ecosystems, land use, and rainfall are detailed in other sections of this report.

Measurement Approaches

Sustained land imaging from Landsat-8, Sentinel-2a, and Sentinel-2b, combined with in situ data, provides data needed to address carbon, nutrient, and particulate fluxes from land ecosystems to aquatic and marine ecosystems. Because the objective (transport in rivers to coastal waters) requires high revisit frequency (2-3 days), sustained land imaging can characterize downstream transport. Hyperspectral data provides additional biochemical information on carbon, nutrients, and dissolved organic matter and particulates and quantifies changes in aquatic and wetland ecosystem characteristics by quantifying these parameters at 30 m pixels but with 16-day revisit intervals (Mouroulis et al., 2016).

Objective E-2c

Objective E-2c. Assess ecosystem subsidies from solid Earth.

Motivation

The panel determined that assessing ecosystem subsidies from solid Earth is an Important priority.

Dust Emissions from Wind Erosion

Surface emissions of mineral dust impacts climate variability and change through direct radiative forcing (RF) over arid and semiarid regions around the globe. In these regions climate alterations have a significant impact on agriculture, precipitation, and desert encroachment (e.g., desertification). Dust particles contribute to both positive and negative forcing, depending on the composition of the particles, which is a function of the mineralogy of source regions. Iron and phosphorus deposition affects ocean biogeochemistry, and can be as important as changes in climate for changing ocean productivity (Mahowald et al., 2011). The mineralogy matters greatly for these impacts, as some iron species are more bioavailable in the ocean than other iron (Shi et al., 2012). Currently, poor knowledge of mineral dust source composition (MDSC) limits the ability of models to predict dust climate and biogeochemistry impacts in various ecosystems.

Soil Resource Movement

Soil erosion caused by water, or tillage operations, is important landscape process in agroecosystems causing landscape redistribution of an estimated 0.47 to 0.61 Pg C globally (Van Oost et al., 2007). Breakdown of soil aggregates can release labile organic matter and enhances microbial decomposition (Lal, 2003), whereas burial at the site of deposition may stabilize mobilized soil carbon (McCarty et al., 2009). Current terrestrial carbon models do not fully account for the impacts of soil carbon stock redistributions in landscapes and thereby overestimate net C flux from cropland by up to 40 percent (Chappell et al., 2015). To close this information gap, better measurements of soil redistribution patterns on landscapes are required. Development of topographic models based on lidar-derived high-resolution digital elevation models (DEMs) has been shown to have utility for mapping soil redistribution and organic carbon in agricultural ecosystems at field and watershed scales (Xi et al., 2017). The resulting topographic models are expected to improve predictions of process-based models for soil carbon fate in the biosphere.

Black Carbon Emissions

Black carbon is a short-term atmospheric pollutant emitted from incomplete combustion of carbonaceous fuels from industrial sources such as diesel engines and from open biomass burning associated with wildfires and prescribed fires for rangeland, forests, and cropland management. Black carbon is discussed in detail in Objective E-5c due to its connection with wildfires.

Dissolved Organic Carbon Fluxes

Freshwater ecosystems annually receive on the order 1.9 Pg C from terrestrial landscapes, and of that amount at least 0.8 Pg C is respired to the atmosphere, 0.2 Pg C is buried, and the remaining 0.9 Pg C is delivered to the oceans (Cole et al., 2007). These C fluxes are additional to internal primary production sequestering C in aquatic ecosystems, but lakes, streams, and rivers are usually net sources of CO_2 to the atmosphere. To further close the information gap on carbon fluxes in aquatic ecosystems, remote sensing approaches are needed for monitoring dissolved organic carbon (DOC).

Measurement Objectives

To achieve the science target for mineral dusts, the type and relative abundance of the key dust source minerals need to be measured comprehensively for the arid and semiarid regions of Earth. Such measurements could be incorporated into Earth system models that require information on dust mineralogy, saltation, and emission of dust particles to the atmosphere; transport and dispersion processes; and deposition.

Relative to soil erosion concern, remote sensing approaches that provide high-resolution DEMs can help model redistribution patterns at watershed and regional scales. These approaches can involve use of advanced lidar and Synthetic Aperture Radar (SAR) sensors for acquisition of meter-scale elevation data.

Measurement Approaches

To achieve the science target, comprehensive measurement of 10 key minerals is required—hematite, goethite, illite, vermiculite, calcite, dolomite, montmorillonite, kaolinite, chlorite, and gypsum—each with a unique spectral signature tied to its composition and measureable by imaging spectroscopy (Clark, 1999). The modeling of mineral dust is based on the fractional abundance of component minerals. Changes in the abundance of individual components will constrain the abundance of the remaining components. Currently, imaging spectroscopy mapping of dust source regions is the only feasible path to measure the occurrence and relative abundance of the key dust source minerals with sufficient detail and global arid land coverage (Clark, 1999; Ehlmann et al., 2006). Complete measurement of the spectral range from 410 to 2450 nm is required to capture the diagnostic absorptions of the minerals. Spectral sampling of ≤15 nm, response function width ≤20 nm, and ≤5 percent spectral calibration uncertainty are required to discriminate overlapping absorption features. This spectral range also captures the atmospheric features used in the atmospheric correction, aerosol, and cloud screening. To cover the brightness of arid dust source regions, the radiometric range of the spectroscopic measurement is required to extend to ≥80 percent of a Lambertian reflectance target under direct illumination. To screen for nondust source surface materials, the spectral features of green and nonphotosynthetic vegetation are captured in this spectral range as well.

Single-photon and Geiger lidar systems as well as SAR sensors will facilitate large-scale acquisition of high-resolution DEMs needed for accurate assessment of soil redistribution patterns on landscapes. Information on soil redistribution can then be used in terrestrial carbon models to reduce errors estimates of net carbon flux.

Use of the Operational Land Imager (OLI) aboard Landsat-8 has demonstrated the ability to detect colored dissolved organic carbon (DOC) in inland waters (Brezonik et al., 2015; Herrault et al., 2016) and export of terrestrial DOC to coastal ocean waters (Del Castillo and Miller, 2008; Slonecker et al., 2016). Additionally, hyperspectral remote sensing has shown utility for estimating colored organic matter in river plume regions (Zhu et al., 2011).

Connections to Other Panels

Atmospheric measurements of CO_2 and CH_4 concentrations for understanding ecosystem-atmosphere fluxes have been identified as a high priority by the Climate Panel (Questions C-3 and C-8), while active measurements of tropospheric CH_4 have been identified by the Weather and Air Quality Panel as a priority observation (Question W-8). In order to reliably estimate fluxes from GHG measurements, high-quality information about atmospheric transport is also needed, as discussed by the Weather and Air Quality Panel.

Connections to other panels include the Hydrology Panel's objective regarding land use and land cover anthropogenic changes that affect water quantity and quality and the Hydrology Panel's objective where evapotranspiration is required to determine groundwater recharge rates. There are also connections to the Solid Earth Panel's objective to quantify global, decadal landscape change produced by both abrupt changes in the topography and character of the surface as well as continuous deformations due to mass movements; fluvial, hillslope, and coastal processes; soil creep; and thawing permafrost and their objective to map geological disaster extent and severity for mitigation purposes.

E-3: Fluxes Within Ecosystems

Question E-3. What are the fluxes (of carbon, water, nutrients, and energy) within ecosystems, and how and why are they changing?

Objective E-3a

Objective E-3a. Quantify the flows of energy, carbon, water, nutrients, and so on sustaining the life cycle of terrestrial and marine ecosystems and partitioning into functional types.

Motivation

This objective was identified as a Most Important priority. In this section the panel provides details about the type of measurements needed to observe these flux components.

A major challenge in understanding the carbon cycle is that the atmosphere, terrestrial vegetation, soils, the ocean, freshwater bodies, and geological sediments all serve as substantial reservoirs of carbon. Tracing the movement of carbon between and within these reservoirs requires observations of a number of geophysical parameters that must be measured simultaneously. Many of the observations needed to better understand flux processes are currently being made or are in the POR, while new measurements discussed in more detail in Questions E-1 and E-2 support improved quantification of fluxes. Later, we briefly discuss the major ecosystem flux processes and remote sensing data sets used to study them. This objective is related closely to Objective E-2a, which aims to use atmospheric carbon observations to constrain net ecosystem-atmosphere flux.

Terrestrial Primary Production

Measurement Objectives

Observationally informed model estimates of GPP provide valuable information on the spatial distribution and temporal variability of primary production, which can be used to better understand underlying processes and improve their representation in climate models. One technique involves extrapolating information from Eddy-covariance flux tower observations using satellite-measured absorbed photosynthetically active radiation (Beer et al., 2010; Jung et al., 2011). Another approach uses MODIS satellite observations in conjunction with a simple light-use efficiency model to produce GPP estimates (Zhao and Running, 2010). An advantage of these two approaches is that the satellite observations provide realistic surface conditions of vegetation photosynthetic capacity, phenology, disturbances, recovery, and human management. Despite this progress, there is no consensus among the various estimates on global GPP (e.g., Beer et al., 2010; Welp et al., 2016). As a result, prognostic models yield a wide range of estimates that disagree on the amplitude, interannual variability, and trends of GPP (Anav et al., 2015). There is urgency to improve observation-based estimates of GPP to improve the predictive skill of such models and to better understand the influence of disturbance, which satellite estimates implicitly include.

Measurement Approaches

On the observation-driven GPP approaches, sustained land imaging is now providing global 30 m multispectral imagery from Landsat-8, Sentinel-2a, and Sentinel-2b at an equatorial repeat frequency of 3.7 days (Mandanici and Bitelli, 2016). This will lead to improving the observation-based estimates of GPP by enabling a 30-60 m refinement of the MODIS GPP method that currently provides results at 1 km resolution. In 2020, when Landsat-9 is launched, the equatorial repeat frequency will fall to 3 days. Sentinel-2c and Sentinel-2d are authorized, the imagers are built, and they stand ready to replace Sentinel-2a or Sentinel-2b as needed. Sustained land imaging will thus continue at least through 2025 as it is now constituted. The panel also advocates for Landsat-10 and Landsat-11 to continue the 30 m multispectral high-revisit frequency time series as needed in 2025 to 2030. An imaging spectrometer at 30 m resolution could provide improved information on vegetation traits related to productivity, such as leaf nitrogen concentration, leaf mass area, and status of the xanthophyll cycle pigments, as well as various stress indicators.

MODIS-like 250 and 500 m imagery will be continued beyond 2030 by the VIIRS instrument's 375-750 m imagery on the NASA and NOAA Joint Polar Satellite System (JPSS) satellites. MODIS data run from 2000 to the present and VIIRS will continue these observations beyond 2035, with the four JPSS) satellites.

Together, these data sets will provide continuity of observationally based GPP estimates and significant enhancement in temporal and spatial resolution.

Another observation-based method for quantifying GPP has been proposed using solar-induced chlorophyll fluorescence (Frankenberg et al., 2011; Joiner et al., 2011; Guanter et al., 2014; Wood et al., 2016; Zhang et al., 2016; Goulas et al., 2017). SIF is detected when photosynthesis is occurring, while MODIS observations provide indications of vegetation greenness that may lag photosynthesis. The disadvantage of SIF is that it must be measured where no downwelling solar spectral irradiance is present. This can be accomplished only within Fraunhoffer lines that have a narrow bandwidth (<1 Å) or in the oxygen A or B lines. This very narrow bandwidth means that SIF observations will never be more detailed than 300 m spatial resolution. Currently, GOSAT SIF data are 10 × 10 km and GOME-2 SIF data are 40 × 80 km. The European Space Agency's FLEX mission, scheduled for launch in 2022, will be the first mission dedicated to investigating SIF from orbit at spatial resolutions of 0.3 to 1.0 km.

Respiration

Measurement Objectives

Ecosystem respiration is the sum of autotrophic respiration by plants and heterotrophic respiration by soil microbes. The balance between carbon removed from the atmosphere by GPP and carbon released to the atmosphere by ecosystem respiration, land use change, and fires governs the magnitude of the land carbon sink. Heterotrophic respiration, the larger of the two respiration fluxes, is controlled by temperature, moisture, and the nitrogen content of plant litter (Schimel et al., 1994; Ise and Moorcroft, 2006; Bond-Lamberty and Thompson, 2010; Suseela et al., 2012; Schlesinger and Bernhardt, 2013; Anderegg et al., 2015; Lombardozzi et al., 2015; Ballantyne et al., 2017). Soil respiration feedbacks, either from permafrost or mineral soils, pose one of the largest uncertainties in projecting climate change impacts given the large pools of carbon stored belowground. Ecosystem respiration cannot be observed directly from space, although meteorological information provides crucial information to model-based estimates and autotrophic respiration is typically assumed to be proportional to GPP.

Measurement Approaches

The observations needed to advance our understanding of respiration are land-surface temperature (LST) and soil moisture (Ballantyne et al., 2017). Presently, LST data are derived primarily from TIR measurements acquired by a number of satellites that provide information at a range of spatial and temporal scales. For example, geostationary satellites like GOES-16 provide LST at ~4 km resolution hourly, MODIS provides near-daily global data at a 1 km resolution, and Landsat-8 provides biweekly LST data at 30 m spatial resolution using sharpening techniques that combine information from multiple bands.

To advance our knowledge of the central role of heterotrophic respiration in the carbon cycle and hence climate, 30-60 m TIR observations in the 10.5-11.5 μm and 11.5-12.5 μm spectral region are needed with a 2-4 day revisit frequency for consistency with the sustained land imaging revisit frequency (currently 3.7 days). It should be mentioned that there are no thermal imagers on the four Sentinel-2 satellites. This is a major deficiency of Sentinel-2 and an opportunity for NASA to provide the instruments to move 30-60 m thermal imaging into the time domain with sustained land imaging.

Soil moisture observations are now being provided with ESA's Soil Moisture Ocean Salinity (SMOS) and NASA's Soil Moisture Active-Passive (SMAP) and are discussed in detail in Objective E-1d. The combination of soil moisture and LST observations are crucial for refining understanding of evapotranspiration, respiration, and the global terrestrial carbon cycle.

Biomass Burning

Measurement Objectives

Wildfires are an important natural influence on many ecosystems, including forests, which store between 350 to 500 Pg carbon (Le Quéré et al., 2014), an amount 35-50 times greater than current annual fossil fuel emissions. However, the incidence and severity of wildfires has markedly increased in recent decades worldwide, at least in part due to climate change (Jolly et al., 2015; Abatzoglou and Williams, 2016). The major effect of wildfires from the point of view of the carbon cycle is to release carbon into the atmosphere (as discussed in Objective E-5c). The emission of carbon to the atmosphere from biomass burning varied from 1.8 to 3.0 Pg C/yr from 1997 to 2015 and continues to be a major source of C to the atmosphere (van der Werf et al., 2017). Determination of biomass burning carbon emissions requires accurate estimates of the extent of area burned (Giglio et al., 2010; van der Werf et al., 2017), information on active fire combustion temperature (Giglio et al., 2009), land cover characteristics (Hansen et al., 2010), and plant productivity or fuel load (Myneni et al., 2002). These observations are then typically run through a simple ecosystem model to estimate biomass burning emissions (van der Werf et al., 2010). In addition to the initial combustion, carbon is also released from subsequent decomposition of dead biomass. In fact, the decomposition of dead biomass can release up to three times the amount of carbon released in the initial combustion. It is very likely that the incidence and severity of wildfires will continue to increase in the 21st century (Williams and Abatzoglou, 2016).

Measurement Approaches

Estimates of biomass burning can be improved by using sustained land imaging 30 m data instead of using MODIS 500 m imagery to provide higher resolution information about burned area and plant productivity. In addition, measurements of terrestrial vegetation structure (Objective E-1b) will provide greater information on fuel load than previously available. Thermal imagery in the 3.5 to 4.0 μm spectral region at 30-60 m spatial resolution provides more explicit active fire combustion temperatures at finer spatial scales. Active fire products are particularly critical for providing near real-time information on fire emissions to fire and air quality managers, which cannot be obtained using burned area techniques because of data latency issues (e.g., Kaiser et al., 2012; Darmenov and da Silva, 2015). More details on observations needed to understand the response of ecosystems to fire are given in the discussion of Objective E-5c.

Disturbance and Recovery

Measurement Objectives

Vegetation disturbance and recovery are important aspects of the terrestrial carbon cycle that strongly influence the ability of forests to sequester carbon (e.g., Arneth et al., 2017). Disturbance includes deforestation, forest degradation, and biomass burning, after which recovery or regrowth can occur. Disturbance can also be followed by a change in land use—for example, from forest to agricultural—with a drastic change in standing carbon stocks. Disturbances follow extreme weather events like hurricanes or severe droughts that change the distribution and density of vegetation types. Other types of disturbances result from pollution events, from air- or waterborne chemicals and toxins—for example, volcanic SO_2 and methane emissions, chemical pollution from defoliating chemicals, oil spills, explosives and other warfare devices, or other contaminants. Disturbances release biomass carbon to the atmosphere, either directly through burning or slowly via decomposition within soil, litter, and harvested products pools. The frequency of disturbance also controls the age distribution of woody vegetation (including forests). The origin of the midlatitude forest carbon sink has been postulated to reflect, wholly or in part, recovery from past land use and disturbance (Pan et al., 2011). However, the current partitioning of the sink between regrowth (from prior land use) and enhanced growth (from climate change and CO_2 enrichment) remains poorly understood (Williams et al., 2016). Measurements over the next decade will support continued reconstruction of global disturbance history over the last 50 years (Hansen et al., 2013) and quantification of biomass losses and gains. These data sets will also enhance understanding of the influence of climate variability and change on disturbance/recovery dynamics and the ecosystem impacts of major disease outbreaks.

Measurement Approaches

While active sensors have been used for disturbance and recovery purposes (e.g., Goetz et al., 2010), Landsat imagery has been used primarily for mapping disturbance, recovery, and land use changes from space (Hansen et al., 2010, 2013; Huang et al., 2010; White et al., 2017). The combined use of Landsat-8, Sentinel-2a, and Sentinel-2b multispectral data will provide greater opportunities with their 3.7-day equatorial revisit frequency (Mandanici and Bitelli, 2016). The U.S. Sustained Land Imaging and ESA Copernicus programs should continue the availability of these data beyond 2030 to support understanding of disturbance and recovery. The combination of Sustained Land Imaging, imaging spectroscopy, and lidar measurements of terrestrial vegetation structure (Objective E-1b) will substantially improve understanding of ecosystem disturbance and vegetation regrowth.

Methane Emissions

Measurement Objectives

Together, ecosystem sources of methane contribute an average of 485 Tg CH_4/yr to the atmosphere, approximately 66 percent of the global methane budget (Saunois et al., 2016). Most of these emission processes have large discrepancies between bottom-up and top-down emission estimates (Ciais et al., 2013; Kirschke et al., 2013). Relevant to this panel are methane emissions from freshwater bodies, wetlands, thawing permafrost, and agricultural practices with smaller emissions thought to result from wild animals and termites (anthropogenic emissions are discussed in more detail in the Chapter 9). Of these the panel focuses primarily on wetland emissions, which represent the largest source and one that is particularly vulnerable to both human disturbance and climate change. Permafrost emissions are discussed in Objective E-5b.

Wetlands are important in the Earth system not only for biogeochemistry and the carbon cycle but also for food production, biodiversity, and water resources. Wetlands store about 20-30 percent of global soil carbon, despite their land area being less than 10 percent, and emit around 21-31 percent of global methane emissions, with 60 percent of these emissions from tropical wetlands (Saunois et al., 2016). Large uncertainties remain regarding the spatial distribution of global wetlands, their seasonal inundation and freeze/thaw dynamics, and the sensitivity of methane emissions to water table height and climate. Current wetland models exhibit extensive disagreement in both wetland extent and CH_4 emissions, making it impossible to predict the magnitude of potential climate feedbacks (Melton et al., 2014).

Mapping wetlands is particularly challenging because observations must represent both wetland types and their seasonal dynamics. There are many different types of wetlands, characterized by whether they are forested or not, whether the soils are mineral or organic, or whether permafrost is present. The type of wetlands has a strong effect on the biophysical properties of soil, and on the pathways that control soil methane emissions to the atmosphere. The seasonal dynamics of wetland area determine the presence of anaerobic conditions, which lead to methanogenesis, and influence the temporal variability of emissions (e.g., Zona et al., 2016). High spatial resolution (<100 m) is needed to identify smaller wetlands, but such data sets typically have limited temporal resolution, which provides little information on seasonal variability. Optical and IR data sets can provide information on wetland types and their seasonal dynamics but are limited by cloud cover. To account for these limitations, satellite-based techniques have employed different combinations of visible, infrared, and microwave observations to map a variety of metrics related to wetlands. For example, scatterometer and SAR data sets have been used to estimate surface inundation, yielding monthly time series of global inundation at ~25 km resolution (i.e., Prigent et al., 2007; Schroeder et al., 2015). However, these approaches are unable to efficiently map surface inundation in dense, closed-canopy forests, and the surface inundation metric misses wetlands with water tables just below the surface, where anaerobic conditions are still present. Disagreements between satellite-derived products have made it difficult to improve wetland emission models (Melton et al., 2014).

Measurement Approaches

Higher spatial and temporal resolution remote sensing observations, combined with optical imagery, are expected to significantly improve multisensor wetland type and dynamics mapping. Space-based SARs aboard Sentinel-1 and ALOS-2 provide backscatter information at subhectare resolution that can penetrate clouds for improved characterization of wetland areas. This capability is expected to increase when NISAR is launched, with continuity of the study of the surface deformation and change advocated in the Solid Earth, Hydrology, and Climate panels. NASA's Surface Water Ocean Topography (SWOT) mission will provide altimeter data that can be used to identify water bodies larger than 250 m^2 and rivers wider than 100 m, which may help in improved mapping of vegetated wetlands with surface inundation. The increased frequency of observations provided by Sustained Land Imaging will also support better characterization of the seasonal dynamics of wetlands and surrounding vegetation. Improved atmospheric methane observations (Objective E-2a) will provide an important constraint on methane emissions from wetlands.

Emissions from freshwater bodies represent 8-24 percent of global emissions, a number notable for both its size and the magnitude of uncertainty (Saunois et al., 2016). Global estimates are typically produced by upscaling data obtained from in situ sampling of a limited number of lakes, which introduces a high degree of uncertainty. Information about global lake abundance has previously been derived by applying advanced detection algorithms to Landsat data (e.g., Verpoorter et al., 2014), but these techniques have had a limited ability to track changes in lake cover over time, which is particularly important for high-latitude systems. Sustained Land Imaging (discussed in more detail earlier) will also support more refined lake mapping techniques that may reduce uncertainty in emissions estimates, although field studies will continue to play a critical role.

Agricultural methane emissions come mainly from enteric fermentation in livestock, primarily cattle. When manure is treated in a manner that promotes anaerobic conditions, methane is also emitted from animal waste. The cultivation of rice on shallow flooded fields also produces anaerobic conditions that support the emission of methane. Because of the availability of good-quality statistics from the Food and Agriculture Organization of the United Nations, agricultural emissions are thought to be better known than the natural emissions sources discussed earlier (16-20 percent of total emissions according to Saunois et al., 2016). Although emissions can vary substantially due to agricultural practices, such small-scale processes are unlikely to be detectable by satellite. Satellite data are likely to contribute by providing information on variations in temperature and moisture, similar to the measurement approaches included in the discussion of respiration earlier.

Imaging spectroscopy (hyperspectral imaging) can be used for identifying point source emission locations and corresponding methane concentrations from aircraft over constrained geographic areas (Frankenberg et al., 2016). Emissions estimates based on such data may be useful for separating the influences of natural and anthropogenic emissions of atmospheric methane.

Ocean Primary Production

Measurement Objectives

Satellite data are required to calculate global ocean net primary productivity (NPP) that cannot be achieved with in situ sampling alone (e.g., Carr et al., 2006). Satellite observations of ocean color have become the most important method of monitoring global ocean ecosystems and calculating their productivity (McClain, 2009; Yoder et al., 2010). The primary output of ocean color measurements has been the near-surface concentration of chlorophyll-a (Chl_a, mg m^{-3}), which is also a major input to empirical ocean primary productivity models (Behrenfeld and Falkowski, 1997). Recently, mechanistically based satellite NPP algorithms have been developed that incorporate remote estimates of phytoplankton physiological state using satellite Chl/C retrievals and complete spectral light fields as a function of depth (e.g., Westberry et al., 2008; Silsbe et al., 2016). Based on satellite measurements of phytoplankton pigment concentration in the ocean, global estimates of NPP average around 100 Pg C/year, with about an equal amount occurring in the ocean and on land (Field et al., 1998). Decadal time series of satellite-measured ocean chlorophyll-a indicate that NPP may be declining in the ocean gyres with as yet unknown impacts on ocean food webs (Vantrepotte and Melin, 2009), although not all agree (e.g., Siegel et al., 2013). NPP in both the ocean and land changes significantly during the El Niño Southern Oscillation (ENSO) cycles (Chavez et al., 2011; Bastos et al., 2013).

As noted by the National Research Council (NRC, 2011), "simply sustaining the current capabilities of ocean color remote sensing will fall short of supporting the array of [required] ocean color applications." Hyperspectral observations of ocean water leaving radiance spectra will enable the complex variation of open ocean water conditions and optical constituents to be untangled and quantified. PACE will quantify key carbon concentrations and biogeochemical fluxes comprising the biological pump, such as net primary production, net community (or ecosystem) production, and carbon export from surface waters to the deep sea and over the global ocean. Together with the PACE capabilities for assessing size and some taxa of global ocean phytoplankton, researchers will be able to better quantify the links between ocean ecology and the biological pump, a key unknown in the global carbon cycle.

Measurement Approaches

PACE is a critical mission for quantifying the role of the ocean ecosystem in the global carbon cycle. Among the novel data products that PACE will produce are measures relevant to phytoplankton physiology including NPP, phytoplankton carbon concentration, phytoplankton growth rate, particle size distributions, and phytoplankton community composition—all are required to quantify the biological pump and understand the storage of carbon within the ocean.

PACE data products combined with in situ measurements provided by ocean field programs, such as NASA's upcoming Export Processes in the Ocean from Remote Sensing (EXPORTS) field campaign (NASA, 2017). EXPORTS will advance our quantitative understanding of the export and fate of global ocean NPP and develop predictive tools to monitor these processes on global scales (Siegel et al., 2016). Measurement systems for the open ocean, coastal ocean, and inland waters are identical to those described for Objectives E-1a through E-1c.

The SWOT altimeter will provide stage height determination of major rivers, informing freshwater fluxes to the coastal environments. Also, salinity measurements from Aquarius follow-on missions will detect the seaward extent of freshwater plumes onto the continental shelf, at least for systems dominated by large rivers. PACE will contribute concentration measurements that when combined with water fluxes will yield C fluxes. Thus, particulate and dissolved organic carbon fluxes and exchanges between coastal and open ocean waters require advective and mixing fluxes (from remote and in situ measurements and models) as well as radiometry at 30 m (proposed high-fidelity hyperspectral imager) to 1 km pixel resolution (PACE) to determine concentrations of particulate and dissolved organic carbon content. Other sensors that capture ancillary measurements, such as SST, sea-ice cover, and wind speed, may also be important to achieving this objective, but are not the primary measurements required.

Objective E-3b

Objective E-3b.Understand how ecosystems support higher trophic levels of food webs.

Motivation

The panel identified understanding how ecosystems support higher trophic levels of food webs as an Important priority.

Chlorophyll is one of the few biological components of ocean ecosystems that has been continuously accessible via remote sensing for many decades. Global measurement of chlorophyll, a measure of phytoplankton biomass, is an important metric related to ecosystem function. However, most species of interest are several trophic levels above the remotely sensed parameter of chlorophyll and the primary producers of pelagic ecosystems. Anchovies, sardines, and other similar marine fish species feed directly on phytoplankton (Ware and Thomson, 2005). Other fish species feed on zooplankton (small animals), which in turn graze on phytoplankton. The trophic pathways can be quite complicated, although phytoplankton are generally at the base supporting the other components. Regardless, satellite chlorophyll data are crucial information used in fisheries management for characterizing and monitoring the habitat of a wide range of living marine resources (LMRs; e.g., Conti and Scardi, 2010).

Measurement Objectives

Currently, monitoring of LMRs in marine ecosystems is hampered by the low temporal resolution of ocean color satellites and the relatively crude biological information provided by chlorophyll, which by itself does not provide functional trait information. Most coastal ocean color and atmospheric composition data collected through remote sensing are collected from low Earth orbit (LEO) once or twice each day for any particular location. This is only for noncloudy regions. Coverage for most of the world's oceans is greatly reduced, and for most regions data has to be composited into weekly (or longer) averages to get sufficient spatial coverage to detect relevant features. More frequent observations, such as from geostationary Earth orbit (GEO), are necessary to resolve processes with diurnal evolution on appropriate time scales. The more frequent coverage of a single Earth location by OCR sensors in geostationary orbit provides the capability to resolve processes operating on subdaily time scales (e.g., those affected by tides). The more frequent coverage from geostationary orbit also increases the chances of viewing a given location when clouds are not present. Many processes and phenomena that are not well studied by polar orbiters can be better resolved by geostationary orbit, including coastal fluxes and formation and dissipation of harmful algal blooms.

OCR is often augmented by SST measurements, which can be made in geostationary orbit and in the microwave portion of the spectrum, serving to alleviate data losses due to cloud cover. A tremendous benefit from geostationary ocean color would be the increased spatial coverage on daily time scales for chlorophyll, productivity, and related functional traits. Based on the results of instrument design efforts, science studies, and two field campaigns supporting the Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission, the technical requirements for a GEO sensor are well established. A temporal resolution threshold value of ≤2 hours, with a baseline requirement remaining of ≤1 hour, would meet planning objectives for the coastal United States for a desired orbit position of 94 degrees±2 degrees W longitude and spatial resolution of 250-375 m and spectral resolution of 5 nm from 345-1050 nm.

Extrapolating from the primary production of phytoplankton to the secondary production of higher trophic levels requires modeling. This in turn requires information on the depth structure of both phytoplankton and zooplankton, which is currently not available from satellite measurements, but which could be obtained with lidar measurements. Characterization of the specific types of phytoplankton (phytoplankton functional types) from satellite ocean color measurements is also needed to infer how this primary level of production cascades up different trophic levels, or is exported to the deep ocean. While efforts have moved forward on characterization of phytoplankton functional types with heritage sensors, this information clearly requires hyperspectral observations (IOCCG, 2014) as provided by PACE for the open ocean, and as described in Objectives E-1c and E-1e for the coastal ocean.

Measurement Approaches

Measurements in the western hemisphere coastal ocean and inland waters can be achieved through a geostationary approach with a spatial resolution of 100-300 m, spectral band width of 5-10 nm, observational frequency of every 2-3 hours repeat, and a ground sample distance of ~250 m. Alternatively, a constellation of small satellites with orbits optimized to cover priority coastal waters (e.g., U.S. coastal waters) may also be appropriate.

As mentioned earlier, hyperspectral observations, such as those made by PACE for the open ocean and a higher spatial resolution imaging spectrometer for coastal waters, are necessary to characterize phytoplankton functional types.

Connections to Other Panels

The carbon cycle, including CO_2 and CH_4, are priority science topics of the Climate Panel, as is the quantification of the atmosphere-ocean CO_2 and CH_4 fluxes, and understanding the land carbon sink (Questions C-3, C-8, and C-9). The Weather Panel's objective (Question W-8) to reduce uncertainty in tropospheric CH_4 concentrations aligns well with this panel's CH_4 concentration emphasis. The Hydrology Panel's priority science questions involve evapotranspiration (Questions H-1, H-2, and H-3) that is directly linked to GPP, are directly related to how land use and land cover change influence water quality, and are directly related to drought monitoring. The 30-60 m thermal data with a high-revisit frequency that the Hydrology Panel needs for better ET measurements (related to Question H2) also enable better carbon cycle respiration and biomass burning determinations.

In addition to the provisioning of food for human use, trophic interactions within ecosystems also contribute to the sequestration and cycling of carbon and energy. The cascading impacts of these trophic interactions can have significant impacts, which are directly relevant to the Climate Panel (Questions C-3 and C-8).

E-4: Carbon Accounting

Question E-4. How is carbon accounted for through carbon storage, turnover, and accumulated biomass? Have all of the major carbon sinks been quantified, and how are they changing in time?

Objective E-4a

Objective E-4a. Improve assessments of the global inventory of terrestrial C pools and their rate of turnover.

Motivation

The panel identified improving assessments of the global inventory of terrestrial C pools and their rate of turnover as an Important priority.

Carbon accounting is the process of measuring stocks of carbon in vegetation and soils and the changes in stocks due to disturbance and recovery. It provides the means to improve assessments of the global terrestrial C pools and their rate of turnover. Disturbances include deforestation, forest degradation, fire, and other drivers of land cover change that reduce carbon stocks and soil organic matter. Changes in stocks can also occur as increases, resulting from reforestation and other forms of land use change that increase biomass and soil organic matter. Traditionally, carbon accounting has been a necessary means for estimating emissions when observations needed to estimate carbon fluxes are not available. As such, carbon stock and stock change have been the mainstay of carbon cycle measurements from remote sensing of land cover change, and recently, mapping of carbon stocks and densities based on cover maps.

Even with new, more direct measurements of fluxes, carbon accounting will be important for understanding human disturbance to the carbon cycle by providing an independent check or constraint to flux estimates from direct observations. In this way, carbon accounting provides the basic land cover and carbon stock inventory against which the fluxes measures are based. Moreover, for most societal benefit applications related to carbon cycle science, such as forest management and GHG management, carbon accounting will be important to a large class of end users and policy makers. Interventions are most often made in the context of the inventory of carbon stocks in a region rather than the fluxes themselves.

Measurement Objectives

The critical measurement targets include biomass in forest and nonforest vegetation, aboveground carbon density, and their changes. These measurements are derived from land cover measurements. The measurements require spatial delineation so that independent observations of deforestation, fire, and other forms of disturbance can be co-registered to carbon stocks to estimate net fluxes over time. Observation of vegetation dynamics over time also provide information on GPP and NPP that, when combined with estimates of heterotrophic and autotropic respiration, provide data on carbon storage and stocks in biomass.

Landsat- and Sentinel-class observations provide the main basis for measuring land cover over space and time, and can be combined with other measures, including ground-based inventories and lidar-derived canopy structure metrics, to estimate carbon stocks and carbon densities over time that can be enhanced by the addition of imaging spectroscopy-measured vegetation traits over time. Since the last decadal survey new methods using mixture models and other techniques have been able to provide continuous fields that can be used to measure both vegetation condition and degradation within land cover classes, as well as changes from one land cover to another. Some of the POR platforms, particularly land continuity missions, can be leveraged. New measurements of 3D structure and direct measurements of fluxes can also be used to support carbon accounting. Constellations of optical sensors (e.g., Landsat and Sentinel-2) provide repeat cycles of approximately 3 days (at the equator).

Measurement Approaches

Measurements of vegetation structure, such as canopy height profiles, can be retrieved from spaceborne lidar similar to the GEDI and ICESat-2 mission. High-resolution (few meter horizontal) digital surface models (DSMs) are routinely derived from commercial satellite stereo pairs, such as those being generated and made freely available to the science community by the National Science Foundation (NSF)-sponsored Polar Geospatial Center (PGC). These DSMs can also be used to generate canopy structure maps when calibrated with 3D structure measurements from lidar. High-resolution maps of these structure metrics can easily be aggregated to spatial resolution comparable to Landsat and Sentinel-2 (20-30 m). To address GPP and carbon flux processes, intra-annual time series measurements, like those available from MODIS and VIIRS data products, can be generated at 30 m resolution.

Sustained land imaging from Landsat-8, Sentinel-2a, and Sentinel-2b provide 30 m spatial mapping of forests that, when combined with forest vertical structure, provide forest biomass to be determined from space. Imaging spectroscopy with lidar can produce maps of forest species. Comparisons between the prefire forest density and the postfire observations provide the degree the vegetation in question was consumed in the fire.

Objective E-4b

Objective E-4b. Constrain ocean C storage and turnover.

Motivation

The panel identified constraining ocean C storage and turnover as an Important priority. Unlike terrestrial systems where carbon is stored in the form of organic material, the majority of carbon stored in the ocean is in the form of inorganic carbon in the deep sea. This pool results from sinking and decomposition of photosynthetically derived organic carbon from the surface ocean. A small fraction of the particulate organic material reaches the seafloor, where it is stored in deep-sea sediments for millions of years. Much of the fossil fuels that are currently burned were derived from the products of marine photosynthesis stored in ocean sediments.

Ocean sequestration of CO_2 is set by the air-sea CO_2 flux balance, the export of organic carbon from the surface ocean to depth via the biological pump, and the advective transport into the ocean's interior via the meridional overturning circulation in the physical pump. Air-sea CO_2 fluxes are driven by differences between the partial pressures of CO_2, wind speed, and sea-surface temperatures, which determine the solubility of CO_2 in seawater. Seasonally, CO_2 in the atmosphere increases during the northern hemisphere winter and is drawn down during the summer due to changes in terrestrial photosynthesis. Over longer time scales, atmospheric CO_2 is modulated by volcanic eruptions, fossil fuel burning, wildfires, and climate variability. Since the surface ocean on average remains in equilibrium with the atmosphere, an increase (decrease) in the atmosphere will result in absorption (release) of CO_2 by the surface ocean. This absorption or release by the surface ocean can result either from changes in atmospheric CO_2 or from changes in temperature, since less CO_2 can be held in a given volume at higher temperature. This physically driven exchange between ocean and atmosphere is referred to as the "carbon solubility pump." The vertical export of photosynthetically derived organic carbon from the surface to the deep ocean is referred to as the "carbon biological pump," and can also vary over time. The turnover of the large inorganic marine carbon pool is slow (centuries), while the turnover of the small organic marine carbon pool is fast (days to decades).

Measurement Objectives

A combination of remote sensing, in situ observations (i.e., BioArgo), and circulation/carbon cycle ecosystem models will lead to better constrains of the activity of the carbon biological and physical pumps. Remote sensing of physical variables (temperature, wind), together with in situ measurements of ocean chemistry, are used to quantify the stability and turnover of the inorganic carbon pool and the activity of the solubility pump. Measurements of GPP, NPP, and ocean carbon fluxes are described in the previous sections.

Measurement Approaches

One promising measurement approach would be to use novel global inverse ocean circulation models to merge satellite and field observations, enabling rates of CO_2 sequestration via the coupled biological and physical pumps to be assessed (e.g., Weber and DeVries, 2016; DeVries and Weber, 2017; DeVries et al., 2017). These inverse-model approaches presently assume steady-state models of circulation and biogeochemistry; however, we expect these tools to improve in the coming years, enabling rates of carbon transformations and storage within the ocean interior to be evaluated on seasonal to interannual time scales.

Connections to Other Panels

There is a strong connection between this panel and the Climate Panel (Questions C-3 and C-8) on carbon cycle feedbacks on land, for the land carbon sink, for carbon in forests and soils, for biomass burning, for permafrost as the Arctic warms, and for better quantification of the ocean waters and ocean ecosystems' future capacities to absorb atmospheric CO_2. The potential for substantial CO_2 and CH_4 releases to the atmosphere from carbon in forests and soils, from biomass burning of forests, and from thawing permafrost are substantial, and the ability of the ocean and its ecosystems to absorb CO_2 at a higher rate than at the present time are unknown.

Understanding carbon storage in the oceans and the coupled biological and physical pumps will have important implications, especially for the Climate Panel.

E-5: Carbon Sinks

Question E-5. Are carbon sinks stable, are they changing, and why?

Objective E-5a

Objective E-5a. Discover ecosystem thresholds in altering C storage.

Motivation

The panel identified discovering ecosystem thresholds in altering C storage as an Important priority.

Current understanding of the global carbon cycle suggests that the ocean carbon pools and sinks are relatively stable on scales of years to decades, and that most of the interannual variability in atmospheric carbon dioxide is driven by changes in the terrestrial carbon pools and processes (Chavez et al., 2011). However, on longer time scales (decadal to ice ages), the ocean becomes the driver of varying atmospheric CO_2, with debate over the relative roles of the biological and solubility pumps. Changes in iron supply that enhance or suppress the carbon biological pump have been invoked as drivers of the observed variability in atmospheric CO_2, indicating that marine ecosystems have significant impacts on the global carbon cycle. We currently do not know if there are thresholds to changes in the carbon biological pump and cascading effects on the food web. Remote sensing of ocean biomass and composition together with in situ data and ecosystem models are the path to accurately quantify changes in the carbon biological pump over time. Measurements of GPP, NPP, and ocean carbon fluxes are described in the previous sections.

There are a myriad of ecological feedbacks that influence long-term carbon storage in marine and terrestrial ecosystems. Changes in temperature and moisture, land use, plant and plankton community structure, ocean circulation and sea-level patterns, ocean acidification, and other environmental changes can affect the storage of carbon in Earth's ecosystems. Many of these influences will have a threshold response below which responses to environmental changes to long-term carbon storage are undetectable but above which large changes are likely. Examples of threshold effects include melting permafrost and tundra carbon storage, rising sea level on mangrove ecosystems, and changes in the ocean's meridional overturning circulation on the ocean's sequestration of anthropogenic carbon dioxide. Other ecosystems influences have cascading effects (discussed in the next section), such as the role of bark beetle invasions on forest stand mortality, increasing the probability of aboveground carbon storage loss in trees (Meigs et al., 2011). Similar cascading effects occur in marine environments, where the demise of large phytoplankton blooms can lead to hypoxia (critically low dissolved oxygen concentrations) in subsurface waters, which in turn alters zooplankton grazer communities that influence rates of vertical carbon export and storage.

Measurement Objectives

Understanding the coupled processes linking changes of ecosystems to long-term carbon storage is clearly a high priority for the Earth sciences and for return of the nation's investment in satellite observations. However, their interdisciplinary nature makes the detailed description of required measurements complicated. Clearly, as many aspects of the coupled system need to be measured as possible so that thresholds and cascading processes can be quantified and hypotheses about their roles on carbon storage tested.

An example of how ecological threshold effects can be estimated from satellite observation is shown in Figure 8.6. Here, time series of giant kelp forest canopy biomass from a 28-year time series of Landsat-5

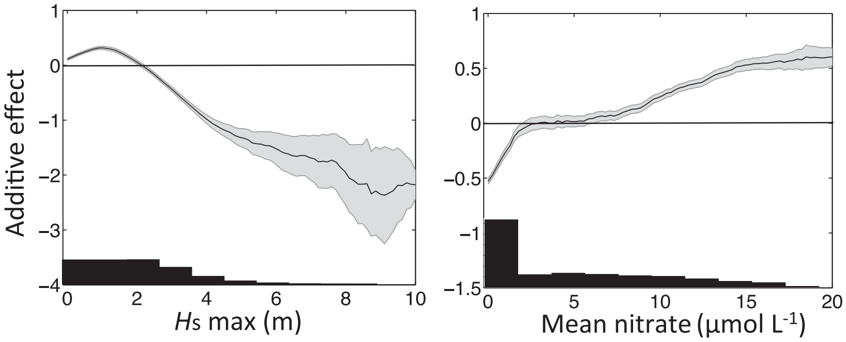

FIGURE 8.6 *Left panel:* Additive effects of surface wave significant wave height (from swell propagation wave model) on coincident giant kelp forest canopy biomass observations from Landsat-5. *Right panel:* Additive effects of surface nitrate concentration (from MODIS SST and known nitrate/SST relationships) on coincident giant kelp forest canopy biomass. Gray regions denote 95 percent confidence intervals in the calculated additive effects. SOURCE: Adapted from Bell et al. (2015).

imagery from the California coast are used to assess the controls on their population density (Bell et al., 2015a). Giant kelp populations are controlled by many processes, including nitrate availability and disturbance from surface waves forcings. Figure 8.6 shows the additive effects for changes in significant wave height (left) and nitrate concentrations (right). This demonstrates detrimental threshold effects on California giant kelp forests for significant wave heights above 3 meters and nitrate concentration below 2 μM. Positive effects are also found for smaller significant wave heights ($H_S \le 2$ m) and nitrate concentrations above 7 μM. Similar threshold detection analyses can be conducted for other ecosystems.

Better estimation of carbon emissions of terrestrial ecosystems from disturbance, particularly fire severity related to thresholds of warming and drying, have the potential to dramatically increase our ability to model combustion of forest biomass as well as soil organic matter, particularly in high-latitude ecosystems. Threshold changes in terrestrial ecosystems are particularly relevant to rapid thawing and degradation of permafrost carbon as the freezing temperature threshold of melting ice is crossed at greater depths (Schuur et al., 2015; Schädel et al., 2016). This issue is exacerbated when fire disturbance combusts insulating soil layers and accelerates the rate of permafrost thaw (Grosse et al., 2011). These issues are addressed in greater detail in a recent National Academy workshop report (NRC, 2014).

Measurement Approaches

The measurement approach for elucidating ecological threshold and cascading effects on carbon storage will require the satellite observation of the stocks and fluxes for the ecosystem of interest as well as indices for processes known to affect the ecosystem. For the kelp forest ecological thresholding example earlier (see Figure 8.6), kelp biomass variations in time and space from Landsat imagery are compared with significant wave height and nitrate concentration estimates based on remote sensing, field observations, and models (see Bell et al., 2015a, for details). In this example, generalized additive models (GAMs; Hastie and Tibshirani, 1990; Wood, 2006) were used to quantify the nonlinear responses of the population density (kelp canopy biomass) to known forcing time series (see Figure 8.6). Many other statistical techniques can be used to assess ecological thresholds. The extension of this approach to other ecosystems is clearly dependent upon the ecosystem to be explored and known processes driving its variability in its components. Key for the elucidation of ecological thresholds from remote sensing observations are extensive data on ecosystem stocks and potentially rates and concurrent forcings on the appropriate time and space scales. The previous sections of this report provided approaches for assessing ecosystem stocks and rates that would useful for this general approach for quantifying ecological thresholds from satellite observations.

Objective E-5b

Objective E-5b. Discover cascading perturbations in ecosystems related to carbon storage.

Motivation

The panel identified discovering cascading perturbations in ecosystems related to carbon storage as an Important priority.

Alterations or perturbations in one component of an ecosystem may have cascading impacts for the entire ecosystem via altering rates of disturbance, trophic interactions, or other ecological processes. Improved understanding of the extent and direction of these relationships is critical for understanding ecosystem changes in a changing climate. This panel focused on the role of cascading perturbations in ecosystems in the context of altering C storage. Three examples of perturbations that can significantly affect carbon storage are wildfire, permafrost thaw, and pine beetle infestations.

Permafrost Thaw, Fire Regimes, and Their Interactions

Fire plays an integral role in shaping the surface properties of ecosystems underlain by permafrost, and a recent shift to larger and more severe fires (Mack et al., 2011; Turetsky et al., 2011) already indicates a shift toward a more intense fire regime in boreal (Kelly et al., 2013) and even in tundra areas (Higuera et al., 2011). The severity of burning modifies soil organic layer depth, with cascading effects on surface energy balance, active layer thickness, surface hydrology, and vegetation succession (Boby et al., 2010; Grosse et al., 2011). The implications of this shift in the fire regime on permafrost thaw are important for quantifying potentially large positive feedbacks to climate warming, but are currently poorly understood or quantified over spatial extents larger than field plots.

A large and growing body of evidence documents how permafrost thaw, and the consequent mobilization of its long-sequestered carbon to the atmosphere, can greatly amplify warming via a positive feedback cycle of albedo changes and thawing (Schuur et al., 2007; Schädel et al., 2016).

Forest diebacks impact climate through decreased evapotranspiration. Maness et al. (2013) showed that pine beetle infestation of British Columbia in an area of 170,000 km^2 led to a warming of 1°C.

As discussed in Objective E-3a, wildfires are also a key influence on other ecosystems and the carbon cycle.

Pine Beetle Infestation

Infestations by pine beetles and other pests lead to large-scale forest diebacks, with subsequent reduction of photosynthesis and enhancement of decomposition. Assessing the impact of insect infestations on carbon storage require inventories of forest biomass and function before and after the dieback.

Measurement Objectives and Approaches for Three Key Ecosystem Perturbations

As discussed earlier, wildfires, permafrost thaw, and pine beetle infestations represent only three examples of cascading perturbations in ecosystems. The measurements and approaches necessary to examine other cascading perturbations may vary. In the following, the panel discusses those that would address our three examples.

Satellite observations of biomass burning involve using MODIS and VIIRS 3.5-4.0 μm data to map the combustion temperature and location of active or smoldering fires. Measurements of vegetation forest structure can be retrieved from spaceborne lidar similar to the GEDI and ICESat-2 missions. Sustained land imaging from Landsat-8, Sentinel-2a, and Sentinel-2b provide 30 m spatial mapping of forests that, when combined with forest vertical structure, enables forest biomass to be determined from space. Identification of community composition and comparisons between the prefire forest composition and density and the postfire observations provides the type and degree of how much the vegetation in question was consumed in the fire.

Sustained measurements are needed to document the influence and implications of fire disturbance on permafrost thaw. Fire disturbance extent, timing, and severity can be readily mapped using optical imagery, but changes in permafrost properties require measurements of surface deformation from repeat lidar and interferometric SAR (e.g., Short et al., 2011; Chen et al., 2012). Sustained measurements are also needed to establish meaningful baselines against which future change can be assessed (Grosse et al., 2016; Jorgenson and Grosse, 2016).

Achieving an inventory of forest biomass and function before and after a pine beetle or other insect infestation can be accomplished by observations of leaf chlorophyll via Normalized Difference Vegetation Index (NDVI), GPP via SIF, and aboveground biomass via lidar.

Objective E-5c

Objective E-5c. Understand ecosystem response to fire events.

Motivation

The panel identified improved understanding of ecosystem response to fire events as an Important priority.

Smoke emissions from wildfires are injected into the atmosphere, acting as air pollutants including gases and aerosols and affecting atmospheric thermodynamics, altering local-to-regional weather and larger-scale climate systems. Fire emissions affect climate systems by producing cloud condensation nuclei (Hobbs et al., 1997) and aerosols that directly and indirectly affect radiative forcing and altering the radiation balance of the land surface (vegetation change, deposition on ice; Randerson et al., 2006). Aerosols can influence the cloud formation, thereby impacting the energy balance and the hydrological cycle. Smoke can also contain limiting nutrients, affecting both land and ocean ecosystems (Schulz et al., 2012).

Fire influences ecosystem health by affecting the biogeochemistry of carbon and nitrogen cycles and thereby affecting nutrient availability and ecosystem productivity. The ability to map and monitor postfire recovery provides important information for proper natural resource management and allows resource managers to make decisions affecting biodiversity, species protection, and overall ecosystem health.

Fire affects atmospheric thermodynamics by impacting flows of carbon and energy in terrestrial, atmospheric, and hydrologic subsystems of the biosphere and thereby influences the global climate system. Specifically, fires contribute to increasing atmospheric carbon, which impacts the climate system. But importantly, fires also substantially impact nutrient cycling and affect carbon uptake by the biosphere and impose constraints on how the carbon cycle responds to variations in climate (Thornton et al., 2007). The incomplete combustion of biomass produces varying forcing agents, including changed surface albedo from black carbon, which can absorb and scatter solar radiation, deposit on snow and ice to change surface albedo, and effects on cloud properties and formulation (Randerson et al., 2006).

As described in Objective E-2c, black carbon is a short-term atmospheric pollutant that results from incomplete combustion of carbonaceous fuels from industrial sources and from open biomass burning. Recent estimates (Bond et al., 2013) have placed black carbon as the second most important anthropogenic climate forcing (+1.1 W/m^2) relative to carbon dioxide forcing (1.83 W/m^2). However, the influence of black carbon on the climate is complex, as it has a direct effect on atmospheric warming due to absorption of shortwave radiation and an indirect influence such as change in surface albedo of snow and ice in polar regions (AMAP, 2011).

Measurement Objectives

Sustained satellite observations of fire activity including characterizations of fire occurrence, fire area, fire temperature, and fire radiative power (FRP) are required to assess global impacts of wildfires.

Forest Recovery

Vegetation composition can be characterized by vegetation functional types as measured by assemblages of species by structure, physiology, and phenology that characterize ecosystem response to environmental conditions or disturbance severity. New technologies provide continuous characterization of optical classes that inform functional type classifications and map functional diversity, which can be linked to biodiversity within ecosystems. Vegetation structure requires observations of mean and variation of canopy height, canopy base height, stem density, stem volume, basal area, and fractional canopy cover.

Canopy Carbon and Nitrogen Composition

Mapping canopy chemical composition characterizes the vegetation. Additionally, mapping canopy fuel load using aboveground biomass and leaf area index is essential for refining estimates of fire carbon fluxes and pre- and postfire carbon and nitrogen stocks.

Ecosystem condition can be characterized by the following:

1. Discrimination between live, senescent/scorched, and charred vegetation, which can inform the health of the ecosystem and provide information on burn fraction.
2. Measurement of vegetation stress, which is a critical observation for understanding how flammable an ecosystem is, including observations of precipitation, temperature, relative humidity, wind speed and direction, soil moisture, soil temperature, and vegetation water content or equivalent water thickness.
3. Measurement of ecosystem flux affecting fuel accumulation and mapping postfire regeneration. For this, observations are needed of gross primary productivity, which can be derived from fraction of photosynthetic active radiation, leaf area index, vegetation photosynthetic capacity, and solar-induced fluorescence.

Measurement Approaches

Reliable detection of wild and prescribed fires and associated fuel loads requires measurements across three platforms: (1) thermal infrared radiometer (TIR); (2) a visible-shortwave-infrared imaging spectrometer; and (3) an active sensor to detect 3D vegetation structure.

Fire detections and land surface temperature need sustained global TIR radiometric retrievals at ≤375 m pixel resolution at nadir ± 60 degrees, with subdaily observations with at least nine bands at ~8.3 μm, ~8.6 μm, ~9.1 μm, ~11 μm, ~12 μm to distinguish land surface temperature from emissivity, ~4 μm with ≥400 K saturation and sufficient thermal range for fire detections, and two bands (~1.6 μm and ~2.2 μm) to have sufficient sensitivity at the lower temperatures for cloud detection, geolocation, and flagging false positives (Schroeder et al., 2014).

Vegetation functional types, gross primary productivity, and fire severity need continued coverage through recovery from imaging spectrometer data. A VSWIR imaging spectrometer is needed with continuous spectral range 0.4-2.5 μm at ≤10 nm spectral sampling, ≤30 m pixel resolution, ≤16-day observation repeat, a 185 km swath, and high signal-to-noise and global coverage. This provides Landsat spatial resolution hyperspectral observations using spectral-response functions; canopy chemical composition and equivalent water thickness; and live, senescent or scorched, and charred vegetation characterization.

Vegetative structure and aboveground biomass can be observed using full waveform or discrete return lidar and single-band microwave synthetic aperture radar (SAR; Lefsky et al., 2002; Neuenschwander et al., 2006). Use of full waveform lidar can improve penetration of dense vegetation structure for improved characterization. Lidar can also be used to obtain vertical profiles of atmospheric plumes containing black carbon (e.g., the CALIPSO satellite). SAR has the advantage of penetrating cloud cover and providing measurement of soil moisture and vegetation water content, which are important factors in fire intensity.

Consistent TIR measurements are required across missions or through continued existence of these missions. It is assumed that measurements from MODIS and VIIRS will continue through the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) and JPSS programs. To advance beyond current status requires a new global mapping mission that ideally increases the saturation temperature while providing subdaily <375 m pixel resolution. Requirements for a VSWIR imaging spectrometer have a strong legacy of previous investments in response to the 2007 NRC Decadal Survey (NRC, 2007) and the 2014 NRC sustainable land imaging report (NRC, 2014).

Many existing satellites have proven the feasibility and affordability for collecting measurements characterizing Earth's surface from active sensors (both lidar and SAR). But more research is needed for development of better algorithms that extract needed information and bridge observations across satellite platforms.

To characterize black carbon emissions and track transport to remote locations, a vertical lidar is needed similar in concept to the CALIOP instrument. CALIOP successfully demonstrated the utility and feasibility of these measurements from space.

Connections to Other Panels

This objective has many connections to several other panels. It especially relates to extreme events affecting water, weather, and the solid Earth (e.g., Questions C-7, C-8, H-4, W-4, S-1, and S-2).

Connections to the Hydrology Panel include their objective to quantify the magnitude of anthropogenic causes (e.g., forest management, black carbon, and infrastructure) that affect snowmelt and icemelt (Questions H-1 and H-4). Question E-5 also relates to the Hydrology Panel's objectives to understand linkages between anthropogenic modification of the land, including fire suppression, land use, and urbanization on frequency of and response to hazards (Questions H-2 and H-4).

Connections to other panels include synergies with the Climate Panel's objectives for quantifying variations in the global carbon cycle and associated climate and ecosystem impacts in the context of past and projected anthropogenic carbon emissions, and assessing uncertainty in total climate forcing that arises from aerosol changes and their interactions with clouds (Questions C-2, C-3, and C-5). An example is the Climate Panel's Question C-5, which asks how changes in aerosols affect Earth's radiation budget and how to better quantify the magnitude and variability of emissions of natural aerosols. Connections to the Hydrology Panel include their objective (H-2b) to quantify the magnitude of anthropogenic activities (e.g., forest management, black carbon, and infrastructure) that affect snowmelt and icemelt, atmospheric radiation, and temperature changes, thereby altering downstream distribution of water quantity and quality. Another connection to the Hydrology Panel is their Objective H-4d, which seeks to understand linkages between anthropogenic modification of the land, including fire suppression, land use, and urbanization on frequency of and response to hazards.

RESULTING SOCIETAL BENEFIT

The resulting societal benefits of achieving the stated objectives cover a broad range of both direct and indirect benefits. The direct benefits include more precise and comparable measurements of the structure, composition, and dynamics of terrestrial and marine biomass (Objectives E-1a, E-1b, and E-1c) as well as the fluxes and flows of carbon and energy between ecosystems and the atmosphere (Objectives E-2a and E-3a). These direct observations provide evidence-based decision support to inform a wide array of economically important applications concerning the sustainable management of terrestrial landscapes, coastal environments, and open-ocean ecosystems. For example, these observations provide the detailed time series required to monitor the health and productivity of both managed and natural vegetated landscapes as well as highly dynamic coastal and ocean biological processes. Specific data products will inform a wide range of critical resource management sectors including forestry, agriculture, water management, public health, fisheries, disaster relief, and conservation management.

For example, the same satellite observations identified for measuring land GPP have direct use in accurately estimating global agricultural production and are used to provide monthly reports that remove uncertainty in global agricultural markets (USDA, 2017) and provide the satellite data used by GEO GLAM. The same satellite observations that enable land GPP measurements are also used to predict extensive outbreaks of mosquito-borne diseases of dengue, Rift Valley fever, Murray Valley encephalitis, and West Nile virus (Anyamba et al., 2014). Landsat data that have been widely used to document forest disturbance and recovery at the 30 m scale globally for carbon cycle research have also been used to manage forest resources for countries at the national level (Hansen et al., 2013). In addition to direct resource management, data products and information derived from these objectives will inform critical national and international efforts to better manage GHG emissions and carbon sequestration.

Earth observations data products and synthesis information derived from meeting the stated objectives will also support a number of national and international agreements and objectives. These include international agreements on sustainable use of the oceans, trade in endangered species, economic and trade agreements related to timber and agriculture, reducing emissions from deforestation and forest degradation, and the UN Sustainable Development Goals. Observations here will also support national laws and polices such as the Soil and Water Conservation Act (SWCA), the National Environmental Policy Act (NEPA), the Clean Water Act (CWA), the Safe Resource Conservation and Recovery Act (RCRA), the Comprehensive Environmental Response, Compensation, and Liability Act/Superfund Amendments and Reauthorization Act (CERCLA/SARA), the Endangered Species Act (ESA), the Marine Mammal Protection Act (MMPA), the Magnuson-Stevens Fishery Conservation and Management Act, and a variety of other standing societal mandates.

Here, the panel provides some specific examples of societal benefits from land and ocean ecosystem observations.

United Nations Sustainable Development Goals

These observations support at least three important international sustainable development goals. First, United Nations Sustainable Development Goal (SDG) 14 focuses on conservation and sustainable use of the oceans, seas, and marine resources, specifically economic utilization of natural resources of marine systems using evidence-based and data-rich management approaches. Second, SDG 15.2 focuses on sustainable management of forests, including reducing deforestation and increasing afforestation and reforestation throughout the world. Third, SDG 15.3 seeks to combat desertification and reverse land degradation. The ocean and terrestrial ecosystem characterization and monitoring objectives (Objectives E-1a, E-1b, E-1c, E-1e, E-3a, and E-5c) of this effort will specifically inform these stated international development goals.

Emerging International Coordination Mechanisms for Earth Observations

As Earth observing systems proliferate internationally, and many new countries begin to contribute their space assets and observations to a growing global pool of measurements, the international community is responding through increased coordination of programs, with a high priority on societal benefits of the combined observing systems. The ecosystem observations defined here are critical contributions.

The Group on Earth Observing Biodiversity Observing Networks (GEO-BON) in collaboration with other initiatives are prioritizing the development of Essential Biodiversity Variables (EBVs) to provide measurement and monitoring of ecological condition and ecosystem services to inform international agreements and protocols, such as the Convention on Biological Diversity (CBD), the Convention on Migratory Species (CMS), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). The CBD uses remote sensing products to evaluate the distribution and status of habitats, and the CMS uses remote sensing data to evaluate the connectivity of habitats and populations for migratory species. Both of these conventions interact directly with the United Nations Environment Program (UNEP) on endangered wildlife species as well as the International Union for Conservation of Nature (IUCN) "red list" listing of endangered species and illegal wildlife trade.

Similarly, the Global Ocean Observing System (GOOS) has developed complementary Essential Ocean Variables (EOVs) for Biology and Ecosystems that include phytoplankton biomass and diversity, live coral, macroalgal canopy, and seagrass cover, all of which specify remote sensing as a critical tool, while the GOOS Biogeochemistry Panel has defined an Ocean Color EOV. This panel's stated objectives closely support these established initiatives. The Global Observations of Forest Initiative is an international attempt to coordinate observing systems and measurements for forest status, health, and carbon stocks. The GEO GLAM initiative is addressing global land and agriculture monitoring systems. The ecosystem measurements found in all of the science objectives here will provide significant contributions from NASA and the United States to the international collection of observations. The ocean and terrestrial ecosystem characterization and monitoring objectives (Objectives E-1a, E-1b, E-1c, and E-1e) of this effort will specifically inform these stated international development goals.

National Forest Monitoring Systems for Sustainable Forest Management and GHG Inventory

For many developing countries, conversion and degradation of forests is the most significant source of greenhouse gases (GHGs), often in far greater amounts than from industrial sources. International estimates of GHG emissions from many developing countries reflect a clear picture of socioeconomic circumstances: economies dependent on agriculture and natural resources, with small and underdeveloped energy and industrial sectors. Recent reports document large current emissions as well as project large future emissions from forest conversion and degradation. Taking action to reduce these emissions is a fundamental aim of international climate change mitigation programs.

This international mitigation initiative, commonly termed REDD+ (reduce emissions from deforestation and forest degradation), is a policy process that incentivizes reductions in emissions from forested lands and encourages investments in low-carbon, sustainable development, particularly in developing countries. It does so by assigning financial value to carbon stored in forests. REDD+ goes beyond deforestation and forest degradation, and includes the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks. Outside the diplomatic policy process associated with the conventions, other multilateral REDD+ initiatives are being implemented to provide private capital and large financial investments in low-carbon forest management. These initiatives include the Forest Carbon Partnership Facility (FCPF), hosted by the World Bank, and the Forest Investment Program (FIP), implemented by various multilateral development banks, including the African Development Bank. There are different types of potential arrangements for achieving REDD+ results: private-private, public-private, nongovernmental organization (NGO)-public, as programs with subnational jurisdictions, or as federal government policy.

Each of these domains has significant technical requirements for measurement and monitoring of forests that would immediately benefit from Objectives E-1a, E-1b, E-1e, and E-3a. The international conventions advise countries that are implementing REDD+ activities to follow specific methodologies for estimating GHG emissions and removals developed by the International Panel on Climate Change (IPCC). These methodologies require a system for estimating forest GHG stocks and fluxes, using a national forest monitoring and measurement system (NFMS). Thus, all countries participating in REDD+ actions and programs need to have a basic level of "readiness" for implementing a NFMS to produce the data needed for REDD+ measurement, reporting, and verification (MRV) focused on carbon accounting.

In most countries with deforestation-related GHG emissions, and where forestland is an important national resource, increasing technical capacity to monitor and measure forest status and condition through a NFMS will have both climate *and* economic benefits. The services that forest and woodlands provide to these countries are numerous—including food, water, and fuel. However, these ecosystems are decreasing at rapidly increasing rates owing to unsustainable use of fuel wood and charcoal, poor agricultural practices, limited economic choices, and high population growth. Earth Observations will contribute to building capacities for REDD+ MRV. REDD+ offers a holistic framework for supporting sustainable land management by integrating policy and resource governance in the rural landscape with the development of analytical capacities and economic incentives.

Sustainable forest management and GHG emission reductions actions require countries to develop national platforms for measuring, reporting, and verifying GHG emissions and removals on a regular basis. For the most part, this requires that countries have the technical capacity to systematically measure a set of factors related to (1) changes in the extent and condition of forest cover; (2) carbon stocks in forests of various stature and condition, and changes over time in those stocks; and (3) emissions or removals of GHGs associated with changes in forest cover and changes in carbon stocks.

Precision Agriculture

Satellite data such as Landsat 30 m and comparable foreign satellite imagery have been used to evaluate agricultural fields impacted by weeds, excessive moisture, low soil pH, or an imbalance of plant nutrients (Johannsen and Daughtry, 2009; see Figure 8.7). Recently, commercial multispectral imagery from Ikonos, World View, GeoEye, QuickBird, and other satellites at a 1 m to 4 m spatial resolution has been available to farmers for the management of high-value crops such as vineyards, fruit orchards, and vegetables, although the cost of obtaining these data has been prohibitive for widespread use.

The recent development and use of small imagers on Unmanned Aerial Vehicles and on tractors, both linked to global positioning systems, provides an alternative platform with greater flexibility for digital image data collection with improved spatial resolution, very frequent data collection, and a significantly lower cost. The within-field collection of remotely sensed multispectral imagery has enabled what is now known as "precision agriculture." These precision technologies developed for agriculture include accurate identification of within-field fertilizer application rates, "smart irrigation systems" that work along with remotely sensed images to maximize water use efficiency based on plant needs, evaporation rates, soil texture, and soil structure. These systems minimize irrigation frequency and avoid unnecessary fertilizer application expenses while increasing yield and improving crop product quality.

While commercial remote sensing companies have provided these services in the past to farmers, precision farming now permits farmers to perform more timely operations related to better soil management such as tillage, plan more accurate crop-protection programs, adjust seeding rates, and map the yield variability commonly caused by soil and nutrient differences within fields. Farmers can now implement variable-rate nutrient fertility plans, including applying nitrogen when planting crops and applying nitro-

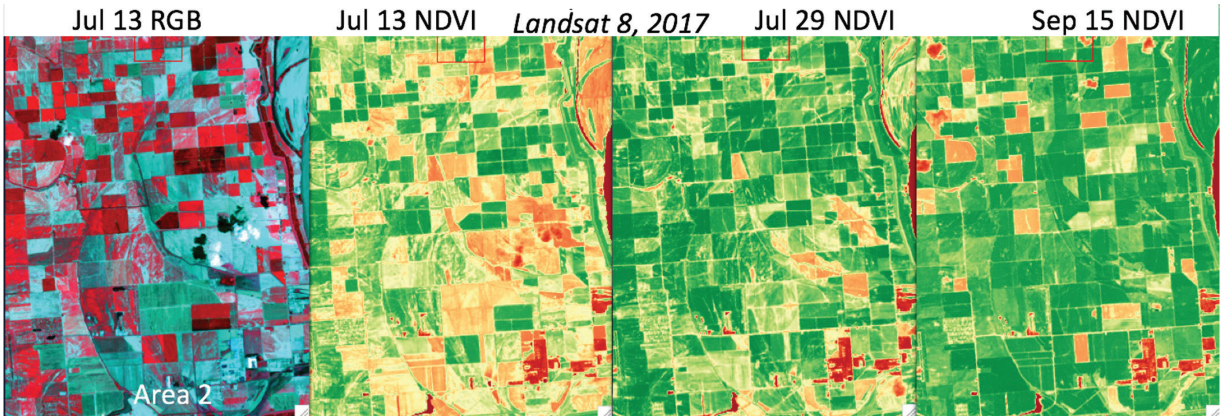

FIGURE 8.7 Landsat-8 Operational Land Imager (OLI) images of central Arkansas from July 13, July 29, and September 15, 2017. These images show the 30 m multispectral monitoring potential of Landsat-8, where individual fields can be discriminated and crop type determined from multitemporal acquisitions during the growing season. SOURCE: Landsat-8 Project Office, NASA Goddard Space Flight Center.

gen during cultivation only when needed. This translates into a greater net return per acre and improved management of seeding rates, specific application of fertilizers, and specific applications of agricultural chemicals. This also leads to improving soils, reducing the loss of topsoil, and minimizing water quality threats. This potential depends on the farmer's management skill and frequently on the services of a knowledgeable crop consultant. Precision agriculture's use of multispectral remote sensing coupled with accurate GPS location information involves the 4Rs—right product, right rate, right time, and right place (Johannsen et al., 1997).

Another benefit of precision agriculture is that remotely sensed data can be analyzed and geocoded and merged with soil maps, to establish a digital record of field operation by year. This can be used to guide further field operations in future years and establishes a permanent farm record. For example, this means that remotely sensed data would complement the yield data collected by the farmer's harvesting equipment and identify specific locations of yield variations within a crop field for diagnostic postharvest analysis (Johannsen and Carter, 2002).

Commercial remote sensing companies have also used weekly images to map the acreage of agricultural crops and monitor their conditions throughout the growing season. The images and interpretations provide farmers with a better bargaining position when selling their crops, since they have knowledge of their crops' progress as well as how their competitor's crops are doing.

In addition to the tractor-mounted imagers and imagers on UAVs, Planet, a commercial company, is moving forward with daily 5 m global visible and near-infrared data (Planet Team, 2017). This is a good example of work begun by the U.S. government with the Landsat series of satellites, where applications of satellite technology led to demonstrating the potential of remote sensing in agriculture. Developments in smaller satellites like Planet's CubeSats, the development of UAVs with imagers, and the development of imagers on tractor, all linked to GPS systems, will advance precision agriculture while sustaining our agricultural lands.

Over 60 percent of the farmers in the United States are now using forms of precision agriculture. New observations proposed in this chapter—specifically, hyperspectral and multitemporal multispectral—could begin layering plant physiological and process-level information on agricultural maps as well (Johannsen and Carter, 2004).

Ocean and Marine Health Monitoring

There are many societal benefits of ocean color remote sensing that are fairly well established, having been developed and expanded upon over three decades of practice. Increasing economic costs are associated with unhealthy marine systems, and improvements in management depend on improved monitoring. Advancements in technologies and science applications (Objectives E-1b and E-1c) should enhance the benefits that already exist, as well as lead to novel ones, as in the following examples:

- Creation of cost-effective ecological indicators, which can be applied to ecosystem-based management and characterization of change due to natural and anthropogenic perturbations or disturbances;
- Monitoring of the onset, expansion, and fate of harmful algal blooms, aiding the tourism and aquaculture industries;
- Monitoring of coastal water quality as a tool in coastal zone management;
- Delineation of marine protected areas and identification of habitats for threatened/endangered species;
- Sustainable management of fisheries and more cost effective harvesting;
- Measurement of phytoplankton photosynthesis, which is essential information for ocean ecosystem models, as well as for understanding the role of the ocean in climate change and global carbon cycles;
- Creation of outstanding material for education at all levels, both in formal classroom environments and in informal education, developing public awareness of ocean processes; and
- International governance on the high seas.

The coastal zone, especially shallow waters <30 m depth, represent a very small proportion of the global ocean area, yet coastal ecosystems are among the most productive in the world. Importantly, about 40 percent of the world's human population lives within 100 km of the coast (United Nations, 2007). The social and economic well-being of people living in these regions is inextricably linked with the surrounding coastal ecosystem. Information about this ecosystem provided by high spatial and high spectral resolution remote sensing (Objective E1-a) stands to be of great societal benefit, as follows:

- Creation of new baseline global maps of wetland distribution, type, and composition, leading to better understanding of change in wetlands ecosystem goods and services;
- Creation of critical ecology and resource inventories for coral reefs, seagrasses, kelp, and other submerged aquatic systems;
- Identification and delineation of coastal fisheries habitats, with applications to management and enforcement;
- Measuring and monitoring of changes in biodiversity;
- Improved coastline mapping and tracking of shoreline changes; and
- Creation of outstanding material for education at all levels, both in formal classroom environments and in informal education, developing public awareness of ocean processes.

REFERENCES

Abatzoglou, J.T., and A.P. Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* 113:11770-11775.

Anav, A., P. Friedlingstein, C. Beer, P. Ciais, A. Harper, C. Jones, G. Murray-Tortarolo, D. Papale, N.C. Parazoo, and P. Peylin. 2015. Spatiotemporal patterns of terrestrial gross primary production: A review. *Reviews of Geophysics* 53:785-818.

Anderegg, W.R.L., J.A. Hicke, R.A. Fisher, C.D. Allen, J. Aukema, B. Bentz, S. Hood, et al. 2015. Tree mortality from drought, insects, and their interactions in a changing climate. *New Phytologist* 208:674-683.

Anderson, M.C., W.P. Kustas, J.M. Norman, C.R. Hain, J.R. Mecikalski, L. Schultz, M.P. González-Dugo, C. Cammalleri, G. D'urso, A. Pimstein, and F. Gao. 2011. Mapping daily evapotranspiration at field to continental scales using geostationary and polar orbiting satellite imagery. *Hydrology and Earth System Sciences* 15:223-239.

Anderson, M.C., R.G. Allen, A. Morse, and W.P. Kustas. 2012. Use of Landsat thermal imagery in monitoring evapotranspiration and managing water resources. *Remote Sensing of Environment* 122:50-65.

Anyamba, A., J.L. Small, S.C. Britch, C.J. Tucker, E.W. Pak, C.A. Reynolds, J. Crutchfield, and K.J. Linthicum. 2014. Recent weather extremes and impacts on agricultural production and vector-borne disease outbreak patterns. *PLoS One* 9:e92538.

AMAP (Arctic Monitoring and Assessment Programme). 2011. *The Impact of Black Carbon on Arctic Climate (2011)*. Oslo, Norway.

Arneth, A., S. Sitch, J. Pongratz, B. Stocker, P. Ciais, B. Poulter, A. Bayer, A. Bondeau, L. Calle, and L. Chini. 2017. Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed. *Nature Geoscience* 10:79-84.

Arnone, R., R. Vandermeulen, S. Ladner, M. Ondrusek, C. Kovach, H. Yang, and J. Salisbury, 2016. Diurnal changes in ocean color in coastal waters. *Ocean Sensing and Monitoring VIII* 9827:982711.

Arora, V.K., G.J. Boer, P. Friedlingstein, M. Eby, C.D. Jones, J.R. Christian, G. Bonan, L. Bopp, V. Brovkin, and P. Cadule. 2013. Carbon-concentration and carbon-climate feedbacks in CMIP5 Earth system models. *Journal of Climate* 26:5289-5314.

Asner, G.P., D.E. Knapp, C.B. Anderson, R.E. Martin, and N. Vaughn. 2016a. Large-scale climatic and geophysical controls on the leaf economics spectrum. *Proceedings of the National Academy of Sciences* 113:E4043-E4051.

Asner, G.P., D.E. Knapp, T. Kennedy-Bowdoin, M.O. Jones, R.E. Martin, J. Boardman, and R.F. Hughes. 2008. Invasive species detection in Hawaiian rainforests using airborne imaging spectroscopy and LiDAR. *Remote Sensing of Environment* 112:1942-1955.

Asner, G.P., P.G. Brodrick, C.B. Anderson, N. Vaughn, D.E. Knapp, and R.E. Martin. 2016b. Progressive forest canopy water loss during the 2012-2015 California drought. *Proceedings of the National Academy of Sciences* 113:E249-E255.

Asner, G.P., and R.E. Martin. 2016. Spectranomics: Emerging science and conservation opportunities at the interface of biodiversity and remote sensing. *Global Ecology and Conservation* 8:212-219.

Asner, G.P., R.E. Martin, D.E. Knapp, R. Tupayachi, C.B. Anderson, F. Sinca, N.R. Vaughn, and W. Llactayo. 2017. Airborne laser-guided imaging spectroscopy to map forest trait diversity and guide conservation. *Science* 355:385-389.

Asner, G.P., R.E. Martin, R. Tupayachi, R. Emerson, P. Martinez, F. Sinca, G.V.N. Powell, S.J. Wright, and A.E. Lugo. 2011. Taxonomy and remote sensing of leaf mass per area (LMA) in humid tropical forests. *Ecological Applications* 21:85-98.

Asner, G.P., R.E. Martin, R. Tupayachi, C.B. Anderson, F. Sinca, L. Carranza-Jiménez, and P. Martinez. 2014. Amazonian functional diversity from forest canopy chemical assembly. *Proceedings of the National Academy of Sciences* 111:5604-5609.

Atzberger, C. 2013. Advances in remote sensing of agriculture: Context description, existing operational monitoring systems and major information needs. *Remote Sensing* 5:949-981.

Baccini, A., S.J. Goetz, W.S. Walker, N.T. Laporte, M. Sun, D. Sulla-Menashe, J. Hackler, P.S.A. Beck, R. Dubayah, M.A. Friedl, S. Samanta, and R.A. Houghton. 2012. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change* 2:182-185.

Badgley, G., C.B. Field, and J.A. Berry. 2017. Canopy near-infrared reflectance and terrestrial photosynthesis. *Science Advances* 3:e1602244.

Baldeck, C.A., G.P. Asner, R.E. Martin, C.B. Anderson, D.E. Knapp, J.R. Kellner, and S.J. Wright. 2015. Operational tree species mapping in a diverse tropical forest with airborne imaging spectroscopy. *PLoS One* 10:e0118403.

Ballantyne, A., W. Smith, W. Anderegg, P. Kauppi, J. Sarmiento, P. Tans, E. Shevliakova, Y. Pan, B. Poulter, and A. Anav. 2017. Accelerating net terrestrial carbon uptake during the warming hiatus due to reduced respiration. *Nature Climate Change* 7:148-152.

Barthlott, W., W. Lauer, and A. Placke. 1996. Global distribution of species diversity in vascular plants: Towards a world map of phytodiversity (Globale Verteilung der Artenvielfalt Höherer Pflanzen: Vorarbeiten zu einer Weltkarte der Phytodiversität). *Erdkunde* 50:317-327.

Bastos, A., S.W. Running, C. Gouveia, and R.M. Trigo. 2013. The global NPP dependence on ENSO: La Nina and the extraordinary year of 2011. *Journal Geophysical Research: Biogeosciences* 118:1247-1255.

Basu, S., S. Guerlet, A. Butz, S. Houweling, O. Hasekamp, I. Aben, P. Krummel, P. Steele, R. Langenfelds, and M. Torn. 2013. Global CO_2 fluxes estimated from GOSAT retrievals of total column CO_2. *Atmospheric Chemistry and Physics* 13:8695-8717.

Beer, C., M. Reichstein, E. Tomelleri, P. Ciais, M. Jung, N. Carvalhais, C. Rödenbeck, M.A. Arain, D. Baldocchi, and G.B. Bonan. 2010. Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate. *Science* 329:834-838.

Behrenfeld, M.J., and P.G. Falkowski. 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. *Limnology and Oceanography* 42:1-20.

Behrenfeld, M.J., E. Boss, D.A. Siegel, and D.M. Shea. 2005. Carbon‐based ocean productivity and phytoplankton physiology from space. *Global Biogeochemical Cycles* 19.

Behrenfeld, M.J., R.T. O'Malley, D.A. Siegel, C.R. Mcclain, J.L. Sarmiento, G.C. Feldman, A.J. Milligan, P.G. Falkowski, R.M. Letelier, and E.S. Boss. 2006. Climate-driven trends in contemporary ocean productivity. *Nature* 444:752-755.

Behrenfeld, M.J., T.K. Westberry, E.S. Boss, R.T. O'Malley, D.A. Siegel, J.D. Wiggert, B. Franz, C. McClain, G. Feldman, and S.C. Doney. 2009. Satellite-detected fluorescence reveals global physiology of ocean phytoplankton. *Biogeosciences* 6:779-794.

Behrenfeld, M.J., S.C. Doney, I. Lima, E.S. Boss, and D.A. Siegel. 2013. Annual cycles of ecological disturbance and recovery underlying the subarctic Atlantic spring plankton bloom. *Global Biogeochemical Cycles* 27:526-540.

Behrenfeld, M.J., Y. Hu, C.A. Hostetler, G. Dall'Olmo, S.D. Rodier, J.W. Hair, and C.R. Trepte. 2013. Spaceﾐbased lidar measurements of global ocean carbon stocks. *Geophysical Research Letters* 40:4355-4360.

Behrenfeld, M.J., Y. Hu, R.T. O'Malley, E.S. Boss, C.A. Hostetler, D.A. Siegel, J.L. Sarmiento, J. Schulien, J.W. Hair, X. Lu, S. Rodier and A.J. Scarino. 2017. Annual boom-bust cycles of polar phytoplankton biomass revealed by space-based lidar. *Nature Geoscience* 10:118-122.

Bell, T.W., K.C. Cavanaugh, D.C. Reed, and D.A. Siegel. 2015a. Geographical variability in the controls of giant kelp biomass dynamics. *Journal of Biogeography* 42:2010-2021.

Bell, T.W., K.C. Cavanaugh, and D.A. Siegel, 2015b. Remote monitoring of giant kelp biomass and physiological condition: An evaluation of the potential for the Hyperspectral Infrared Imager (HyspIRI) mission. *Remote Sensing of the Environment* 167:218-228.

Ben-Dor, E., S. Chabrillat, J.A.M. Demattê, G.R. Taylor, J. Hill, M.L. Whiting, and S. Sommer. 2008. Using imaging spectroscopy to study soil properties. *Remote Sensing of Environment* 113:S38-S55.

Ben-Dor, E. and J. Demattê. 2016. Remote Sensing of Soil in the Optical Domains. In *Land Resources Monitoring, Modeling, and Mapping with Remote Sensing* (Prasad S. Thenkabail, ed.). Boca Raton, FL: CRC Press.

Bergen, K., S. Buckley, C. Dobson, A. Donnellan, R. Dubayah, Y. Fialko, E. Fielding, et al. (DESDynI Writing Committee). 2007. Report of the July 17-19, Orlando, Florida Workshop to Assess the National Research Council Decadal Survey Recommendation for the DESDynI Radar/Lidar Space Mission. https://cce.nasa.gov/pdfs/Volz2_DESDynI.pdf.

Bergen, K.M., S.J. Goetz, R.O. Dubayah, G.M. Henebry, C.T. Hunsaker, M.L. Imhoff, R.F. Nelson, G.G. Parker, and V.C. Radeloff. 2009. Remote sensing of vegetation 3-D structure for biodiversity and habitat: Review and implications for lidar and radar spaceborne missions. *Journal of Geophysical Research: Biogeosciences* 114.

Boby, L.A., E.A.G. Schuur, M.C. Mack, D. Verbyla, and J.F. Johnstone. 2010. Quantifying fire severity, carbon, and nitrogen emissions in Alaska's boreal forest. *Ecological Applications* 20:1633-1647.

Bolten, J.D., and W.T. Crow. 2012. Improved prediction of quasi-global vegetation conditions using remotely-sensed surface soil moisture. *Geophysical Research Letters* 39.

Bond, T.C., S.J. Doherty, D. Fahey, P. Forster, T. Berntsen, B. Deangelo, M. Flanner, S. Ghan, B. Kärcher, and D. Koch. 2013. Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres* 118:5380-5552.

Bond-Lamberty, B., and A. Thomson. 2010. Temperature-associated increases in the global soil respiration record. *Nature* 464:579.

Bopp, L., C. Le Quéré, M. Heimann, A.C. Manning, and P. Monfray. 2002. Climateﾐinduced oceanic oxygen fluxes: Implications for the contemporary carbon budget. *Global Biogeochemical Cycles* 16.

Botha, E.J., V.E. Brando, J.M. Anstee, A.G. Dekker, and S. Sagar. 2013. Increased spectral resolution enhances coral detection under varying water conditions. *Remote sensing of environment* 131:247-261.

Brezonik, P.L., L.G. Olmanson, J.C. Finlay, and M.E. Bauer. 2015. Factors affecting the measurement of CDOM by remote sensing of optically complex inland waters. *Remote Sensing of Environment* 157:199-215.

Bruneau, D., J. Pelon, F. Blouzon, J. Spatazza, P. Genau, G. Buchholtz, N. Amarouche, A. Abchiche, and O. Aouji. 2015. 355-nm high spectral resolution airborne lidar LNG: System description and first results. *Applied Optics* 54:8776-8785.

Burton, S.P. 2015. Observations of the spectral dependence of particle depolarization ratio of aerosols using NASA Langley airborne High Spectral Resolution Lidar. *Atmospheric Chemistry and Physics Discussions* 15:24751.

Cardinale, B.J., J.E. Duffy, A. Gonzalez, D.U. Hooper, C. Perrings, P. Venail, A. Narwani, et al. 2012. Biodiversity loss and its impact on humanity. *Nature* 486:59-67.

Carr, M.E., M.A. Friedrichs, M. Schmeltz, M.N. Aita, D. Antoine, K.R. Arrigo, I. Asanuma, O. Aumont, R. Barber, and M. Behrenfeld. 2006. A comparison of global estimates of marine primary production from ocean color. *Deep Sea Research Part II: Topical Studies in Oceanography* 53:741-770.

Carter, P.G., C.J. Johannsen, and B.A. Engel. 2008. Recognizing patterns within cropland vegetation: A crop anomaly classification system. *Journal of Terrestrial Observation* 1:38-49.

Cavender-Bares, J., J.E. Meireles, J.J. Couture, M.A. Kaproth, C.C. Kingdon, A. Singh, S.P. Serbin, A. Center, E. Zuniga, and G. Pilz. 2016. Associations of leaf spectra with genetic and phylogenetic variation in oaks: Prospects for remote detection of biodiversity. *Remote Sensing* 8:221.

Chappell, A., J. Baldock, and J. Sanderman. 2015. The global significance of omitting soil erosion from soil organic carbon cycling schemes. *Nature Climate Change* 6:187-191.

Chavez, F.P., M. Messié, and J.T. Pennington. 2011. Marine primary production in relation to climate variability and change. *Annual Review of Marine Science* 3:227-260.

Chen, F., H. Lin, Z. Li, Q. Chen, and J. Zhou. 2012. Interaction between permafrost and infrastructure detected via joint analysis of C- and L-band small baseline SAR interferometry. *Remote Sensing of Environment* 123:532-540.

Cheng, T., B. Rivard, A. Sánchez-Azofeifa, J.B. Feret, S. Jacquemoud, and S.L. Ustin. 2014. Deriving leaf mass per area (LMA) from foliar reflectance across a variety of plant species using continuous wavelet analysis. *ISPRS Journal of Photogrammetry and Remote Sensing* 87:28-38.

Chevallier, F., P.I. Palmer, L. Feng, H. Boesch, C.W. O'Dell, and P. Bousquet. 2014. Toward robust and consistent regional CO_2 flux estimates from in situ and spaceborne measurements of atmospheric CO_2. *Geophysical Research Letters* 41:1065-1070.

Christian, B., N. Joshi, M. Saini, N. Mehta, S. Goroshi, R.R. Nidamanuri, P. Thenkabail, A.R. Desai, and N.S.R. Krishnayya. 2015. Seasonal variations in phenology and productivity of a tropical dry deciduous forest from MODIS and Hyperion. *Agricultural and Forest Meteorology* 214:91-105.

Churnside, J.H. 2014. Review of profiling oceanographic lidar. *Optical Engineering* 53.

Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, et al. 2014. Carbon and Other Biogeochemical Cycles. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (T.F. Stocker et al.). Cambridge and New York: Cambridge University Press.

Clark, R.N. 1999. Spectroscopy of Rocks and Minerals and Principles of Spectroscopy. Chapter 1, pp. 3-58 in *Manual of Remote Sensing* (A.N. Rencz, ed.). New York: Wiley and Sons. http://speclab.cr.usgs.gov.

Clevers, J.G.P.W., and L. Kooistra. 2011. Using hyperspectral remote sensing data for retrieving canopy chlorophyll and nitrogen content. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 5:574-583.

Cole, J.J., Y.T. Prairie, N.F. Caraco, W.H. Mcdowell, L.J. Tranvik, R.G. Striegl, C.M. Duarte, P. Kortelainen, J.A. Downing, and J.J. Middelburg. 2007. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems* 10:172-185.

CEOS (Committee on Earth Observation Satellites). 2014. Strategy for Carbon Observations from Space. The Committee on Earth Observation Satellites (CEOS) Response to the Group on Earth Observations (GEO) Carbon Strategy. April. Issued September 30, 2014. http://ceos.org/home-2/the-ceos-carbon-strategy-space-satellites/.

Conti, L., and M. Scardi. 2010. Fisheries yield and primary productivity in large marine ecosystems. *Marine Ecology Progress Series* 410:233-244.

Corson, M.R., and C.O. Davis. 2011. A new view of coastal oceans from the space station. *Eos, Transactions American Geophysical Union* 92:161-162.

Crow, W.T., W.P. Kustas, and J.H. Prueger. 2008. Monitoring root-zone soil moisture through the assimilation of a thermal remote sensing-based soil moisture proxy into a water balance model. *Remote Sensing of Environment* 112:1268-1281.

Currie, D.J. 1991. Energy and large-scale patterns of animal-and plant-species richness. *The American Naturalist* 137:27-49.

Darmenov, A.S., and A. Da Silva. 2015. *The Quick Fire Emissions Dataset (QFED): Documentation of Versions 2.1, 2.2 and 2.4* (R.D. Koster, ed.). NASA Technical Report Series on Global Modeling and Data Assimilation, Volume 38. NASA TM-2015-104606. http://gmao.gsfc.nasa.gov/pubs/docs/Darmenov796.pdf.

Davies, A.B., and G.P. Asner. 2014. Advances in animal ecology from 3D-LiDAR ecosystem mapping. *Trends in Ecology & Evolution* 29:681-691.

Dechant, B., M. Cuntz, M. Vohland, E. Schulz, and D. Doktor. 2017. Estimation of photosynthesis traits from leaf reflectance spectra: Correlation to nitrogen content as the dominant mechanism. *Remote Sensing of Environment* 196:279-292.

DeFries, R.S., and J.R.G. Townshend. 1999. Global land cover characterization from satellite data: From research to operational implementation? *Global Ecology and Biogeography* 8:367-379.

Del Castillo, C.E., and R.L. Miller. 2008. On the use of ocean color remote sensing to measure the transport of dissolved organic carbon by the Mississippi River Plume. *Remote Sensing of Environment* 112:836-844.

Demattê, J.A., L. Ramirez-Lopez, K. Marques, and A. Rodella. 2017. Chemometric soil analysis on the determination of specific bands for the detection of magnesium and potassium by spectroscopy. *Geoderma* 288:8-22.

Dennison, P.E., K. Charoensiri, D.A. Roberts, S.H. Peterson, and R.O. Green. 2006. Wildfire temperature and land cover modeling using hyperspectral data. *Remote Sensing of Environment* 100:212-222.

Devred, E., K.R. Turpie, W. Moses, V.V. Klemas, T. Moisan, M. Babin, G. Toro-Farmer, M.H. Forget, and Y.H. Jo. 2013. Future retrievals of water column bio-optical properties using the Hyperspectral Infrared Imager (HyspIRI). *Remote Sensing* 5:6812-6837.

Devries, T., M. Holzer, and F. Primeau. 2017. Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning. *Nature* 542:215-218.

Devries, T., and T. Weber. 2017. The export and fate of organic matter in the ocean: New constraints from combining satellite and oceanographic tracer observations. *Global Biogeochemical Cycles* 31:535-555.

Diaz, S., J.G. Hodgson, K. Thompson, M. Cabido, J.H.C. Cornelissen, A. Jalili, G. Montserrat-Marti, J.P. Grime, F. Zarrinkamar, Y. Asri, and S.R. Band. 2004. The plant traits that drive ecosystems; evidence from three continents. *Journal of Vegetation Science* 15:295-304.

Dierssen, H.M., R.C. Zimmerman, R.A. Leathers, T.V. Downes, and C.O. Davis. 2003. Ocean color remote sensing of seagrass and bathymetry in the Bahamas Banks by high-resolution airborne imagery. *Limnology and Oceanography* 48:444-455.

Drake, N.A., S. Mackin, and J.J. Settle. 1999. Mapping vegetation, soils, and geology in semiarid shrublands using spectral matching and mixture modeling of SWIR AVIRIS imagery. *Remote Sensing of Environment* 68:12-25.

Drijfhout, S.S., A.T. Blaker, S.A. Josey, A.J.G. Nurser, B. Sinha, and M.A. Balmaseda. 2014. Surface warming hiatus caused by increased heat uptake across multiple ocean basins. *Geophysical Research Letters* 41:7868-7874.

Dubayah, R.O., S.L. Sheldon, D.B. Clark, M.A. Hofton, J.B. Blair, G.C. Hurtt, and R.L. Chazdon. 2010. Estimation of tropical forest height and biomass dynamics using lidar remote sensing at La Selva, Costa Rica. *Journal of Geophysical Research: Biogeosciences* 115.

Ehlmann, B.L., J. Mustard, G.A. Swayze, R.N. Clark, J. Bishop, F. Poulet, D. Des Marais, L. Roach, R. Milliken, J. Wray, O. Barnouin-Jha, and S. Murchie. 2009. Identification of hydrated silicate minerals on Mars using MRO-CRISM: Geologic context near Nili Fossae and implications for aqueous alteration. *Journal of Geophysical Research* 114.

Falkowski, P.G., R.T. Barber, and V. Smetacek. 1998. Biogeochemical controls and feedbacks on ocean primary production. *Science* 281:200-206.

Féret, J.B., and G.P. Asner. 2013. Tree species discrimination in tropical forests using airborne imaging spectroscopy. *IEEE Transactions on Geoscience and Remote Sensing* 51:73-84.

Féret, J.B., and G.P. Asner. 2014. Mapping tropical forest canopy diversity using high-fidelity imaging spectroscopy. *Ecological Applications* 24:1289-1296.

Ferreira, M.P., M. Zortea, D.C. Zanotta, Y.E. Shimabukuro, and C.R. De Souza Filho. 2016. Mapping tree species in tropical seasonal semi-deciduous forests with hyperspectral and multispectral data. *Remote Sensing of Environment* 179:66-78.

Field, C.B., M.J. Behrenfeld, J.T. Randerson, and P. Falkowski. 1998. Primary production of the biosphere: integrating terrestrial and oceanic components. *Science* 281:237-240.

Field, R., B.A. Hawkins, H.V. Cornell, D.J. Currie, J.a.F. Diniz-Filho, J.F. Guégan, D.M. Kaufman, J.T. Kerr, G.G. Mittelbach, and T. Oberdorff. 2009. Spatial species-richness gradients across scales: a meta-analysis. *Journal of Biogeography* 36:132-147.

Fisher, J.B., F. Melton, E. Middleton, C. Hain, M. Anderson, R. Allen, M.F. McCabe, et al. 2017. The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management,and water resources, *Water Resource Research* 53:2618-2626.

Fishman, J., L.T. Iraci, J. Al-Saadi, K. Chance, F. Chavez, M. Chin, P. Coble, C. Davis, P.M. DiGiacomo, D. Edwards, and A. Eldering. 2012. The United States' next generation of atmospheric composition and coastal ecosystem measurements: NASA's Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission. *Bulletin of the American Meteorological Society* 93(10):1547-1566.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C.S. Holling. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics* 35:557-581.

Frankenberg, C., J.B. Fisher, J. Worden, G. Badgley, S.S. Saatchi, J.E. Lee, G.C. Toon, A. Butz, M. Jung, and A. Kuze. 2011. New global observations of the terrestrial carbon cycle from GOSAT: Patterns of plant fluorescence with gross primary productivity. *Geophysical Research Letters* 38.

Frankenberg, C., A.K. Thorpe, D.R. Thompson, G. Hulley, E.A. Kort, N. Vance, J. Borchardt, et al. 2016. Airborne methane remote measurements reveal heavy-tail flux distribution in Four Corners region. *Proceedings of the National Academy of Sciences* 113:9734-9739.

Galloway, A.W., and M. Winder. 2015. Partitioning the relative importance of phylogeny and environmental conditions on phytoplankton fatty acids. *PLoS One* 10:e0130053.

Galvão, L.S., J.C.N. Epiphano, and E.M. Breuning. 2012. Crop type discrimination using hyperspectral data. In *Hyperspectral Remote Sensing of Vegetation* (P.S. Thankabail, J.G. Lyon, and A. Huete, eds.). Boca Ratan, FL: CRC Press.

Gamon, J.A., K.F. Huemmrich, C.Y. Wong, I. Ensminger, S. Garrity, D.Y. Hollinger, A. Noormets, and J. Peñuelas. 2016. A remotely sensed pigment index reveals photosynthetic phenology in evergreen conifers. *Proceedings of the National Academy of Sciences* 113:13087-13092.

Garbulsky, M. F., J. Peñuelas, J. Gamon, Y. Inoue, and I. Filella. 2011. The photochemical reflectance index (PRI) and the remote sensing of leaf, canopy and ecosystem radiation use efficiencies: A review and meta-analysis. *Remote Sensing of Environment* 115:281-297.

Gaston, K.J. 2000. Global patterns in biodiversity. *Nature* 405:220.

Giglio, L., T. Loboda, D.P. Roy, B. Quayle, and C.O. Justice. 2009. An active-fire based burned area mapping algorithm for the MODIS sensor. *Remote Sensing of Environment* 113:408-420.

Giglio, L., J. Randerson, G. Van Der Werf, P. Kasibhatla, G. Collatz, D. Morton, and R. Defries. 2010. Assessing variability and long-term trends in burned area by merging multiple satellite fire products. *Biogeosciences* 7:1171-1186.

Gitelson, A.A. 2004. Wide dynamic range vegetation index for remote quantification of biophysical characteristics of vegetation. *Journal of Plant Physiology* 161:165-173.

Goetz, S.J., D. Steinberg, M.G. Betts, R.T. Holmes, P.J. Doran, R. Dubayah, and M. Hofton. 2010. Lidar remote sensing variables predict breeding habitat of a Neotropical migrant bird. *Ecology* 91:1569-1576.

González-Zamora, Á., N. Sánchez, J. Martínez-Fernández, and W. Wagner. 2016. Root-zone plant available water estimation using the SMOS-derived soil water index. *Advances in Water Resources* 96:339-353.

Goulas, Y., A. Fournier, F. Daumard, S. Champagne, A. Ounis, O. Marloie, and I. Moya. 2017. Gross primary production of a wheat canopy relates stronger to far red than to red solar-induced chlorophyll fluorescence. *Remote Sensing* 9:97.

Gregory, J.M., C. Jones, P. Cadule, and P. Friedlingstein. 2009. Quantifying carbon cycle feedbacks. *Journal of Climate* 22:5232-5250.

Grosse, G., J. Harden, M. Turetsky, A.D. McGuire, P. Camill, C. Tarnocai, S. Frolking, et al. 2011. Vulnerability of high-latitude soil organic carbon in North America to disturbance. *Journal of Geophysical Research: Biogeosciences* 116.

Grosse, G., S. Goetz, A.D. Mcguire, V.E. Romanovsky, and E.A. Schuur. 2016. Changing permafrost in a warming world and feedbacks to the Earth system. *Environmental Research Letters* 11:040201.

Gruber, N., M. Gloor, S.E. Mikaloff Fletcher, S.C. Doney, S. Dutkiewicz, M.J. Follows, M. Gerber, A.R. Jacobson, F. Joos, and K. Lindsay. 2009. Oceanic sources, sinks, and transport of atmospheric CO_2. *Global Biogeochemical Cycles* 23.

Guan, K., J. Wu, J.S. Kimball, M.C. Anderson, S. Frolking, B. Li, C.R. Hain, and D.B. Lobell. 2017. The shared and unique values of optical, fluorescence, thermal and microwave satellite data for estimating large-scale crop yields. *Remote Sensing of Environment* 199:333-349.

Guanter, L., Y. Zhang, M. Jung, J. Joiner, M. Voigt, J.A. Berry, C. Frankenberg, A.R. Huete, P. Zarco-Tejada, and J.-E. Lee. 2014. Global and time-resolved monitoring of crop photosynthesis with chlorophyll fluorescence. *Proceedings of the National Academy of Sciences* 111:E1327-E1333.

Hair, J.W., C.A. Hostetler, A.L. Cook, D.B. Harper, R.A. Ferrare, T.L. Mack, W. Welch, L.R. Izquierdo, and F.E. Hovis. 2008. Airborne High Spectral Resolution Lidar for profiling aerosol optical properties. *Applied Optics* 47:6734-6752.

Hair, J., C. Hostetler, Y. Hu, M. Behrenfeld, C. Butler, D. Harper, R. Hare, T. Berkoff, A. Cook, J. Collins, N. Stockey, M. Twardowski, I. Cetinic, R. Ferrare, and T. Mack. 2016. Combined atmospheric and ocean profiling from an airborne high spectral resolution lidar. *EPJ Web of Conferences* 119:22001.

Hales, B., P.G. Strutton, M. Saraceno, R. Letelier, T. Takahashi, R. Feely, C. Sabine, and F. Chavez. 2012. Satellite-based prediction of pCO2 in coastal waters of the eastern North Pacific. *Progress in Oceanography* 103:1-15.

Han, X., R.L. Smyth, B.E. Young, T.M. Brooks, A.S. De Lozada, P. Bubb, S.H. Butchart, F.W. Larsen, H. Hamilton, and M.C. Hansen. 2014. A biodiversity indicators dashboard: Addressing challenges to monitoring progress towards the Aichi biodiversity targets using disaggregated global data. *PloS One* 9:e112046.

Hansen, M.C., S.V. Stehman, and P.V. Potapov. 2010. Quantification of global gross forest cover loss. *Proceedings of the National Academy of Sciences* 107:8650-8655.

Hansen, M.C., P.V. Potapov, R. Moore, M. Hancher, S. Turubanova, A. Tyukavina, D. Thau, S. Stehman, S. Goetz, and T. Loveland. 2013. High-resolution global maps of 21st-century forest cover change. *Science* 342:850-853.

Harrison, S., and R. Noss. 2017. Endemism hotspots are linked to stable climatic refugia. *Annals of Botany* 119:207-214.

Hastie, T.J., and R.J. Tibshirani. 1990. *Generalized Additive Models*. London, UK: Chapman & Hall.

Hawkins, B.A., R. Field, H.V. Cornell, D.J. Currie, J.-F. Guégan, D.M. Kaufman, J.T. Kerr, G.G. Mittelbach, T. Oberdorff, and E.M. O'Brien. 2003. Energy, water, and broadścale geographic patterns of species richness. *Ecology* 84:3105-3117.

Hedley, J.D. 2013. Hyperspectral Applications. Pp. 79-112 in *Coral Reef Remote Sensing: A Guide for Mapping, Monitoring and Management* (J.A. Goodman, S.J. Purkis, S.R. Phinn, eds.). Heidelberg: Springer-Verlag.

Heikkilä, J. 2010. Economics of biosecurity across levels of decision-making: A review. *Agronomy for Sustainable Development* 31:119-138.

Held, A., C. Ticehurst, L. Lymburner, and N. Williams. 2003. High resolution mapping of tropical mangrove ecosystems using hyperspectral and radar remote sensing. *International Journal of Remote Sensing* 24:2739-2759.

Henson, S.A. 2014. Slow science: The value of long ocean biogeochemistry records. *Philosophical Transactions. Series A* 372: 20130334.

Henson, S., H. Cole, C. Beaulieu, and A. Yool. 2013. The impact of global warming on seasonality of ocean primary production. *Biogeosciences* 10:4357-4369.

Herrault, P.-A., L. Gandois, S. Gascoin, N. Tananaev, T. Le Dantec, and R. Teisserenc. 2016. Using high spatio-temporal optical remote sensing to monitor dissolved organic carbon in the Arctic River Yenisei. *Remote Sensing* 8:803.

Hestir, E.L., V.E. Brando, M. Bresciani, C. Giardino, E. Matta, P. Villa, and A.G. Dekker. 2015. Measuring freshwater aquatic ecosystems: The need for a hyperspectral global mapping satellite mission. *Remote Sensing of Environment* 167:181-195.

Hestir, E.L., S. Khanna, M.E. Andrew, M.J. Santos, J.H. Viers, J.A. Greenberg, S.S. Rajapakse, and S.L. Ustin. 2008. Identification of invasive vegetation using hyperspectral remote sensing in the California Delta ecosystem. *Remote Sensing of Environment* 112:4034-4047.

Higuera, P.E., M.L. Chipman, J.L. Barnes, M.A. Urban, and F.S. Hu. 2011. Variability of tundra fire regimes in Arctic Alaska: Millennialścale patterns and ecological implications. *Ecological Applications* 21:3211-3226.

Hobbs, P.V., J.S. Reid, R.A. Kotchenruther, R.J. Ferek, and R. Weiss. 1997. Direct radiative forcing by smoke from biomass burning. *Science* 275:1777-1778.

Hochberg, E.J., A.M. Apprill, M.J. Atkinson, and R.R. Bidigare. 2006. Bio-optical modeling of photosynthetic pigments in corals. *Coral Reefs* 25:99-109.

Hochberg, E.J. 2011. Remote Sensing of Coral Reef Processes. Pp. 25-35 in *Coral Reefs: An Ecosystem in Transition* (Z. Dubinsky and N. Stambler, eds.). The Netherlands: Springer.

Hochberg, E.J., and M. Atkinson. 2000. Spectral discrimination of coral reef benthic communities. *Coral Reefs* 19:164-171.

Hochberg, E.J., and M.J. Atkinson. 2003. Capabilities of remote sensors to classify coral, algae and sand as pure and mixed spectra. *Remote Sensing of Environment* 85:174-189.

Hochberg, E.J., and M. Atkinson. 2008. Coral reef benthic productivity based on optical absorptance and light-use efficiency. *Coral Reefs* 27:49-59.

Hoffman, F.M., J.T. Randerson, V.K. Arora, Q. Bao, P. Cadule, D. Ji, C.D. Jones, M. Kawamiya, S. Khatiwala, and K. Lindsay. 2014. Causes and implications of persistent atmospheric carbon dioxide biases in Earth system models. *Journal of Geophysical Research: Biogeosciences* 119:141-162.

Howitt, R., J. Medellín-Azuara, D. Macewan, J.R. Lund, and D. Sumner. 2015. *Economic Analysis of the 2014 Drought for California Agriculture.* Davis, CA: Center for Watershed Sciences, University of California, Davis.

Huang, C., N. Thomas, S.N. Goward, J.G. Masek, Z. Zhu, J.R. Townshend, and J.E. Vogelmann. 2010. Automated masking of cloud and cloud shadow for forest change analysis using Landsat images. *International Journal of Remote Sensing* 31:5449-5464.

Imhoff, M.L., L. Bounoua, T. Ricketts, and C. Loucks. 2004. Global patterns in human consumption of net primary production. *Nature* 429:870.

IOCCG (International Ocean-Colour Coordinating Group). 2014. Phytoplankton Functional Types from Space. In *Reports of the International Ocean-Color Coordinating Group, No. 15* (S. Sathyendranath, ed.) Dartmouth, Canada.

IPCC (Intergovernmental Panel on Climate Change). 2013. *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, eds.). Cambridge and New York: Cambridge University Press.

Ise, T., and P.R. Moorcroft. 2006. The global-scale temperature and moisture dependencies of soil organic carbon decomposition: An analysis using a mechanistic decomposition model. *Biogeochemistry* 80:217-231.

Jetz, W., J. Cavender-Bares, R. Pavlick, D. Schimel, F.W. Davis, G.P. Asner, R. Guralnick, J. Kattge, A.M. Latimer, and P. Moorcroft. 2016. Monitoring plant functional diversity from space. *Nature Plants* 2:16024.

Jimenez, I., T. Distler, and P.M. Jørgensen. 2009. Estimated plant richness pattern across northwest South America provides similar support for the speciesćenergy and spatial heterogeneity hypotheses. *Ecography* 32:433-448.

Johannsen, C.J., J.H. Arvik, and J.A. Berglund. 1997. Information requirements for precision farming: The next decade. *American Technology* 1:18-21.

Johannsen, C.J., and P.G. Carter. 2004. Site Specific Soil Management: Concepts and Prospects. Pp. 497-503 in *Encyclopedia of Soils in the Environment* (Daniel Hillel, ed.), Vol. III. Elsevier.

Johannsen, C.J., and C.S.T. Daughtry. 2009. Surface Reference Data Collection, Chapter 17, pp. 244-256 in *The Sage Handbook of Remote Sensing* (T.A. Warner, M.D. Nellis, and G. Foody, eds.). London: Sage Publications.

Johannsen, C.J., and P.G. Carter. 2004. Site Specific Soil Management: Concepts and Prospects. In *Encyclopedia of Soils in the Environment* (D. Hillel, ed.). Elsevier.

Johnson, K.S., W.M. Berelson, E.S. Boss, Z. Chase, H. Claustre, S.R. Emerson, N. Gruber, A. Körtzinger, M.J. Perry, and S.C. Riser. 2009. Observing biogeochemical cycles at global scales with profiling floats and gliders: Prospects for a global array. *Oceanography* 22:216-225.

Joiner, J., Y. Yoshida, A. Vasilkov, and E. Middleton. 2011. First observations of global and seasonal terrestrial chlorophyll fluorescence from space. *Biogeosciences* 8:637-651.

Joiner, J., L. Guanter, R. Lindstrot, M. Voigt, A. Vasilkov, E. Middleton, K. Huemmrich, Y. Yoshida, and C. Frankenberg. 2013. Global monitoring of terrestrial chlorophyll fluorescence from moderate spectral resolution near-infrared satellite measurements: Methodology, simulations, and application to GOME-2. *Atmospheric Measurement Techniques* 6:2803-2823.

Joiner, J., Y. Yoshida, A. Vasilkov, K. Schaefer, M. Jung, L. Guanter, Y. Zhang, S. Garrity, E. Middleton, and K. Huemmrich. 2014. The seasonal cycle of satellite chlorophyll fluorescence observations and its relationship to vegetation phenology and ecosystem atmosphere carbon exchange. *Remote Sensing of Environment* 152:375-391.

Jolly, W.M., M.A. Cochrane, P.H. Freeborn, Z.A. Holden, T.J. Brown, G.J. Williamson, and D.M. Bowman. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications* 6.

Jorgenson, M.T., and G. Grosse. 2016. Remote sensing of landscape change in permafrost regions. *Permafrost and Periglacial Processes* 27:324-338.

Ju, J., and J.G. Masek. 2016. The vegetation greenness trend in Canada and US Alaska from 1984-2012 Landsat data. *Remote Sensing of Environment* 176:1-16.

Jucks, K., S. Neeck, J. Abshire, D. Baker, E. Browell, A. Chatterjee, et al. (ASCENDS Ad Hoc Science Definition Team). 2015. *Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission: Science Mission Definition Study. Summary of a Workshop.* Pasadena, CA: California Institute of Technology.

Jung, M., M. Reichstein, H.A. Margolis, A. Cescatti, A.D. Richardson, M.A. Arain, A. Arneth, C. Bernhofer, D. Bonal, and J. Chen. 2011. Global patterns of landćatmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. *Journal of Geophysical Research: Biogeosciences* 116.

Kaiser, J., A. Heil, M. Andreae, A. Benedetti, N. Chubarova, L. Jones, J.-J. Morcrette, M. Razinger, M. Schultz, and M. Suttie. 2012. Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. *Biogeosciences* 9:527.

Kalacska, M., G.A. Sanchez-Azofeifa, B. Rivard, T. Caelli, H.P. White, and J. Calvo-Alvarado. 2007. Ecological fingerprinting of ecosystem succession: Estimating secondary tropical dry forest structure and diversity using imaging spectroscopy. *Remote Sensing of Environment* 108:82-96.

Kamal, M., and S. Phinn. 2011. Hyperspectral data for mangrove species mapping: A comparison of pixel-based and object-based approach. *Remote Sensing* 3:2222-2242.

Kattge, J., W. Knorr, T. Raddatz, and C. Wirth. 2009. Quantifying photosynthetic capacity and its relationship to leaf nitrogen content for globalćscale terrestrial biosphere models. *Global Change Biology* 15:976-991.

Kattge, J., S. Diaz, S. Lavorel, I.C. Prentice, P. Leadley, G. Bönisch, E. Garnier, M. Westoby, P.B. Reich, and I.J. Wright. 2011. TRY—a global database of plant traits. *Global Change Biology* 17:2905-2935.

Kefauver, S.C., J. Peñuelas, and S. Ustin. 2014. Using topographic and remotely sensed variables to assess ozone injury to conifers in the Sierra Nevada (USA) and Catalonia (Spain). *Remote Sensing of Environment* 139:138-148.

Kelly, R., M.L. Chipman, P.E. Higuera, I. Stefanova, L.B. Brubaker, and F.S. Hu. 2013. Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proceedings of the National Academy of Sciences* 110:13055-13060.

Khanna, S., M.J. Santos, S.L. Ustin, and P.J. Haverkamp. 2011. An integrated approach to a biophysiologically based classification of floating aquatic macrophytes. *International Journal of Remote Sensing* 32:1067-1094.

Khanna, S., M.J. Santos, S.L. Ustin, A. Koltunov, R.F. Kokaly, and D.A. Roberts. 2013. Detection of salt marsh vegetation stress and recovery after the Deepwater Horizon oil spill in Barataria Bay, Gulf of Mexico using AVIRIS data. *PLoS One* 8:e78989.

Khatiwala, S., F. Primeau, and T. Hall. 2009. Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. *Nature* 462:346.

Kirschke, S., P. Bousquet, P. Ciais, M. Saunois, J.G. Canadell, E.J. Dlugokencky, P. Bergamaschi, D. Bergmann, D.R. Blake, and L. Bruhwiler. 2013. Three decades of global methane sources and sinks. *Nature Geoscience* 6:813.

Kokaly, R.F. 2001. Investigating a physical basis for spectroscopic estimates of leaf nitrogen concentration. *Remote Sensing of Environment* 75:153-161.

Kokaly, R.F., D.G. Despain, R.N. Clark, and K.E. Livo. 2003. Mapping vegetation in Yellowstone National Park using spectral feature analysis of AVIRIS data. *Remote Sensing of Environment* 84:437-456.

Kokaly, R.F., and A.K. Skidmore. 2015. Plant phenolics and absorption features in vegetation reflectance spectra near 1.66 microns. *International Journal of Applied Earth Observation and Geoinformation* 43:55-83.

Kokaly, R.F., G.P. Asner, S.V. Ollinger, M.E. Martin, and C.A. Wessman. 2009. Characterizing canopy biochemistry from imaging spectroscopy and its application to ecosystem studies. *Remote Sensing of Environment* 113:S78-S91.

Kononen, K. 2001. Eutrophication, harmful algal blooms and species diversity in phytoplankton communities: Examples from the Baltic Sea. *AMBIO: A Journal of the Human Environment* 30:184-189.

Körtzinger, A. 2003. A significant CO_2 sink in the tropical Atlantic Ocean associated with the Amazon River plume. *Geophysical Research Letters* 30.

Kreft, H., and W. Jetz. 2007. Global patterns and determinants of vascular plant diversity. *Proceedings of the National Academy of Sciences* 104:5925-5930.

Kruse, F.A., J.V. Taranik, M. Coolbaugh, J. Michaels, E.F. Littlefield, W.M. Calvin, and B.A. Martini. 2011. Effect of reduced spatial resolution on mineral mapping using imaging spectrometry—Examples using hyperspectral infrared imager (HyspIRI) simulated data. *Remote Sensing* 3:1584-1602.

Kudela, R.M., S.L. Palacios, D.C. Austerberry, E.K. Accorsi, L.S. Guild, and J. Torres-Perez. 2015. Application of hyperspectral remote sensing to cyanobacterial blooms in inland waters. *Remote Sensing of Environment*, 167:196-205.

Kudela, R.M., S.L. Palacios, and L. Guild. 2016. REMOTE: In-water observations and HyspIRI Preparatory Airborne Campaign. HyspIRI Aquatic Forum. Pasadena, CA: Jet Propulsion Laboratory/California Institute of Technology.

Kustas, W., and M. Anderson. 2009. Advances in thermal infrared remote sensing for land surface modeling. *Agricultural and Forest Meteorology* 149:2071-2081.

Lal, R. 2003. Soil erosion and the global carbon budget. *Environment International* 29:437-450.

Laurin, G.V., N. Puletti, W. Hawthorne, V. Liesenberg, P. Corona, D. Papale, Q. Chen, and R. Valentini. 2016. Discrimination of tropical forest types, dominant species, and mapping of functional guilds by hyperspectral and simulated multispectral Sentinel-2 data. *Remote Sensing of Environment* 176:163-176.

Lavorel, S., and Garnier, É. 2002. Predicting changes in community composition and ecosystem functioning from plant traits: Revisiting the Holy Grail. *Functional Ecology* 16:545-556.

Lefsky, M.A., W.B. Cohen, G.G. Parker, and D.J. Harding. 2002. Lidar remote sensing for ecosystem studies: Lidar, an emerging remote sensing technology that directly measures the three-dimensional distribution of plant canopies, can accurately estimate vegetation structural attributes and should be of particular interest to forest, landscape, and global ecologists. *BioScience* 52:19-30.

Le Quéré, C., R. Moriarty, R.M. Andrew, G.P. Peters, P. Ciais, P. Friedlingstein, S.D. Jones, S. Sitch, P. Tans, and A. Arneth. 2014. Global carbon budget 2014. *Earth System Science Data* 7:47-85.

Le Quéré, C., R. Moriarty, R.M. Andrew, J.G. Canadell, S. Sitch, J.I. Korsbakken, P. Friedlingstein, G.P. Peters, R.J. Andres, and T.A. Boden. 2015. Global carbon budget 2015. *Earth System Science Data* 7:349-396.

Li, J., and D.P. Roy 2017. A global analysis of Sentinel-2A, Sentinel-2B and Landsat-8 data revisit intervals and implications for terrestrial monitoring. *Remote Sensing* 9:902.

Li, L., S.L. Ustin, and M. Lay. 2005. Application of multiple endmember spectral mixture analysis (MESMA) to AVIRIS imagery for coastal salt marsh mapping: A case study in China Camp, CA, USA. *International Journal of Remote Sensing* 26:5193-5207.

Liu, J., E. Pattey, J.R. Miller, H. McNairn, A. Smith, and B. Hu. 2010. Estimating crop stresses, aboveground dry biomass and yield of corn using multi-temporal optical data combined with a radiation use efficiency model. *Remote Sensing of Environment* 114:1167-1177.

Loizzo, R., C. Ananasso, R. Guarini, E. Lopinto, L. Candela, and Pisani. 2016. The PRISMA Hyperspectral Mission. *Living Planet Symposium 2016*. http://adsabs.harvard.edu/abs/2016ESASP.740E.415L.

Lomas, M.W., J.A. Bonachela, S.A. Levin, and A.C. Martiny. 2014. Impact of ocean phytoplankton diversity on phosphate uptake. *Proceedings of the National Academy of Sciences* 111:17540-17545.

Lombardozzi, D.L., G.B. Bonan, N.G. Smith, J.S. Dukes, and R.A. Fisher. 2015. Temperature acclimation of photosynthesis and respiration: A key uncertainty in the carbon cycle–climate feedback. *Geophysical Research Letters* 42:8624-8631.

Lu, X., Y. Hu, C. Trepte, S. Zeng, and J.H. Churnside. 2014. Ocean subsurface studies with the CALIPSO spaceborne lidar. *Journal of Geophysical Research: Oceans* 119:4305-4317.

Mack, M.C., M.S. Bret-Harte, T.N. Hollingsworth, R.R. Jandt, E.A. Schuur, G.R. Shaver, and D.L. Verbyla. 2011. Carbon loss from an unprecedented Arctic tundra wildfire. *Nature* 475:489-492.

Mahowald, N., K. Lindsay, D. Rothenberg, S.C. Doney, J.K. Moore, P. Thornton, J.T. Randerson, and C.D. Jones. 2011. Desert dust and anthropogenic aerosol interactions in the Community Climate System Model coupled-carbon-climate model. *Biogeosciences* 8:387.

Mandanici, E., and G. Bitelli. 2016. Preliminary comparison of Sentinel-2 and Landsat 8 imagery for a combined use. *Remote Sensing* 8:1014.

Maness, H., P.J. Kushner, and I. Fung. 2013. Summertime climate response to mountain pine beetle disturbance in British Columbia. *Nature Geoscience* 6:65.

Marshall, M., and P. Thenkabail. 2015. Advantage of hyperspectral EO-1 Hyperion over multispectral IKONOS, GeoEye-1, WorldView-2, Landsat ETM+, and MODIS vegetation indices in crop biomass estimation. *ISPRS Journal of Photogrammetry and Remote Sensing* 108:205-218.

McCarty, G.W., and M.W. Lang. 2009. Lidar intensity for improved detection of inundation below the forest canopy. *Society of Wetland Scientists* 29:1166-1178.

McClain, C.R. 2009. A decade of satellite ocean color observations. *Annual Review of Marine Science* 1:19-42.

McGaraghan, A.R., and R.M. Kudela. 2012. Estimating labile particulate iron concentrations in coastal waters from remote sensing data. *Journal of Geophysical Research: Oceans* 117: C02004.

McKinley, G.A., D.J. Pilcher, A.R. Fay, K. Lindsay, M.C. Long, and N.S. Lovenduski. 2016. Timescales for detection of trends in the ocean carbon sink. *Nature* 530:469-472.

McManus, K.M., G.P. Asner, R.E. Martin, K.G. Dexter, W.J. Kress, and C.B. Field. 2016. Phylogenetic structure of foliar spectral traits in tropical forest canopies. *Remote Sensing* 8:196.

Meerdink, S.K., D.A. Roberts, J.Y. King, K.L. Roth, P.E. Dennison, C.H. Amaral, and S.J. Hook. 2016. Linking seasonal foliar traits to VSWIR-TIR spectroscopy across California ecosystems. *Remote Sensing of Environment* 186:322-338.

Meigs, G.W., D.P. Turner, W.D. Ritts, Z.Q. Yang, and B.E. Law. 2011. Landscape-scale simulation of heterogeneous fire effects on pyrogenic carbon emissions, tree mortality, and net ecosystem production. *Ecosystems* 14:758-775.

Melton, J., R. Wania, E. Hodson, B. Poulter, B. Ringeval, R. Spahni, T. Bohn, C. Avis, D. Beerling, and G. Chen. 2013. Present state of global wetland extent and wetland methane modelling: Conclusions from a model intercomparison project (WETCHIMP). *Biogeosciences* 10:753-788.

MEA (Millennium Ecosystem Assessment). 2005. *Ecosystems and Human Well-Being: Synthesis.* Washington, DC: World Resources institute.

Moran, M.S., Y. Inoue, and E.M. Barnes. 1997. Opportunities and limitations for image-based remote sensing in precision crop management. *Remote Sensing of Environment* 61:319-46.

Moses, W.J., S.G. Ackleson, J.W. Hair, C.A. Hostetler, and W.D. Miller. 2016. Spatial scales of optical variability in the coastal ocean: Implications for remote sensing and in situ sampling. *Journal of Geophysical Research: Oceans* 121:4194-4208.

Mouroulis, P., R.O. Green, B. Van Gorp, L.B. Moore, D.W. Wilson, and H.A. Bender. Landsat swath imaging spectrometer design. *Optical Engineering* 55(1):015104.

Mouw, C.B., S. Greb, D. Aurin, P.M. DiGiacomo, Z. Lee, M. Twardowski, C. Binding, C. Hu, R. Ma, T. Moore, and W. Moses. 2015. Aquatic color radiometry remote sensing of coastal and inland waters: Challenges and recommendations for future satellite missions. *Remote Sensing of Environment* 160:15-30.

Müller, D., C.A. Hostetler, R. Ferrare, S. Burton, E. Chemyakin, A. Kolgotin, J. Hair, A. Cook, D. Harper, and R. Rogers. 2014. Airborne multiwavelength High Spectral Resolution Lidar (HSRL-2) observations during TCAP 2012: Vertical profiles of optical and microphysical properties of a smoke/urban haze plume over the northeastern coast of the US. *Atmospheric Measurement Techniques* 7:3487-3496.

Mutke, J., and W. Barthlott. 2005. Patterns of vascular plant diversity at continental to global scales. *Biologiske Skrifter* 55:521-537.

Myneni, R.B., S. Hoffman, Y. Knyazikhin, J. Privette, J. Glassy, Y. Tian, Y. Wang, X. Song, Y. Zhang, and G. Smith. 2002. Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data. *Remote Sensing of Environment* 83:214-231.

Narayan, S., M.W. Beck, P. Wilson, C. Thomas, A. Guerrero, C. Shepard, B.G. Reguero, G. Franco, C. Ingram, and D. Trespalacios. 2016. *Coastal Wetlands and Flood Damage Reduction: Using Risk Industry-based Models to Assess Natural Defenses in the Northeastern USA.* London: Lloyd's Tercentenary Research Foundation.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2015. *Continuity of NASA Earth Observations from Space: A Value Framework*. Washington, DC: The National Academies Press.

NASA (National Aeronautics and Space Administration). 2017 *EXPORTS: EXport Processes in the Ocean from RemoTe Sensing.* https://cce.nasa.gov/ocean_biology_biogeochemistry/exports/index.html.

Neuenschwander, A., R. Gutierrez, B. Schutz, and T. Urban. 2006. Comparison of small-footprint and large-footprint waveform lidar for terrestrial surface characterization. Pp. 3758-3761 in *Geoscience and Remote Sensing Symposium, 2006.* doi:10.1109/IGARSS.2006.963.

NRC (National Research Council). 2007. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. Washington, DC: The National Academies Press.

NRC. 2011. *Assessing the Requirements for Sustained Ocean Color Research and Operations*. Washington, DC: The National Academies Press.

NRC. 2014a. *Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program*. Washington, DC: The National Academies Press.

NRC. 2014b. *Opportunities to Use Remote Sensing in Understanding Permafrost and Related Ecological Characteristics: Report of a Workshop*. Washington, DC: The National Academies Press.

Nocita, M., A. Stevens, B. Van Wesemael, M. Aitkenhead, M. Bachmann, B. Barthès, E. Ben Dor, et al. 2015. Chapter Four—Soil Spectroscopy: An Alternative to Wet Chemistry for Soil Monitoring. In *Advances in Agronomy* (L.S. Donald, ed.). San Diego, CA: Academic Press.

Ollinger, S.V., and M.L. Smith. 2005. Net primary production and canopy nitrogen in a temperate forest landscape: An analysis using imaging spectroscopy, modeling and field data. *Ecosystems* 8:760-778.

Olsen, A., J.A. Triñanes, and R. Wanninkhof. 2004. Sea-air flux of CO_2 in the Caribbean Sea estimated using in situ and remote sensing data. *Remote Sensing of Environment* 89:309-325.

Osterman, S.N., F.E. Muller-Karger, D.C. Humm, M.W. Noble, S.M. Begley, C.B. Hersman, E.L. Hestir, et al. A Spaceborne Visible-NIR Hyperspectral Imager for Coastal Phenology. *Proceedings Volume 10000, Sensors, Systems, and Next-Generation Satellites XX*. doi:10.1117/12.2241784.

Pahlevan, N., Z. Lee, C. Hu, and J.R. Schott. 2014. Diurnal remote sensing of coastal/oceanic waters: A radiometric analysis for geostationary coastal and air pollution events. *Applied Optics* 53:648-665.

Palacios, S.L., R.M. Kudela, L.S. Guild, K.H. Negrey, J. Torres-Perez, and J. Broughton. 2015. Remote sensing of phytoplankton functional types in the coastal ocean from the HyspIRI Preparatory Flight Campaign. *Remote Sensing of Environment* 167:269-280.

Palacios-Orueta, A., J.E. Pinzon, S.L. Ustin, and D.A. Roberts. 1999. Remote sensing of soil properties in the Santa Monica Mountains. II. Hierarchical foreground and background analysis. *Remote Sensing of Environment* 68:138-151.

Pan, Y., R.A. Birdsey, J. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz, O.L. Phillips, A. Shvidenko, S.L. Lewis, and J.G. Canadell. 2011. A large and persistent carbon sink in the world's forests. *Science* 333:988-993.

Phinn, S.R., E.M. Hochberg, and C.M. Roelfsema. 2013. Visible and infrared overview. *Coral Reef Remote Sensing: A Guide for Mapping, Monitoring and Management* (J.A. Goodman, S.J. Purkis, S.R. Phinn, eds.). Heidelberg, Germany: Springer-Verlag.

Piironen, P. and E. Eloranta. 1994. Demonstration of a high-spectral-resolution lidar based on an iodine absorption filter. *Optics Letters* 19:234-236.

Pimentel, D., R. Zuniga, and D. Morrison. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Economics* 52:273-288.

Planet Team. 2017. "Planet Application Program Interface: In Space for Life on Earth." San Francisco, CA. https://www.planet.com/products/planet-imagery/.

Polonsky, I., D. O'Brien, J. Kumer, and C. O'Dell. 2014. Performance of a geostationary mission, geoCARB, to measure CO_2, CH_4 and CO column-averaged concentrations. *Atmospheric Measurement Techniques* 7:959-981.

Prigent, C., F. Papa, F. Aires, W. Rossow, and E. Matthews. 2007. Global inundation dynamics inferred from multiple satellite observations, 1993-2000. *Journal of Geophysical Research: Atmospheres* 112.

Punalekar, S., A. Verhoef, I.V. Tatarenko, C. Van Der Tol, D.M. Macdonald, B. Marchant, F. Gerard, K. White, and D. Gowing. 2016. Characterization of a highly biodiverse floodplain meadow using hyperspectral remote sensing within a plant functional trait framework. *Remote Sensing* 8:112.

Qiu, J., W.T. Crow, G.S. Nearing, X. Mo, and S. Liu. 2014. The impact of vertical measurement depth on the information content of soil moisture times series data. *Geophysical Research Letters* 41:4997-5004.

Quebbeman, J., and J. Ramirez. 2016. Optimal allocation of leaf‐level nitrogen: Implications for covariation of Vcmax and Jmax and photosynthetic downregulation. *Journal of Geophysical Research: Biogeosciences* 121:2464-2475.

Randerson, J.T., H. Liu, M.G. Flanner, S.D. Chambers, Y. Jin, P.G. Hess, G. Pfister, M. Mack, K. Treseder, and L. Welp. 2006. The impact of boreal forest fire on climate warming. *Science* 314:1130-1132.

Rayner, P., A. Stavert, M. Scholze, A. Ahlstrom, C. Allison, and R. Law. 2014. Recent changes in the global and regional carbon cycle: Analysis of first-order diagnostics. *Biogeosciences Discussions* 11:9919-9947.

Regnier, P., P. Friedlingstein, P. Ciais, F.T. Mackenzie, N. Gruber, I.A. Janssens, G.G. Laruelle, R. Lauerwald, S. Luyssaert, and A.J. Andersson. 2013. Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nature Geoscience* 6:597.

Resplandy, L., R. Séférian, and L. Bopp. 2015. Natural variability of CO_2 and O_2 fluxes: What can we learn from centuries‐long climate models simulations? *Journal of Geophysical Research: Oceans* 120:384-404.

Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feeley, S. Gulev, et al. 2013. Observations: Ocean. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, eds.). Cambridge and New York: Cambridge University Press.

Richardson, A.D., R.S. Anderson, M.A. Arain, A.G. Barr, G. Bohrer, G. Chen, J.M. Chen, et al. 2012. Terrestrial biosphere models need better representation of vegetation phenology: Results from the North American Carbon Program Site Synthesis. *Global Change Biology* 18:566-584.

Ricklefs, R.E. 2004. A comprehensive framework for global patterns in biodiversity. *Ecology Letters* 7:1-15.

Ritter, C.D., G. Mccrate, R.H. Nilsson, P.M. Fearnside, U. Palme, and A. Antonelli. 2017. Environmental impact assessment in Brazilian Amazonia: Challenges and prospects to assess biodiversity. *Biological Conservation* 206:161-168.

Roberts, D.A., M. Gardner, R. Church, S. Ustin, G. Scheer, and R. Green. 1998. Mapping chaparral in the Santa Monica Mountains using multiple endmember spectral mixture models. *Remote Sensing of Environment* 65:267-279.

Roberts, D., P. Dennison, S. Peterson, S. Sweeney, and J. Rechel. 2006. Evaluation of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and Moderate Resolution Imaging Spectrometer (MODIS) measures of live fuel moisture and fuel condition in a shrubland ecosystem in southern California. *Journal of Geophysical Research: Biogeosciences* 111.

Rockström, J., W. Steffen, K. Noone, Å. Persson, F.S. Chapin Iii, E. Lambin, T. Lenton, M. Scheffer, C. Folke, and H.J. Schellnhuber. 2009. Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society* 14:32.

Rogers, A., B.E. Medlyn, J.S. Dukes, G. Bonan, S. Caemmerer, M.C. Dietze, J. Kattge, A.D. Leakey, L.M. Mercado, and Ü. Niinemets. 2017. A roadmap for improving the representation of photosynthesis in Earth system models. *New Phytologist* 213:22-42.

Roth, K.L., P.E. Dennison, and D.A. Roberts. 2012. Comparing endmember selection techniques for accurate mapping of plant species and land cover using imaging spectrometer data. *Remote Sensing of Environment* 127:139-152.

Roth, K.L., D.A. Roberts, P.E. Dennison, M. Alonzo, S.H. Peterson, and M. Beland. 2015a. Differentiating plant species within and across diverse ecosystems with imaging spectroscopy. *Remote Sensing of Environment* 167:135-151.

Roth, K.L., D.A. Roberts, P.E. Dennison, S.H. Peterson, and M. Alonzo. 2015b. The impact of spatial resolution on the classification of plant species and functional types within imaging spectrometer data. *Remote Sensing of Environment* 171:45-57.

Roth, K.L., M. Huesca, M. Garcia, A. Casas, and S.L. Ustin. 2016. Canopy structural attributes derived from AVIRIS imaging spectroscopy data in a mixed broadleaf/conifer forest. *Remote Sensing of Environment* 182:208-226.

Ryan, J.P., C.O. Davis, N.B. Tufillaro, R.M. Kudela, and B.-C. Gao. 2014. Application of the Hyperspectral Imager for the coastal ocean to phytoplankton ecology studies in Monterey Bay, CA, USA. *Remote Sensing of Phytoplankton* 6:1007-1025.

Saatchi, S.S., N.L. Harris, S. Brown, M. Lefsky, E.T. Mitchard, W. Salas, B.R. Zutta, W. Buermann, S.L. Lewis, and S. Hagen. 2011. Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences* 108:9899-9904.

Sanches, I.D., C.R. Souza, and R.F. Kokaly. 2014. Spectroscopic remote sensing of plant stress at leaf and canopy levels using the chlorophyll 680nm absorption feature with continuum removal. *ISPRS Journal of Photogrammetry and Remote Sensing* 97:111-122.

Santos, M.J. E.L. Hestir, S. Khanna, and S.L. Ustin. 2012. Image spectroscopy and stable isotopes elucidate functional dissimilarity between native and non-native plant species in the aquatic environment. *New Phytologist* 193:683-695.

Santos, M.J., S. Khanna, E.L. Hestir, J.A. Greenberg, and S.L. Ustin. 2016. Measuring landscape-scale spread and persistence of an invaded submerged plant community from airborne remote sensing. *Ecological Applications* 26:1733-1744.

Saunois, M., P. Bousquet, B. Poulter, A. Peregon, P. Ciais, J.G. Canadell, E.J. Dlugokencky, G. Etiope, D. Bastviken, and S. Houweling. 2016. The global methane budget 2000-2012. *Earth System Science Data* 8:697.

Schaaf, A.N., P.E. Dennison, G.K. Fryer, K.L. Roth, and D.A. Roberts. 2013. Mapping plant functional types at multiple spatial resolutions using imaging spectrometry data. *GIScience & Remote Sensing* 48:324-344.

Schädel, C., M.K.-F. Bader, E.A. Schuur, C. Biasi, R. Bracho, P. Čapek, S. De Baets, K. Diáková, J. Ernakovich, and C. Estop-Aragones. 2016. Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. *Nature Climate Change* 6:950-953.

Schimel, D.S., B. Braswell, E.A. Holland, R. Mckeown, D.S. Ojima, T.H. Painter, W.J. Parton, and A.R. Townsend. 1994. Climatic, edaphic, and biotic controls over storage and turnover of carbon in soils. *Global Biogeochemical Cycles* 8:279-293.

Schimel, D.S., G.P. Asner, and P.R. Moorcroft. 2013. Observing changing ecological diversity in the Anthropocene. *Frontiers in Ecology and the Environment* 11:129-137.

Schimel, D., R. Pavlick, J.B. Fisher, G.P. Asner, S. Saatchi, P. Townsend, C. Miller, C. Frankenberg, K. Hibbard, and P. Cox. 2015. Observing terrestrial ecosystems and the carbon cycle from space. *Global Change Biology* 21:1762-1776.

Schlesinger, W.H., and E.S. Bernhardt. 2013. The Global Carbon Cycle. In *Biogeochemistry: An Analysis of Global Change.* Waltham, MA: Academic Press.

Schlesinger, W., and J. Andrews. 2000. Soil respiration and the global carbon cycle, *Biogeochemistry* 48:7-20.

Schofield, O., H.W. Ducklow, D.G. Martinson, M.P. Meredith, M.A. Moline, and W.R. Fraser. 2010. How do polar marine ecosystems respond to rapid climate change? *Science* 328:1520-1523.

Schroeder, W., P. Oliva, L. Giglio, and I.A. Csiszar. 2014. The new VIIRS 375m active fire detection data product: Algorithm description and initial assessment. *Remote Sensing of Environment* 143:85-96.

Schroeder, R., K.C. McDonald, B.D. Chapman, K. Jensen, E. Podest, Z.D. Tessler, T.J. Bohn, and R. Zimmermann. 2015. Development and evaluation of a multi-year fractional surface water data set derived from active/passive microwave remote sensing data. *Remote Sensing* 7:16688-16732.

Schulien, J.A., M.J. Behrenfeld, J.W. Hair, C.A. Hostetler, and M.S. Twardowski. 2017. Vertically-resolved phytoplankton carbon and net primary production from a high spectral resolution lidar. *Optics Express* 25:13577-13587.

Schulz, M., J.M. Prospero, A.R. Baker, F. Dentener, L. Ickes, P.S. Liss, N.M. Mahowald, S. Nickovic, C.P.R. García-Pando, and S. Rodríguez. 2012. Atmospheric transport and deposition of mineral dust to the ocean: Implications for research needs. *Environmental Science & Technology* 46:10390-10404.

Schuur, E.A.G., J. Bockheim, J. G. Canadell, E. Euskirchen, C.B. Field, S.V. Goryachkin, S. Hagemann, et al. 2008. Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *BioScience* 58:701-714.

Schuur, E.A.G., A.D. McGuire, C. Schädel, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius, et al. 2015. Climate change and the permafrost carbon feedback. *Nature* 520:171-179.

Serbin, S.P., A. Singh, B.E. McNeil, C.C. Kingdon, and P.A. Townsend. 2014. Spectroscopic determination of leaf morphological and biochemical traits for northern temperate and boreal tree species. *Ecological Applications* 24:1651-1669.

Shi, Z., and A. Ito. 2016. Delivery of anthropogenic bioavailable iron from mineral dust and combustion aerosols to the ocean. *Atmospheric Chemistry and Physics* 16:85-99.

Short, N., B. Brisco, N. Couture, W. Pollard, K. Murnaghan, and P. Budkewitsch. 2011. A comparison of TerraSAR-X, RADARSAT-2 and ALOS-PALSAR interferometry for monitoring permafrost environments, case study from Herschel Island, Canada. *Remote Sensing of Environment* 115:3491-3506.

Siegel, D.A., M.J. Behrenfeld, S. Maritorena, C.R. McClain, D. Antoine, S.W. Bailey, P.S. Bontempi, E.S. Boss, H.M. Dierssen, and S.C. Doney. 2013. Regional to global assessments of phytoplankton dynamics from the SeaWiFS mission. *Remote Sensing of Environment* 135:77-91.

Siegel, D.A., K.O. Buesseler, S.C. Doney, S.F. Sailley, M.J. Behrenfeld, and P.W. Boyd. 2014. Global assessment of ocean carbon export by combining satellite observations and foodóweb models. *Global Biogeochemical Cycles* 28:181-196.

Siegel, D.A., K.O. Buesseler, M.J. Behrenfeld, C.R. Benitez-Nelson, E. Boss, M.A. Brzezinski, A. Burd, et al. 2016. Prediction of the export and fate of global ocean net primary production: The EXPORTS Science Plan. *Frontiers in Marine Science* 3:22.

Silsbe, G.M., M.J. Behrenfeld, K.H. Halsey, A.J. Milligan, and T.K. Westberry. 2016. The café model: A net production model for global ocean phytoplankton. *Global Biogeochemical Cycles* 30:1756-1777.

Singh, A., S.P. Serbin, B.E. McNeil, C.C. Kingdon, and P.A. Townsend. 2015. Imaging spectroscopy algorithms for mapping canopy foliar chemical and morphological traits and their uncertainties. *Ecological Applications* 25:2180-2197.

Slonecker, E.T., D.K. Jones, and B.A. Pellerin. 2016. The new Landsat 8 potential for remote sensing of colored dissolved organic matter (CDOM). *Marine Pollution Bulletin* 107:518-527.

Smetacek, V., and S. Nicol. 2005. Polar ocean ecosystems in a changing world. *Nature* 437:362-368.

Smith, M.-L., S.V. Ollinger, M.E. Martin, J.D. Aber, R.A. Hallett, and C.L. Goodale. 2002. Direct estimation of aboveground forest productivity through hyperspectral remote sensing of canopy nitrogen. *Ecological Applications* 12:1286-1302.

Somers, B., G.P. Asner, L. Tits, and P. Coppin. 2011. Endmember variability in spectral mixture analysis: A review. *Remote Sensing of Environment* 115:1603-1616.

Sommer, J.H., H. Kreft, G. Kier, W. Jetz, J. Mutke, and W. Barthlott. 2010. Projected impacts of climate change on regional capacities for global plant species richness. *Proceedings of the Royal Society B: Biological Sciences* 277:2271-2280.

Stagakis, S., T. Vanikiotis, and O. Sykioti. 2016. Estimating forest species abundance through linear unmixing of CHRIS/PROBA imagery. *ISPRS Journal of Photogrammetry and Remote Sensing* 119:79-89.

Suseela, V., R.T. Conant, M.D. Wallenstein, and J.S. Dukes. 2012. Effects of soil moisture on the temperature sensitivity of heterotrophic respiration vary seasonally in an oldófield climate change experiment. *Global Change Biology* 18:336-348.

Swayze, G.A., R.F. Kokaly, C.T. Higgins, J.P. Clinkenbeard, R.N. Clark, H.A. Lowers, and S.J. Sutley. 2009. Mapping potentially asbestos-bearing rocks using imaging spectroscopy. *Geology* 37:763-766.

Tang, H., and R. Dubayah. 2017. Light-driven growth in Amazon evergreen forests explained by seasonal variations of vertical canopy structure. *Proceedings of the National Academy of Sciences* 114(10):2640-2644.

Tans, P., and K. Thoning. 2008. How We Measure Background CO_2 levels on Mauna Loa. Boulder, CO: National Oceanic and Atmospheric Administration, Earth System Research Laboratory.

Thornton, P.E., J.F. Lamarque, N.A. Rosenbloom, and N.M. Mahowald. 2007. Influence of carbonónitrogen cycle coupling on land model response to CO_2 fertilization and climate variability. *Global Biogeochemical Cycles* 21.

Turetsky, M.R., E.S. Kane, J.W. Harden, R.D. Ottmar, K.L. Manies, E. Hoy, and E.S. Kasischke. 2011. Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. *Nature Geoscience* 4:27.

Turner, W. 2014. Sensing biodiversity. *Science* 346:301-302.

Tyukavina, A., A. Baccini, M. Hansen, P. Potapov, S. Stehman, R. Houghton, A. Krylov, S. Turubanova, and S. Goetz. 2015. Aboveground carbon loss in natural and managed tropical forests from 2000 to 2012. *Environmental Research Letters* 10:074002.

Uitz, J., H. Claustre, B. Gentili, and D. Stramski. 2010. Phytoplankton class-specific primary production in the world's oceans: Seasonal and interannual variability from satellite observations. *Global Biogeochemical Cycles* 24.

Underwood, E., S.L. Ustin, and C. Ramirez. 2007. A comparison of spatial and spectral resolution for mapping invasive plants in coastal California. *Environmental Management* 39:63-83.

Underwood, E., S.L. Ustin, and D. Depietro. 2003. Mapping nonnative plants using hyperspectral imagery. *Remote Sensing of Environment* 6:150-161.

United Nations. 2007. *Percentage of Total Population Living in Coastal Areas*. http://www.un.org/esa/sustdev/natlinfo/indicators/methodology_sheets/oceans_seas_coasts/pop_coastal_areas.pdf.

USDA (U.S. Department of Agriculture). 2017. *World Agricultural Production*. Circular Series WAP 11-17, November. Washington, DC: Foreign Agricultural Service, USDA.

Ustin, S.L., A.A. Gitelson, S. Jacquemoud, M. Schaepman, G.P. Asner, J.A. Gamon, and P. Zarco-Tejada. 2009. Retrieval of foliar information about plant pigment systems from high resolution spectroscopy. *Remote Sensing of Environment* 113:S67-S77.

Ustin, S.L. 2016. Preface: Remote sensing of biodiversity. *Remote Sensing* 8(6):508.

van der Werf, G.R., J.T. Randerson, L. Giglio, G.J. Collatz, P.S. Kasibhatla, and A.F. Arellano, Jr. 2006. Interannual variability in global biomass burning emissions from 1997 to 2004. *Atmospheric Chemistry and Physics* 6:3423-3441.

van der Werf, G.R., J.T. Randerson, L. Giglio, G. Collatz, M. Mu, P.S. Kasibhatla, D.C. Morton, R. Defries, Y.V. Jin, and T.T. Van Leeuwen. 2010. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009). *Atmospheric Chemistry and Physics* 10:11707-11735.

van der Werf, G.R., R.A. Houghton, J.I. House, J. Pongratz, R.S. DeFries, M.C. Hansen, C. Le Quéré, and N. Ramankutty. 2012. Carbon emissions from land use and land-cover change. *Biogeosciences* 9:5125-5142.

van der Werf, G.R., J.T. Randerson, L. Giglio, T.T. Van Leeuwen, Y. Chen, B.M. Rogers, M. Mu, et al. 2017. Global fire emissions estimates during 1997-2016. *Earth System Science Data* 9:697-720.

Van Oost, K., T. Quine, G. Govers, S. De Gryze, J. Six, J. Harden, J. Ritchie, G. Mccarty, G. Heckrath, and C. Kosmas. 2007. The impact of agricultural soil erosion on the global carbon cycle. *Science* 318:626-629.

Vantrepotte, V., and F. Melin. 2009, Temporal variability of 10-year global SeaWiFS time-series of phytoplankton chlorophyll a concentration. *Ices Journal of Marine Science* 66:1547-1556.

Veloso, A., S. Mermoz, A. Bouvet, T.L. Toan, M. Planells, J.F. Dejoux, and E. Ceschia. 2017. Understanding the temporal behavior of crops using Sentinel-1 and Sentinel-2 like data for agricultural applications. *Remote Sensing of Environment* 199:415-426.

Verbesselt, J., A. Zeileis, and M. Herold. 2012. Near real-time disturbance detection using satellite image time series. *Remote Sensing of Environment* 123:98-108.

Verpoorter, C., T. Kutser, D.A. Seekell, and L.J. Tranvik. 2014. A global inventory of lakes based on high-resolution satellite imagery. *Geophysical Research Letters* 41:6396-6402.

Verrelst, J., J.P. Rivera, G. Leonenko, L. Alonso, and J. Moreno. 2014. Optimizing LUT-based RTM inversion for semiautomatic mapping of crop biophysical parameters from Sentinel-2 and -3 data. Role of cost functions. *IRRR Transactions on GeoScience and Remote Sensing* 52:257-269.

Vierling, K.T., L.A. Vierling, W.A. Gould, S. Martinuzzi, and R.M. Clawges. 2008. Lidar: shedding new light on habitat characterization and modeling. *Frontiers in Ecology and the Environment* 6:90-98.

Wang, H., D.J. Jacob, M. Kopacz, D. Jones, P. Suntharalingam, J.A. Fisher, R. Nassar, S. Pawson, and J. Nielsen. 2009. Error correlation between CO_2 and CO as constraint for CO_2 flux inversions using satellite data. *Atmospheric Chemistry and Physics* 9:7313-7323.

Wang, R., J.A. Gamon, C.A. Emmerton, H. Li, E. Nestola, G.Z. Pastorello, and O. Menzer. 2016a. Integrated analysis of productivity and biodiversity in a southern Alberta prairie. *Remote Sensing* 8:214.

Wang, R., J.A. Gamon, R.A. Montgomery, P.A. Townsend, A.I. Zygielbaum, K. Bitan, D. Tilman, and J. Cavender-Bares. 2016b. Seasonal variation in the NDVI-species richness relationship in a prairie grassland experiment (Cedar Creek). *Remote Sensing* 8:128.

Ware, D.M., and R.E. Thomson. 2005. Bottom-up ecosystem trophic dynamics determine fish production in the Northeast Pacific. *Science* 308:1280-1284.

Weber, T., J.A. Cram, S.W. Leung, T. DeVries, and C. Deutsch. 2016. Deep ocean nutrients imply large latitudinal variation in particle transfer efficiency. *Proceedings of the National Academy of Sciences* 113:8606-8611.

Welp, L.R., P.K. Patra, C. Rödenbeck, R. Nemani, J. Bi, S.C. Piper, and R.F. Keeling. 2016. Increasing summer net CO_2 uptake in high northern ecosystems inferred from atmospheric inversions and comparisons to remote-sensing NDVI. *Atmospheric Chemistry and Physics* 16:9047-9066.

Westberry, T., M. Behrenfeld, D. Siegel, and E. Boss. 2008. Carbon-based primary productivity modeling with vertically resolved photoacclimation. *Global Biogeochemical Cycles* 22.

Westberry, T.K., M. J. Behrenfeld, A.J. Milligan and S.C. Doney. 2013. Retrospective satellite ocean color analysis of purposeful and natural ocean iron fertilization. *Deep Sea Research Part I: Oceanographic Research Papers* 73:1-16.

White, J.C., M.A. Wulder, T. Hermosilla, N.C. Coops, and G.W. Hobart. 2017. A nationwide annual characterization of 25 years of forest disturbance and recovery for Canada using Landsat time series. *Remote Sensing of Environment* 194:303-321.

Wiens, J.J., and M.J. Donoghue. 2004. Historical biogeography, ecology and species richness. *Trends in Ecology & Evolution* 19:639-644.

Williams, A.P., and J.T. Abatzoglou. 2016. Recent advances and remaining uncertainties in resolving past and future climate effects on global fire activity. *Current Climate Change Reports* 2:1-14.

Wood, S.N. 2006. *Generalized Additive Models: An Introduction with R*. 2nd edition. Texts in Statistical Science. Boca Raton, FL: CRC Press.

Wright, D.H., D.J. Currie, and B.A. Maurer. 1993. Energy Supply and Patterns of Species Richness on Local and Regional Scales. Pp. 66-74 in *Species Diversity in Ecological Communities: Historical and Geographical Perspectives* (R.E. Ricklefs and D. Schluter, eds.). Chicago: University of Chicago Press.

Wulder, M.A., J.C. White, R.F. Nelson, E. Næsset, H.O. Ørka, N.C. Coops, T. Hilker, C.W. Bater, and T. Gobakken. 2012. Lidar sampling for large-area forest characterization: A review. *Remote Sensing of Environment* 121:196-209.

Xi, X., G.W. McCarty, D.L. Karlen, and C.A. Cambardella. 2017. Topographic metric predictions of soil redistribution and organic carbon in Iowa cropland fields. *CATENA* 160:222-232.

Xia, J., S. Niu, P. Ciais, I.A. Janssens, J. Chen, C. Ammann, A. Arain, P.D. Blanken, A. Cescatti, D. Bonal, and N. Buchmann. 2015. Joint control of terrestrial gross primary productivity by plant phenology and physiology. *Proceedings of the National Academy of Sciences* 112: 2788-2793.

Yoder, J.A., S.C. Doney, D.A. Siegel, and C. Wilson. 2010. Study of marine ecosystems and biogeochemistry now and in the future: Examples of the unique contributions from space. *Oceanography* 23:104-117.

Zhang, Q., E.M. Middleton, Y.B. Cheng, K.F. Huemmrich, B.D. Cook, L.A. Corp, W.P. Kustas, A.L. Russ, J.H. Prueger, and T. Yao. 2016. Integrating chlorophyll fAPAR and nadir photochemical reflectance index from EO-1/Hyperion to predict cornfield daily gross primary production. *Remote Sensing of Environment* 186:311-321.

Zhang, Y., X. Xiao, L. Guanter, S. Zhou, P. Ciais, J. Joiner, S. Sitch, X. Wu, J. Nabel, and J. Dong. 2016. Precipitation and carbon-water coupling jointly control the interannual variability of global land gross primary production. *Scientific Reports* 6:39748.

Zhao, M., and S.W. Running. 2010. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science* 329:940-943.

Zheng, B.J., J.B. Campbell, Y. Shao, and R.H. Wynne. 2013. Broad-scale monitoring of tillage practices using sequential Landsat imagery. *Soil Science Society of America Journal* 77:1755-1764.

Zhu, W., Q. Yu, Y.Q. Tian, R.F. Chen, and G.B. Gardner. 2011. Estimation of chromophoric dissolved organic matter in the Mississippi and Atchafalaya river plume regions using abovećsurface hyperspectral remote sensing. *Journal of Geophysical Research: Oceans* 116.

Zona, D., B. Gioli, R. Commane, J. Lindaas, S.C. Wofsy, C.E. Miller, S.J. Dinardo, S. Dengel, C. Sweeney, and A. Karion. 2016. Cold season emissions dominate the Arctic tundra methane budget. *Proceedings of the National Academy of Sciences* 113:40-45.

9

Climate Variability and Change: Seasonal to Centennial

INPUT SUMMARY

Earth system science—theory, observations, and modeling—of the coupled atmosphere-ocean-biosphere-cryosphere system (Figure 9.1)—has advanced significantly in recent decades. There is now a better recognition of the principal gaps in knowledge that need to be filled in order to understand and predict both the natural variability and the long-term human-induced changes occurring in the Earth system. Reducing uncertainties in our predictions of the changing Earth system will help realize numerous economic benefits (e.g., the ability to reduce costs in mitigation and adaptation strategies, provide increased security for the agricultural sector, and improve the overall health of society). Increasingly accurate quantification of variability, changes, trends, and extremes in the climate system, on time scales from seasonal to centennial and longer, will positively impact several societal sectors and provide sustained opportunities to improve quality of life, safeguarding both lives and property.

Beginning with a focus on the impacts of improved understanding of climate variability and change, the Panel on Climate Variability and Change: Seasonal to Centennial identified a number of priority science topics for which key satellite measurements, together with complementary measurements from other platforms, will make a significant scientific impact with corresponding societal benefits. Table 9.1 summarizes the panel's scientific and application priorities, as addressed in its questions and the measurement objectives.

These climate topics and the measurements needed to address them (Table 9.2) crosscut through all aspects of our Earth system, such as weather and air quality (including extreme events), ecosystems, and hydrology. Many of the topics and questions accordingly lend themselves to consideration under the various crosscutting and integrating theme concepts identified by this decadal survey (e.g., water and energy cycles, carbon cycle, etc.). Crucial and often unique elements of measurements targeted for climate questions are (1) the need for continuity of measurements across multiple decades, (2) observations of a wide variety of

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NOTE: This chapter was written by members of the Panel on Climate Variability and Change: Seasonal to Centennial and is provided for reference only. Any study finding or consensus recommendation will appear in Chapters 1-5, the report from the survey steering committee.

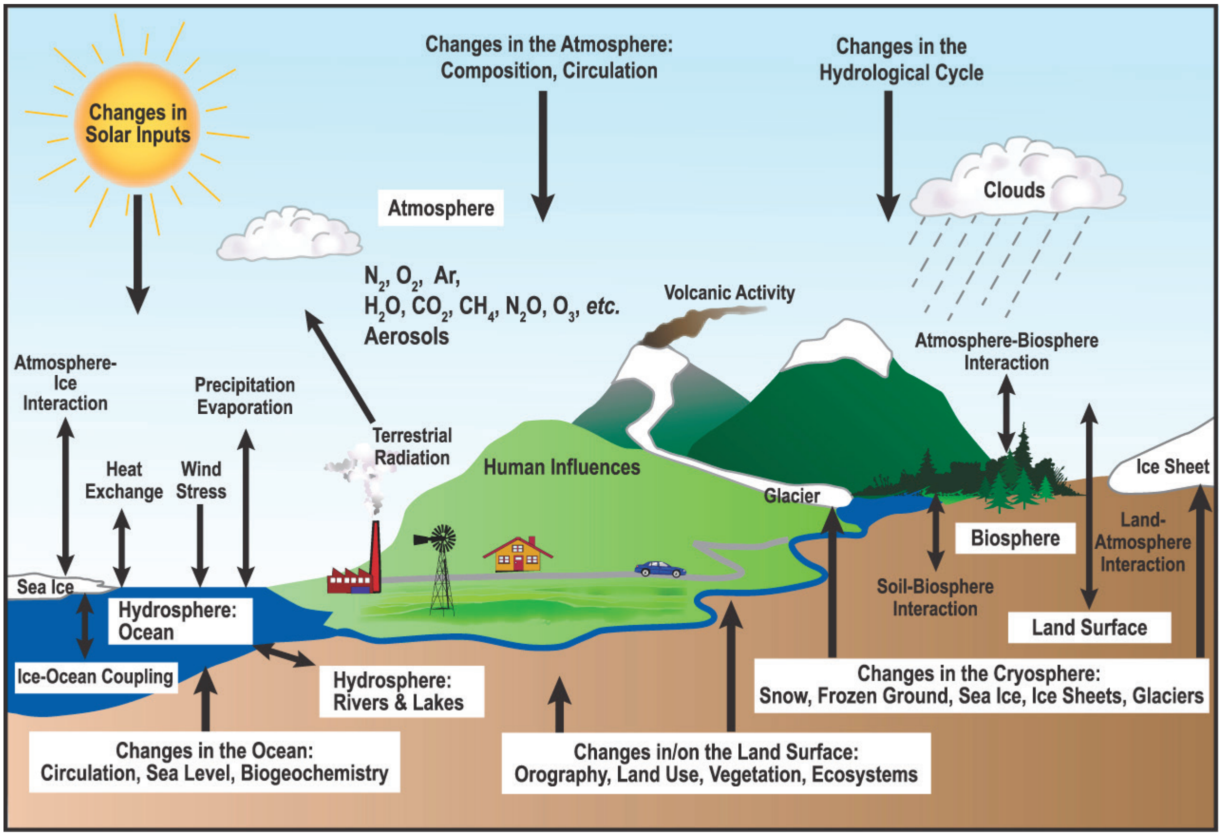

FIGURE 9.1 Schematic depicting components of the Earth system illustrating the coupled atmosphere, oceans, biosphere, and cryosphere system. Important processes such as changes in atmospheric composition owing to natural and human-influenced factors, and feedbacks such as those involving the hydrologic cycle (e.g., clouds), influence the state of the system—for example, land and ocean surface temperatures, precipitation, and sea level. SOURCE: IPCC (2007, p. 96).

variables, and (3) a need for highly precise and accurate measurements. In Table 9.2, the highest priority science and application objectives are mapped to the Targeted Observables that will strongly contribute to addressing those objectives.[1]

Observation strategies to address the complexity of climate processes and their interactions in the Earth system require careful coordination and synergy among satellite and in situ measurement programs. This is a critical time for climate observations, as several National Aeronautics and Space Administration (NASA) climate-related satellite observation platforms are aging, pointing to a risk of shortfalls in crucial, societally relevant scientific information. A number of new techniques, measurement strategies, and observational technologies are now available for the production of new, cost-effective, and beneficial measurements, thus providing an invaluable opportunity to advance the science for improved understanding of the Earth system and societal benefits.

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[1] Not mapped here are cases where the Targeted Observables may provide a narrow or an indirect benefit to the objective, although such connections may be cited elsewhere in this report.

TABLE 9.1 Summary of Science and Applications Questions and Their Priorities

Science and Applications Questions		Highest Priority Science and Applications Objectives (MI=Most Important, VI=Very Important)
C-1	How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?	**(MI) C-1a.** Determine the global mean sea-level rise to within 0.5 mm/yr over the course of a decade. **(MI) C-1b.** Determine the change in the global oceanic heat uptake to within 0.1 W/m^2 over the course of a decade. **(MI) C-1c.** Determine the changes in total ice-sheet mass balance to within 15 Gton/yr over the course of a decade and the changes in surface mass balance and glacier ice discharge with the same accuracy over the entire ice sheets, continuously, for decades to come. **(VI) C-1d.** Determine regional sea-level change to within 1.5-2.5 mm/yr over the course of a decade (1.5 corresponds to a ~6000 km^2 region, 2.5 corresponds to a ~4000 km^2 region).
C-2	How can we reduce the uncertainty in the amount of future warming of Earth as a function of fossil fuel emissions, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?	**(MI) C-2a.** Reduce uncertainty in low and high cloud feedback by a factor of 2. **(VI) C-2b.** Reduce uncertainty in water vapor feedback by a factor of 2. **(VI) C-2c.** Reduce uncertainty in temperature lapse rate feedback by a factor of 2. **(MI) C-2d.** Reduce uncertainty in carbon cycle feedback by a factor of 2. **(VI) C-2f.** Determine the decadal average in global heat storage to 0.1 W/m^2 (67% confidence) and interannual variability to 0.2 W/m^2 (67% confidence). **(VI) C-2g.** Quantify the contribution of the upper troposphere and stratosphere (UTS) to climate feedbacks and change by determining how changes in UTS composition and temperature affect radiative forcing with a 1-sigma uncertainty of 0.05 W/m^2/decade. **(MI) C-2h.** Reduce the IPCC AR5 total aerosol radiative forcing uncertainty by a factor of 2. One objective associated with this question was ranked Important (C-2e). See subsequent sections for details.
C-3	How large are the variations in the global carbon cycle and what are the associated climate and ecosystem impacts in the context of past and projected anthropogenic carbon emissions?	**(VI) C-3a.** Quantify CO_2 fluxes at spatial scales of 100-500 km and monthly temporal resolution with uncertainty <25% to enable regional-scale process attribution explaining year-to-year variability by net uptake of carbon by terrestrial ecosystems (i.e., determine how much carbon uptake results from processes such as CO_2 and nitrogen fertilization, forest regrowth, and changing ecosystem demography.) Six objectives associated with this question were ranked Important (C-3b, C-3c, C-3d, C-3e, C-3f, C-3g). See subsequent sections for details.
C-4	How will the Earth system respond to changes in air-sea interactions?	**(VI) C-4a.** Improve the estimates of global air-sea fluxes of heat, momentum, water vapor (i.e., moisture), and other gases (e.g., CO_2 and CH_4) to the following global accuracy in the mean on local or regional scales: (1) radiative fluxes to 5 W/m^2, (2) sensible and latent heat fluxes to 5 W/m^2, (3) winds to 0.1 m/s, and (4) CO_2 and CH_4 to within 25%, with appropriate decadal stabilities. Three objectives associated with this question were ranked Important (C-4b, C-4c, C-4d). See subsequent sections for details.

TABLE 9.1 Continued

	Science and Applications Questions	Highest Priority Science and Applications Objectives (MI=Most Important, VI=Very Important)
C-5	A. How do changes in aerosols (including their interactions with clouds, which constitute the largest uncertainty in total climate forcing) affect Earth's radiation budget and offset the warming due to greenhouse gases? B. How can we better quantify the magnitude and variability of the emissions of natural aerosols, and the anthropogenic aerosol signal that modifies the natural one, so that we can better understand the response of climate to its various forcings?	**(VI) C-5a.** Improve estimates of the emissions of natural and anthropogenic aerosols and their precursors via observational constraints. **(VI) C-5c.** Quantify the effect that aerosol has on cloud formation, cloud height, and cloud properties (reflectivity, lifetime, cloud phase), including semidirect effects. Two objectives associated with this question were ranked Important (C-5b, C-5d). See subsequent sections for details.
C-6	Can we significantly improve seasonal to decadal forecasts of societally relevant climate variables?	**(VI) C-6a.** Decrease uncertainty, by a factor of 2, in quantification of surface and subsurface ocean states for initialization of seasonal-to-decadal forecasts. Two objectives associated with this question were ranked Important (C-6b, C-6c). See subsequent sections for details.
C-7	How are decadal-scale global atmospheric and ocean circulation patterns changing, and what are the effects of these changes on seasonal climate processes, extreme events, and longer term environmental change?	**(VI) C-7a.** Quantify the changes in the atmospheric and oceanic circulation patterns, reducing the uncertainty by a factor of 2, with desired confidence levels of 67% ("likely" in IPCC parlance). **(VI) C-7c.** Quantify the linkage between global climate sensitivity and circulation change on regional scales including the occurrence of extremes and abrupt changes. Quantify the expansion of the Hadley cell to within 0.5 degrees latitude per decade (67% confidence desired); changes in the strength of AMOC to within 5% per decade (67% confidence desired); changes in ENSO spatial patterns, amplitude, and phase (67% confidence desired). Three objectives associated with this question were ranked Important (C-7b, C-7d, C-7e). See subsequent sections for details.
C-8	What will be the consequences of amplified climate change already observed in the Arctic and projected for Antarctica on global trends of sea-level rise, atmospheric circulation, extreme weather events, global ocean circulation, and carbon fluxes?	**(VI) C-8a.** Improve our understanding of the drivers behind polar amplification by quantifying the relative impact of snow/ice-albedo feedback versus changes in atmospheric and oceanic circulation, water vapor, and lapse rate feedback. **(VI) C-8b.** Improve understanding of high-latitude variability and midlatitude weather linkages (impact on midlatitude extreme weather and changes in storm tracks from increased polar temperatures, loss of ice and snow cover extent, and changes in sea level from increased melting of ice sheets and glaciers). **(VI) C-8c.** Improve regional-scale seasonal to decadal predictability of Arctic and Antarctic sea-ice cover, including sea-ice fraction (within 5%), ice thickness (within 20 cm), location of the ice edge (within 1 km), and timing of ice retreat and ice advance (within 5 days). **(VI) C-8d.** Determine the changes in Southern Ocean carbon uptake due to climate change and associated atmosphere/ocean circulations. Five objectives associated with this question were ranked Important (C-8e, C-8f, C-8g, C-8h, C-8i). See subsequent sections for details.

TABLE 9.1 Continued

Science and Applications Questions		Highest Priority Science and Applications Objectives (MI=Most Important, VI=Very Important)
C-9	How are the abundances of ozone and other trace gases in the stratosphere and troposphere changing, and what are the implications for Earth's climate?	The objective associated with this question was ranked Important (C-9a). See subsequent sections for details.

NOTE: Important (I) measurement objectives are not shown, but are included in the text in subsequent sections of this chapter. For objectives that reduce uncertainty by a factor of 2 or 3, the uncertainty refers to that described in major recent scientific reports such as the Intergovernmental Panel on Climate Change (IPCC) AR5. Confidence ranges appear for some of the objectives, marking a desired level of quantification.

TABLE 9.2 Priority Targeted Observables Mapped to the Science and Applications Objectives That Were Ranked as Most Important (MI) or Very Important (VI)

Priority Targeted Observables	Science and Applications Objectives
Aerosol Vertical Profiles	C-2g, C-2h, C-5a, C-7a
Aerosol Properties	C-2g, C-2h, C-5a, C-7a
Temperature, Water Vapor, Planetary Boundary Layer (PBL) Height	C-2b, C-2g, C-2h, C-4a, C-7a, C-7c, C-8a
Atmospheric Winds	C-2h, C-4a, C-5a, C-7a, C-7c
Radiance Intercalibration	C-2a, C-2b, C-2c, C-2h, C-5c, C-7c
Precipitation and Clouds	C-2a, C-2g, C-2h, C-5c, C-7a, C-7c
Ice Elevation	C-1c, C-8a, C-8b, C-8c
Mass Change	C-1a, C-1b, C-1c, C-1d
Greenhouse Gases	C-2d, C-3a, C-4a
Surface Characteristics	C-2h, C-3a, C-5a, C-8c
Ozone and Trace Gases	C-2g
Sea-Surface Height (SSH)	C-1a, C-1b, C-1d, C-4a, C-6a, C-7a, C-8a, C-8b, C-8c
Terrestrial Ecosystem Structure	C-2d
Ocean Ecosystem Structure	C-2d
Aquatic-Coastal Biogeochemistry	C-2d, C-5a
Snow Depth and Snow Water Equivalent (SWE)	C-7a C-8c
Soil Moisture	C-3a, C-5a, C-6a, C-7a
Salinity	C-6a, C-7a
Surface Deformation and Change	C-1c
Ocean Surface Winds and Currents	C-1d, C-4a, C-5a, C-6a, C-7a
Vegetation, Snow, and Surface Energy Balance	C-7a
Surface Topography and Vegetation	C-1c, C-7a

The societal benefits derived from the improved observations associated with each objective include the improved health and well-being of the nation's and world's population and the global ecosystems, along with improvements in global economic and social infrastructure. Observations providing insights into variability and processes and observations providing continued monitoring of the Earth system are both important for assessing the risks associated with climate variations and trends. As improved climate information becomes available, the advancement of knowledge about the Earth system and reductions in uncertainties will allow improved analysis and detection of climate variations and trends, and this can be translated into improved information for vulnerability, mitigation, and adaptation assessments—information that can be used in planning and decision making by stakeholders.

INTRODUCTION AND VISION

Motivation

Climate is intricately intertwined in virtually every aspect of the environment and human activity, shaping ecosystems, societies, and their economies (Carleton and Hsiang, 2016). Climate sets the stage and continually influences the development of natural systems. Whether determining what crops to grow, how to secure freshwater, or where to seek food and fiber from the land and seas, the critical role of climate has long been recognized by civilizations that have flourished around the world. A desire to make the best use of our natural resources has motivated scientific research and observations to better understand what drives climate and to improve predictions of future climate conditions. Indeed, sustained investments in climate observations and scientific research have yielded widespread scientific and societal benefits.

Understanding of climate variation and change across seasons, years, decades, and centuries has improved significantly. The increased knowledge in recent decades has led to improved capabilities to predict regional probabilities for fair weather, extreme heat or cold, droughts, heavy rainfall events, sea-ice coverage, and other climate conditions. For example, several national and international initiatives to investigate and improve seasonal prediction have been launched, including the North American Multi-Model Ensemble (NMME; Kirtman et al., 2014), EUROSIP (Vitart et al., 2007), and the Sea Ice Prediction Network (SIPN). Although still early in the development process, these forecasts are already used by farmers to help decide what seed varieties to plant each year, by water managers to inform choices about reservoir levels, by the military and transportation sectors to guide Arctic operations, and by many others (NASEM, 2016).

Understanding of long-term climate drivers—including greenhouse gases (GHGs) and aerosols in the atmosphere, land use, and volcanic aerosols and solar variability—and how they affect climate across decades and centuries, has also advanced, allowing us to anticipate, mitigate, and prepare for shifts in climate conditions and their impacts. This knowledge is particularly important today, as the climate is in the midst of a significant worldwide transition. Global mean surface air temperature has increased by 1°C since 1901, and the past 3 years have been the warmest on record (USGCRP, 2017). Through careful observation, analysis, and modeling, a peer-reviewed assessment by the world's scientists (IPCC WG1, 2013) concludes that "it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century,"[2] with more than half of the observed increase in global average surface temperature caused by the anthropogenic increase of greenhouse gas concentrations (arising from burning of fossil fuels, cement production, deforestation, and agriculture) and other anthropogenic forcings together. Assessment of the projected climate change due to different emissions scenarios indicates that, with significant reduction in emissions of greenhouse gases, global average temperature increase could

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[2] IPCC (2013) uses the following terms to indicate the assessed likelihood of an outcome or a result: extremely likely (>95 percent); likely (>66 percent).

be limited to 2°C by the end of the 21st century. With higher emissions scenarios, the annual average global temperature could reach 5°C or more by the end of the century compared to preindustrial times (USGCRP, 2017).

Global warming has impacts on many other parts of the climate system—for example, causing sea ice, glaciers, and ice caps to melt, sea levels to increase, and ecosystems to shift both on land and in the ocean. Some of these climate changes could be effectively irreversible, lasting hundreds to thousands of years, including increasing ocean acidification due to increases in carbon dioxide, sea-level rise, melting of land ice masses, and a reduction in permafrost coverage (IPCC, 2014). A changing climate implies risks to national and global security (food, water, conflicts, and migrations), to major economic sectors (agriculture, transportation, freshwater management, and multiple sectors relying on coastal infrastructure), and to unique and threatened terrestrial and marine ecosystems.

Climate change is now well recognized as a major scientific and societal challenge (e.g., NRC, 2011, 2012; IPCC, 2007, 2014; Melillo et al., 2014; USGCRP, 2017). Reflecting global climate change concerns, there have been concerted efforts by the world community to negotiate and make an advance toward agreements on emissions.

Space-based observations of Earth have been critical for advancing our understanding of global climate processes, climate variations and trends (see Box 9.1).

Despite the significant contributions of space-based observations to climate science, the climate system is not yet adequately measured, as there is no long-term commitment to measure all important variables globally, thereby limiting progress in research and applications. For example, accurate climate prediction relies in part on data used to initialize the forecast, yet many critical variables are not measured routinely (e.g., snow depth on sea ice, sea-ice thickness, soil moistures in the root zone, seafloor bathymetry, Antarctic ice thickness). Many of these variables can be measured only on a global scale economically by satellites; others require investments in in situ measurements. Predictions beyond the decadal scale are essentially limited by uncertainties (and associated modeling deficiencies) in aerosol radiative forcing, in climate feedbacks such as those involving clouds (IPCC WG1, 2013), in ocean and ice variability, and in the evolution of carbon and other biogeochemical and ecosystem cycles (IPCC; U.S. Global Change Research Program [USGCRP]; Melillo et al., 2014). The 2007 Decadal Survey for Earth Science and Applications from Space called for a major increase in NASA Earth science investments in these areas, but increases were realized in only some areas of climate science. The international Global Climate Observing System (GCOS) Implementation Plans (WMO, 2016) have been very effective at defining existing observations that are needed for long-term climate monitoring. But the GCOS plan has been much less effective at planning for needed improvements in the observations to address climate science challenges.

Recent studies have estimated just how valuable improvements in climate information would be to the global economy. For example, narrowing scientific uncertainty in climate sensitivity using an improved climate observing system and modeling could be worth as much as $10 trillion U.S. dollars to the world economy[3] (Cooke et al., 2014, 2016a, 2016b; Hope, 2015). The reduced scientific uncertainties enable improved economic decisions on the relative balance of climate change mitigation versus adaptation. At this value the cost of tripling the current level of global climate research for 30 years would provide a $50 return for every $1 invested (Cooke et al., 2014).[4] Even a factor of 5 uncertainty in this economic analysis would lead to a robust return on investment that would range from 10:1 to 250:1.

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[3] Economic value is specified as either the net present value or the real option value of future economic benefits at a 3 percent discount rate, the nominal value specified in the U.S. Social Cost of Carbon Memo (Interagency Working Group on SCC, 2010). The economic value is an expected value of a large ensemble of simulations using the current range of climate sensitivity uncertainty specified in IPCC (2013).

[4] Current global annual investment in climate research (e.g. observations, analysis, and modeling) is approximately $5 billion U.S. dollars (Cooke et al., 2014). Tripling that level of investment to achieve an observing system optimized for climate research would

BOX 9.1 EXAMPLES OF CRITICAL ADVANCES IN CLIMATE SCIENCE ENABLED BY SPACE-BASED OBSERVATIONS

- Sequentially launched satellites with microwave sounding units have produced a ~40-year trend of atmospheric temperature, providing an important means to confirm trends observed by ground-based in situ sensors (MSU, SSU, AMSU, and ATMS).
- Measurements of altimetry from Jason have shown that sea level is rising, and regional sea-level rise can differ substantially from the global mean.
- It is possible to quantify yearly variations in how fast the oceans are gaining heat (CERES), and to confirm the consistency of decadal ocean heating and sea-level rise (TOPEX/Poseidon, Jason, Jason-2, GRACE, ARGO).
- Using a variety of complementary techniques, it is possible to document the melting, or excess flux above that required to maintain mass equilibrium, of land ice into the ocean, the physical processes driving it, and its growing impact on sea-level rise (InSAR, GRACE, Landsat, Operation IceBridge, EVS-2 OMG, ICESat, CryoSat-2).
- Passive microwave observations from the SSMR, SSM-I, SSMIS, and AMSR instruments have documented the reduction in the areal extent of Arctic sea ice during summer, one of the most visible and profound changes observed in the climate system in response to warming.
- Knowledge of Earth's global energy balance consisting of the solar and longwave components, its governing factors, is advancing. It is now possible to better quantify the effect of clouds on the radiative heating of Earth's atmosphere owing to a longer period of measurements (ERBE, CERES, MODIS, GOES, CloudSat, CALIPSO).
- Understanding of aerosols and their influences on liquid water clouds has improved, including natural and human-influenced contributions (MODIS, MISR, CALIPSO, CloudSat).
- Penetrative active radar sensors can now probe into rain formation processes in clouds (TRMM, CloudSat).
- It is possible to track land use change and ecosystem responses to climate variations, which contribute to improving the understanding of the carbon cycle, while methods to quantify carbon stocks and fluxes are rapidly evolving (Landsat, MODIS, AVHRR, OCO-2).
- There is a better understanding of the changes in the atmospheric composition and geographical distributions of the non-carbon-dioxide, climate-influencing atmospheric trace gases (SAGE, OMI, ACE-FTS, HALOE, MLS, MIPAS).

NOTE: Acronyms are defined in Appendix G.

Vulnerabilities associated with severe seasonal anomalies make yet another pressing case for sustained long-term observations and improved predictions. For instance, the cost of seasonal uncertainty to the agricultural sector is between 20 and 40 percent of the average gross margin, with an expected value of forecast information between $1 and $17/ha depending on the crop. Improved accuracy and longer lead-times could increase this value (e.g., Meza et al., 2008).

The present decadal survey provides guidance on the highest priority observations needed within NASA's current budget profile, as well as a more rigorous and complete set of quantified climate science

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cost an additional $10 billion per year. Return on investment assumes a 30-year commitment to such an enhanced climate research effort, and applies the same 3 percent discount rate used for the value of information (VOI) estimates.

objectives that could be used as the basis for a comprehensive climate observing system. This system could be realized as a combination of U.S. and international observations similar to the current international investment and collaboration on global weather observations—for example, World Meteorological Organization (WMO), GCOS—and it would take advantage of developments in active remote sensing technology—for example, backscatter lidar (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations [CALIPSO]/Cloud-Aerosol Lidar with Orthogonal Polarization [CALIOP]), backscatter radar (CloudSat, Global Precipitation Measurement [GPM]), high spectral resolution lidar and Doppler radar (Earth Cloud Aerosol and Radiation Explorer [EarthCARE])—as well as passive remote sensing capability—for example, greatly improved spectral and spatial resolution and higher accuracy calibration methods. Careful attention to calibration and ground truth will be needed to ensure cross-mission continuity and comparability over decadal time scales.

The need for improved climate observations has become more urgent today, as the extent and pace of climate change increases and the value of improved information is more apparent. More significantly, the "nonstationarity" of climate has become evident (e.g., Milly et al., 2008). Climate science has moved from the vast scope of "unknown unknowns" of the 1980s to many "known unknowns" of the present (e.g., IPCC WG1, 2013). Given the societal relevance of climate variations and the inherent value (economic, human health and welfare, human safety and security) of predicting them before they occur, the current deficiencies in measurements that limit effective monitoring and prediction of these variations need to be addressed through the formulation and implementation of science-based global climate observing strategies using innovative technology. Considerable investment in climate measurement is needed now; the return on the dollar from such investment could be tremendous and long-lasting in the decades to come (Weatherhead et al., 2017).

Science and Applications Challenges

Earth system science—theory, observations, and modeling—of the coupled atmosphere-oceans-biosphere-cryosphere system (Figure 9.1)—has advanced significantly in recent decades. There is now a better recognition of the principal gaps in knowledge that need to be filled in order to understand and predict both the natural variability and the long-term human-induced changes occurring in the Earth system. Strategies for observing, and quantifying, the mechanisms driving climate phenomena and the agents producing climate change are more firmly grounded owing to advances in the prior decade. Developments arising from both space-based and in situ observations over the past decades have revealed important insights into the complexity of the interactions occurring between the atmosphere, ocean, land, and cryosphere, as well as in the trends in key variables (e.g., surface temperature, heavy precipitation, Arctic summertime sea ice, northern hemisphere snow cover).

There has been steady progress from qualitative concepts to quantitative climate science over the past decade by virtue of advances in both observations and numerical modeling. In turn, this has made clear the need for further quantitative climate information through advances in the observation of key variables that are critically relevant for societal objectives. Currently recognized scientific uncertainties in climate (e.g., see IPCC WGI, 2013) strongly indicate the critical need to measure continuously an array of variables, for many decades, in order to ensure a comprehensive understanding of climate forcings and feedbacks, global and regional climate sensitivities, natural variations, and forced changes. There is an equally strong and compelling requirement to quantify trends, taking into account the processes influencing the Earth system, and including a better accounting of uncertainties. For instance, difficulties persist in trying to narrow the bounds on the estimate of Earth's climate sensitivity. Reducing the uncertainty in this parameter will require global measurements of key variables—for example, aerosols, clouds, radiation, ocean heat uptake, and related process studies involving the atmosphere, oceans, biosphere, and cryosphere. For the next decade and beyond, the measurement imperatives include (1) global climate observations, contributing to assessments of the rapidity of change in essential climate variables (e.g., frequency and severity of extreme events); (2) advancing the scientific frontiers using the upcoming decade's observations of the climate system, and characterizing especially the societally relevant changes on continental-to-regional scales; and (3) an emphasis on continuity so that gaps in observations that would preclude or impair scientific understanding and societal benefits are avoided. Especially with regard to the estimation of trends in the key variables of concern to society, focus is needed on obtaining higher levels of precision, and planning for redundancy and cross-validation of measurements.

In deciding which observations are to be made, and in using those observations, the increasing complexity of models and the attendant observational data requirements must be taken into account. These include growing demand for measurements of a vast range of space-and-time-dependent variables on which the models need to be tested and improved. Moreover, observational data are needed now on a widening set of Earth system variables—for example, expanding from the details of the physical climate system to include biogeochemistry and ecosystems. A crucial element is gaining improved knowledge of the processes that govern the Earth system. Additionally, accurate observational data sets are needed to initialize and verify models and for model-based predictions and projections.

The systematic establishment of the scientific basis of climate (e.g., NRC 2012, 2016; IPCC, 2013), together with the ever-increasing evidence that climate is not stationary but instead comprises variations and changes, creates a sound rationale for, and compellingly justifies, continuous global measurements of key climate variables. Analyses of the measurements in turn will continue to improve socioeconomic decision making for many sectors, providing quantitative climate information and uncertainties. There is an even greater demand now for credible global and regional climate data to perform impacts and vulnerability assessments, and in mitigation and adaptation planning that links essential global weather and climate information to serving, protecting, and enhancing property and human life. In effect, there are a multitude of users with differing requirements, rendering it a huge challenge to address all the needs effectively. Societal sectors especially benefiting from climate information in the present and future include agriculture, fisheries, water management, ecosystem management, coastal management, and air quality management, as well as management of long-term transportation and energy infrastructure.

The measurement requirements for long-term monitoring (over time scales of decades) of many climate parameters are challenging and necessitate rigorous calibration/validation across missions. The complexity of climate processes, and the interactions among them, motivates careful coordination of satellite and in situ measurement programs. Simultaneous measurements of multiple variables from space and in situ are needed to produce a reasonably complete and consistent picture of Earth system features and to support transparent estimates of uncertainty in measurement and understanding. It is critical that the focus on climate quality observations be strengthened and sustained—in particular, satisfying the GCOS observing principles (NRC, 2007; Trenberth et al., 2013; Simmons et al., 2016; WMO, 2016; Weatherhead et al., 2017). Collaboration with international space agencies will be important, involving access to calibration, processing, algorithm, and data systems (i.e., some measurements may exist on other platforms but are not accessible, or it is not known how they are calibrated).

Last, continuity of observations of critical climate variables for "seamless" (in time scale) understanding and quantification of climate change is a fundamental scientific objective. Such continuity will allow the assessment of the robustness of trends determined for climate variables that are superimposed on the naturally varying system. Thus, sustaining climate observations will need to be an important element of the decadal survey. This will also challenge the current paradigm in the lack of a single agency "owning" the entire end-to-end climate observations and monitoring missions.

A wide range of NASA satellite sensors relevant to climate, including those measuring variables that plausibly have a trend against the backdrop of variations, are aging, and this threatens to produce gaps in the measurement record that would reduce, and perhaps even preclude, our ability to quantify critical trends (NRC, 2015). It is imperative to find ways to sustain key measurements in the face of aging platforms and to rigorously link measurements across missions. Emerging new technologies can be used to avoid these gaps and improve the accuracy of critical climate observations (e.g., aerosols, clouds, radiation balance, temperature and humidity, ice-sheet dynamics). Strategic investments are needed in infrastructure for "ground-truthing" that can link satellite measurements to internationally recognized calibration scales and that can serve multiple missions.

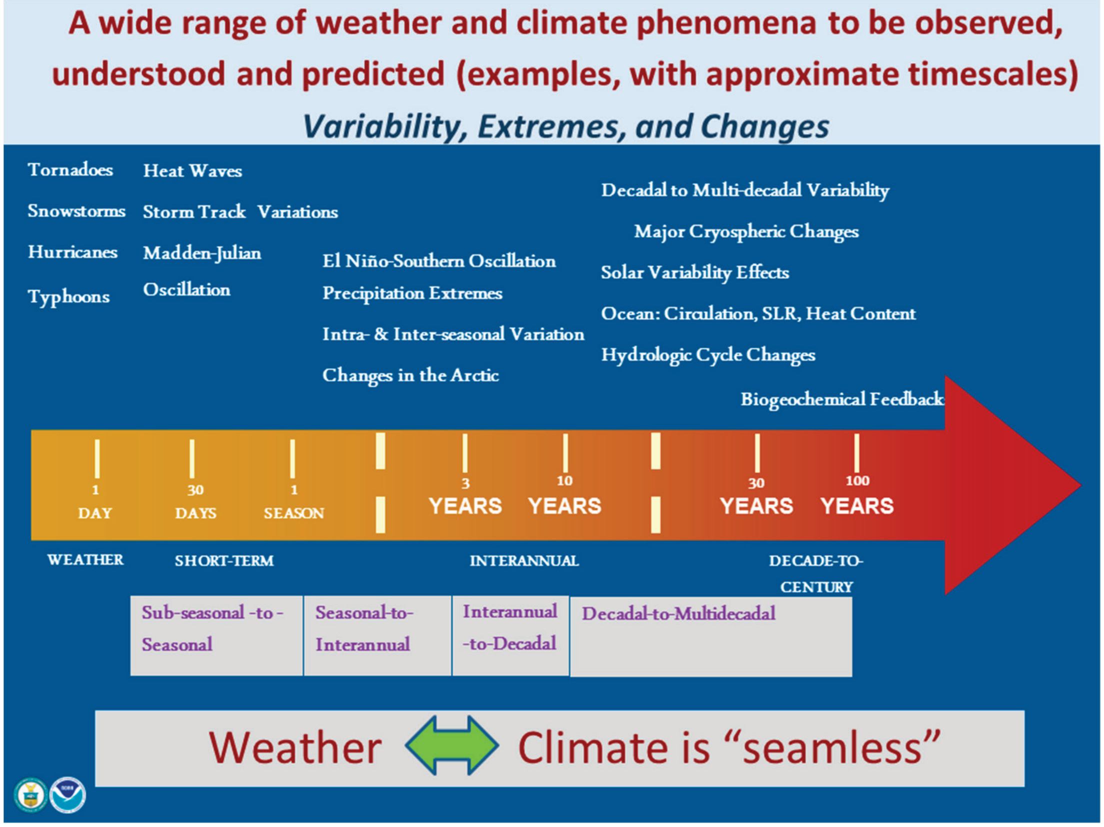
Opportunities

The next decade of space-based climate observations presents opportunities for exciting breakthroughs that would build on the progress of the past decade. As discussed later, these opportunities build upon (1) improvements in understanding of climate processes; (2) advancements in data science and the resulting ability to produce better reanalyses; (3) the use of model projections in concert with advanced instrument capabilities; (4) enhanced coordination among funding agencies; and (5) more widespread recognition and sophisticated tools to ensure continuity of observations.

The first is an improved understanding of the important climate processes and phenomena spanning the short to the long time scales (a few examples are illustrated in Figure 9.2), which have to be understood and predicted, including climate variability, changes, and extremes.

This leads to a sharper realization of the key variables to be monitored for characterizing and quantifying variations/changes of environmental consequence to society, as well as the need for continuity in these measurements. Over the past decade there has been an increased recognition of impact-relevant physical, chemical, dynamical, and biogeochemical processes governing climate (e.g., IPCC AR5; Melillo et al., 2014; WMO, 2014). New insights into phenomena of possible abrupt or irreversible changes in the climate system have also elevated the seriousness and invaluable utility of global observations for resolving key climate questions directly related to societal benefits (NRC, 2013). Further, increasing fidelity of climate models, in conjunction with space-based and other global observations over the past decade, has given rise to insights into processes spanning time scales from weather to climate. This has laid the foundation for a more quantitative understanding of critical mechanisms through comprehensive and sustained observations, which in turn can lead to increased certainty of our understanding of the central challenges—for example, variation and trends in climate variables, climate feedbacks and sensitivity, rate of regional sea-level rise, weather-to-climate information on the mean and extremes, and so on. In this regard, further development and expanded use of Climate Observing System Simulation Experiments (COSSEs) are needed to better understand the utility and quality of the required observations for climate change (see NRC, 2015).

Second, improved data management, data initialization, and data assimilation techniques used with global numerical Earth system models have supported improved "reanalysis procedures," which complement and augment space-based and other observational data to estimate the state of the Earth system. Using mathematically optimized techniques and a high-level understanding of Earth system physics, such reanalyses "fill in the gaps" of the measurement record with reasonable confidence, leading to a picture of the Earth system that is comprehensive in both space and time. Importantly, these reanalyses can also ingest a wide variety of measurement types, so that the resulting complete Earth system picture becomes a reflection of all of them. The modeling framework allows satellite-based measurements of one component of the system to improve estimates of remote quantities (e.g., the assimilation of space-based sea-surface temperature measurements can have an impact on the reanalysis continental temperature product). Most



A wide range of weather and climate phenomena to be observed, understood and predicted (examples, with approximate timescales)

Variability, Extremes, and Changes

Tornadoes
Snowstorms
Hurricanes
Typhoons

Heat Waves
Storm Track Variations
Madden-Julian Oscillation

El Niño-Southern Oscillation
Precipitation Extremes
Intra- & Inter-seasonal Variation
Changes in the Arctic

Decadal to Multi-decadal Variability
Major Cryospheric Changes
Solar Variability Effects
Ocean: Circulation, SLR, Heat Content
Hydrologic Cycle Changes
Biogeochemical Feedback

Sub-seasonal -to - Seasonal
Seasonal-to-Interannual
Interannual -to-Decadal
Decadal-to-Multidecadal

Weather ⟺ Climate is “seamless”

FIGURE 9.2 A sampling of important phenomena from the weather to seasonal to decadal to centennial time scales, rendering seamlessness between weather and climate, which has both scientific and societal implications for opportunities and avoidance of risks. SOURCE: Adapted, with permission, from Higgins (2014).

current reanalyses focus on the ocean or atmosphere components separately, although studies have pointed to new methods involving multiple components of the Earth system—for example, ensemble coupled atmosphere-ocean data assimilation (Zhang et al., 2005) and coupled physical-biogeochemical data assimilation (Verdy and Mazloff, 2017). The future of reanalysis, however, lies in the Integrated Earth System Analysis (IESA), which involves assimilating data into a fully coupled complete climate (ocean-land-atmosphere-cryosphere) system to ensure the highest possible self-consistency amid all of the analysis-enhanced climate variable estimates.

The third element is the wider set of opportunities made possible by (1) state-of-the-science model predictions and projections on time scales ranging from weather to climate, based on observations and future scenarios of emissions of important atmospheric constituents; and (2) the advances in instrument technology and remote sensing strategies—for example, more accurate, cheaper, and lighter instrumentation is available now, and methods are available to quantify the consequences of using this technology in numerical models. Projections and predictions of the future state of the Earth system, together with the rapid advances in technology, ensure that the desired measurements to monitor the evolution of the system across various space scales can be performed to a high degree of accuracy. For example, NASA satellites provide a unique global view of the climate system from the surface to the top of the atmosphere and beyond, with the potential for large improvements in resolution and accuracy over current methods due to improved measurement techniques and sensors. Improved surface-based measurements and field campaigns are enhancing global observations from satellites, often with higher temporal and spatial resolution than can currently be observed from space and capturing the Earth system complexity better than before. Improvements in technology for subsurface ocean observations through autonomous vehicles are also shaping our ability to determine the ocean state more completely than in the past. Together with strategic steps in ocean observations that have been shaped through U.S. (NOAA)-led international partnerships—in particular, Argo (and Deep Argo) floats complemented by the potential of biogeochemistry sensors (Biogeochemical-Argo) deployed worldwide (Riser et al., 2016)—there now emerges the ability to quantify the role of the ocean in the Earth system with enhanced perspectives of ocean-atmosphere interactions—for example, subseasonal-to-decadal prediction, energy and hydrologic cycle variations linked to climate variations and change, and heat and CO_2 exchange between the atmosphere and ocean and storage of these quantities in the ocean (e.g., the Southern Ocean Carbon and Climate Observations and Modeling [SOCCOM] Project is performing measurements of carbon and other variables in the Southern Ocean;[5] carbon-climate feedback is one of the World Climate Research Programme [WCRP] Grand Challenges involving the Earth system[6]).

Fourth, improved synergies being developed among federal agencies for observing/monitoring the atmosphere, the oceans, the climate and ecosystems, and the social and economic implications, are leading to important joint undertakings (e.g., involving National Oceanic and Atmospheric Administration [NOAA], NASA, Department of Energy [DOE], Environmental Protection Agency [EPA], National Geospatial-Intelligence Agency [NGA]). These are creating new observational opportunities through interagency common priorities. Collaboration with new international long-term observation programs such as the European Space Agency (ESA) Copernicus/Sentinel satellites are adding complementary observational platforms, affording an increase in observing instruments. Synergies between programs (e.g., Committee on Space Research [COSPAR]) and space agencies (e.g., Japan Aerospace Exploration Agency [JAXA], Indian Space Research Organization [ISRO], ESA, Canadian Space Agency) are notably augmenting the understanding of the global climate system.

Fifth, a wide range of recent reports has recognized the critical need for continuity of climate records (NRC, 2007; IPCC, 2013a; NASEM, 2015; WMO, 2016). Most climate observations lack the inherent absolute accuracy required to survive even short 1-year gaps without seriously degrading the climate record (NRC, 2007; Trenberth et al., 2013; NASEM, 2015). Continuity is especially challenging for satellite records where instruments have widely varying lifetimes on orbit. A range of recently developed analysis tools make it much easier to consider the statistical risk of satellite record gaps (Loeb et al., 2009), as well as the amount of degradation to climate records should gaps occur (Leroy et al., 2008; Wielicki et al., 2013; NASEM, 2015; Shea et al., 2017). Last, new instrument technologies have been developed to provide international standard traceable spectrometers in orbit to enable accurate calibration across climate record gaps for reflected solar and thermal infrared climate instruments (NRC, 2007; Wielicki et al., 2013; NASEM, 2015). The Global Space-Based Intercalibration System (GSICS) has requested orbiting climate accuracy reference spectrometers to serve as the basis for their intercalibration system to enable reducing the effect of gaps on climate records, as well as to improve the consistency and accuracy of current intercalibration standards for satellite instruments (Goldberg, 2011). A similar approach is envisioned in

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[5] See Princeton University, Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) Project, "Overview," https://soccom.princeton.edu/content/overview.

[6] See World Climate Research Programme, "WCRP Grand Challenges," https://www.wcrp-climate.org/grand-challenges/grand-challenges-overview.

the Committee on Earth Observing Satellites (CEOS)/World Meteorological Organization (WMO)/ Committee for Meteorological Satellites (CGMS) joint study on an Architecture for Climate Monitoring from Space (Dowell et al., 2012). Understanding of the continuously evolving Earth system (depicted in Figure 9.1) crucially requires continuity of observations. Furthermore, continuous measurements of atmospheric, oceanic, biospheric, and cryospheric variables are essential for sustained predictions of the system from the weather to climate time scales. A continuum of time scales also meets the urgent need for the U.S. weather and climate communities to successfully address "seamlessness" in weather-to-climate forecasting (e.g., NRC, 2012), taking into account not only the "average" weather or climate but also the occurrence of the extremes (e.g., the "tails" of the probability distribution function of atmospheric and ocean states; see IPCC, 2013, Technical Summary).

Relevant Climate Topics

A number of critically important and currently unresolved/unanswered science and societally related questions rose to the top of the priority list in the panel's deliberations. The quantified Earth science/ application objectives producing the Most Important priorities are associated with the following questions.

C-1: Sea-level Rise: Ocean Heat Storage and Land-Ice Melt

The rise of the global mean sea level is an integrated response to the change of a major part of the Earth system caused by the warming of the planet. The change of the global mean sea level is now well determined from spaceborne measurements with sufficient accuracy to evaluate not only the rate of change but also the various factors affecting the change (Cazenave et al., 2014; Leuliette and Nerem, 2016). On the basis of observations and modeling studies confidence in projections of global-mean sea level has improved (IPCC WG1, 2013). However, significant uncertainties remain, particularly related to the magnitude and rate of the land ice-sheet contribution for the twenty-first century and beyond, the regional distribution of sea-level rise, and the regional changes in storm frequency and intensity of relevance for coastal impacts. Shown in Figure 9.3 are the IPCC WG1 (2013) estimates of the range of global sea-level rise under various emission scenarios and the contributions from the various sources such as ocean warming and glacier melting. Predicting the geographic pattern and rate of sea-level rise is a grand challenge relevant to coastal infrastructure and human habitation. The need for reliable information on future sea-level rise is further underscored by the increase in flood frequency during high tides in U.S. coastal cities (Sweet and Park, 2014; Sweet and Marra, 2015), which impacts the health of coastal communities.

The rate of future sea-level rise is highly uncertain, especially in terms of upper bounds in potential sea-level rise (Pfeffer et al., 2008; Parris et al., 2012; Sriver et al., 2012). These new studies have placed the upper bound of the rise of the global mean sea level by 2100 from 1 m (IPCC AR5) to 2.5 m (NOAA, 2017). Maintaining, and improving, the sea-level measurement system is crucial for monitoring and predicting the future sea-level rise, which will potentially alter coastlines and affect the security and prosperity of society, particularly with half of the world's population living close to the coast.

Since the industrial revolution the extra heat from greenhouse gas warming is mostly (>90 percent) stored in the ocean (Cheng et al., 2017). The rate of the change of ocean heat storage is of crucial importance to the prediction of future climate and sea level. The global ocean heat gain over the 0-2000 m layer during 2006-2013 was estimated to be 0.4-0.6 W/m^2 (Roemmich et al., 2015). This estimate was based on direct measurement by the Argo array. It shows a large uncertainty. Over the course of the twenty-first century, as the global oceans warm, it will be important to monitor both (1) the warming of the surface, especially in the subtropical and tropical regions; and (2) penetration of heat into the deeper ocean, espe-

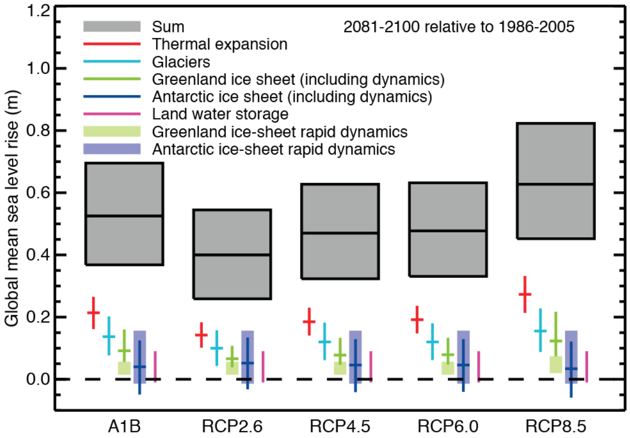

FIGURE 9.3 Projections from process-based models with *likely* ranges and median values for global mean sea-level rise and its contributions in 2081-2100 relative to 1986-2005 for the four representative concentration pathways scenarios (IPCC, 2013) and scenario SRES A1B used in IPCC (2007). The contributions from ice sheets include the contributions from ice-sheet-induced rapid dynamical change, which are also shown separately. The contributions from ice-sheet rapid dynamical change and anthropogenic land-water storage are treated as having uniform probability distributions, and as independent of scenario (except that a higher rate of change is used for Greenland ice-sheet outflow under RCP 8.5). This treatment does not imply that the contributions concerned will not depend on the scenario followed, only that the current state of knowledge does not permit a quantitative assessment of the dependence. Only the collapse of the marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified, but there is *medium confidence* that it would not exceed several tenths of a meter of sea-level rise. SOURCE: Church et al. (2013, p. 1180, Figure 13-10).

cially in the Southern Ocean (IPCC, 2013). A combination of spaceborne and in situ observing systems is required to accurately determine the change of global ocean heat storage (Llovel et al., 2014; Fu, 2016).

C-2: Climate Feedbacks and Sensitivity

A key reason for the well-known uncertainty in climate change projections is the fact that the models making the projections do not fully agree on how sensitive various facets of the climate system (e.g., clouds and their radiative feedbacks) are to radiative forcing of the climate system. Radiative forcings can occur due to natural factors, such as solar irradiance and emissions from volcanic eruptions, or arise due to human influences—for example, greenhouse gas and aerosol emissions and land use changes. The "sensitivity" refers to how the global and regional systems respond to changes in these factors. Physical processes in the climate system produce feedbacks that control the warming of Earth in response to increases in the well-mixed greenhouse gases. Further complicating the matter, the magnitude and sign of the radiative forcing (RF) of climate measured as the perturbation in radiative flux change at the tropopause, due to anthropogenic aerosols, are highly uncertain (Smith and Bond, 2014), as shown in Figure 9.4. The radiative cooling of climate due to anthropogenic aerosols (blue boxes, Figure 9.4) have and could continue to offset a portion of the warming due to greenhouse gases (lower error bar of box labeled Total Anthropogenic) or not (upper error bar, Total Anthropogenic). While observations and model-based studies have contributed to a better understanding of water vapor and cloud feedbacks, there continues to be uncertainty as to the

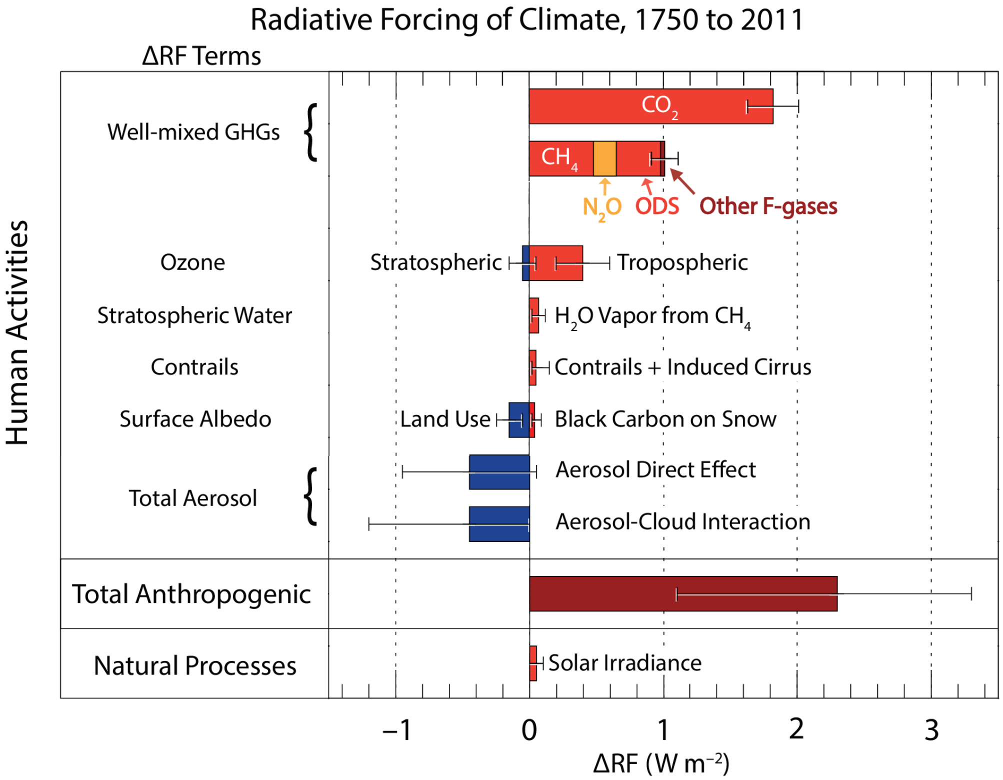

FIGURE 9.4 Change in radiative forcing of climate (ΔRF) over the course of the Anthropocene (1750-2011) due to human factors (GHGs and aerosols) and natural processes (solar irradiance). Error bars represent the 5 and 95 percent confidence intervals. The ODS entry represents ΔRF due to ozone-depleting substances such as CFC-11, CFC-12, and so on. The Other F-gases entry represents ΔRF due to HFCs, PFCs, SF_6, and NF_3. SOURCE: Salawitch et al. (2017, Figure 1.4).

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sign and magnitude of the feedbacks due to clouds. This, in turn, leads to an unacceptably large range in the value of the climate sensitivity.

The influences on precipitation due to the anthropogenic emissions, especially relative to natural variability, are uncertain in the model projections (IPCC, 2013). While climate models generally agree on the projected increase in precipitation in the twenty-first century over the high latitudes, they can disagree on even the sign of change in the low to midlatitudes. Thus, hydrologic cycle-related observations also must be made for a complete understanding of both thermal and hydrologic feedbacks in the surface-atmosphere response to radiative forcings.

Very Important and Important goals were also identified to address the following questions.

C-3: Carbon Cycle, Including Carbon Dioxide and Methane

Changes in radiative forcing arising from greenhouse gas emissions, principally CO_2 and CH_4 (see Figure 9.4), have been and will likely continue to be the most important driver of climate change in the twenty-first century. The land biosphere and the ocean together currently absorb over half of the CO_2 emitted by human activities. Understanding climate-carbon cycle feedbacks—for example, release to the atmosphere of carbon stored in vulnerable reservoirs such as permafrost, frozen methane hydrates, or tropical forests—in a changing climate has been recognized as an important goal by the IPCC WG1 (2013). Additionally, methane is a primary sink for the hydroxyl radical, and thus critically important for atmospheric chemical processes and global air quality due to its regulation of the oxidation capacity of the atmosphere.

C-4: Atmosphere-Ocean Flux Quantification

The current inability to quantify air-sea fluxes is a critical source of uncertainty in closing the global energy, water, and carbon cycles (e.g., L'Ecuyer et al., 2015; Rodell et al., 2015). The interface between atmosphere-ocean, atmosphere-land, and ocean-ice systems represents the coupling of Earth system components operating physically on different time scales such that the interactions between them lead to variations and changes in the states of the climate system. The exchange of heat, moisture, and momentum between the ocean and atmosphere helps drive the atmospheric circulation, contributes to precipitation variability, and modulates the heat storage of the ocean. The carbon exchange between the ocean and atmosphere represents one of the significant unknowns regarding uptake by the surface and the ability of the Earth system to store carbon outside of the atmosphere. It thus becomes important to quantify these accurately.

C-5: Aerosols and Aerosol-Cloud Interactions

The nature of these interactions has a critical—and largely unquantified—impact on climate sensitivity to anthropogenic emissions. An additional critical factor is the influence of the radiative forcings on regional precipitation, with indications that the effect of anthropogenic aerosols could be comparable to that of the greenhouse gases (e.g., Asian monsoon, Bollasina et al., 2011; northern hemisphere precipitation, Polson et al., 2014). Progress on this long-known limitation (e.g., Anderson et al., 2003) has been slow, due to the complexity of the problem and the difficulty of representing these processes within global models.

C-6: Seasonal-to-Interannual Variability and Predictions

Improved seasonal forecasts, including, for example, drought forecasts and sea-ice forecasts and particularly forecasts of the potential for weather extremes governed by atmospheric and ocean states, will lead to direct economic benefits through improved water management, agricultural planning, and so on, yet are currently limited by inaccuracies in forecast initialization arising due to uncertainties in observations and in the model physics used to evolve the states forward (NRC, 2016).

C-7: Decadal-scale Changes and Extremes in Atmospheric and Oceanic Circulation Patterns

Changes in large-scale circulation regimes could have substantial impact on regional weather extremes (droughts, flooding, hurricanes, etc.). Such changes can arise due to the variability in ocean states or to the forcing posed by greenhouse gases, aerosols, and other anthropogenic factors as well as natural (solar, volcanic aerosol) radiative perturbations (Yang et al., 2013). The nature of such circulation changes, however, is very uncertain (Abraham et al., 2013) and is subject to the same challenges as seasonal-to-interannual predictability.

C-8: Causes and Effects of Polar Amplification

Improved understanding of the connection between polar processes and global climate would help improve seasonal-to-decadal prediction. The Arctic and Antarctic are expected to respond relatively quickly to global climate change, and Arctic warming may already be associated with significant impacts on mid-latitude weather (Richter-Menge et al., 2016). In addition, land-ice changes can affect global-to-regional sea-level rise, glacier changes will affect river hydrology and freshwater supply for large populations, while thaw of the large permafrost carbon pool will affect the global carbon cycle. Observations and research are necessary to quantify how the expansion of open water areas from Arctic sea-ice loss and large reductions in hemispheric snow cover extent amplify Arctic warming (e.g., 2-3 times more than the global-mean currently), and how this in turn is correlated with changing atmosphere and ocean conditions in North America including sea-level rise. In the Antarctic the effect of the ozone hole and the increased concentration of greenhouse gases in Earth's atmosphere has caused a strengthening of the westerlies and polar contraction of the winds that can affect sea-ice extent and land-ice melt in a significant way (Thompson et al., 2011; Spence et al., 2014), and may have exerted an influence on the southern hemisphere ocean circulation (Solomon et al., 2015).

C-9: Ozone and Other Trace Gases in the Stratosphere and Troposphere

Due to the success of the Montreal Protocol, which was enabled by space-based and other observations and accompanying model studies, the ozone layer is on course for recovery from prior depletion caused by the buildup of ozone depleting substances (ODSs). The pace and thickness of the ozone layer recovery will be dictated by future evolution of GHGs such as CH_4 and N_2O (Ravishankara et al., 2009; Revell et al., 2015), in addition to ODSs. Since the climate, particularly in the southern hemisphere during summer (Polvani et al., 2011), has been influenced by prior depletion of the ozone layer, the anticipated ozone recovery could cause a further change. Changes in the distributions of radiatively active trace gases such as ozone and H_2O in the upper troposphere and lower stratosphere have also been shown to influence the global climate (Gettelman et al., 2011; Riese et al., 2012).

Together, these questions, the needs and the purposes served by addressing them, and their associated goals, define the measurement objectives identified by the panel.

PRIORITIZED SCIENCE OBJECTIVES AND ENABLING MEASUREMENTS

Rationale

The following questions were used as a basis for determining the scientific rationale for each of the key climate objectives discussed here: What is the unresolved science question being addressed, why is it important, and how is it societally relevant? How does meeting the objective build upon, substantiate, or add innovatively to the knowledge about processes, variations, and change in the Earth system arising from historical measurements? What gaps exist in our current set of measurements? Why are the measurements important today, and what will be needed in the decades ahead? What are the principal climate uncertainties to be reduced—in processes, in understanding, and in making predictions—that lead to tangible, measurable gains for society? It should be noted that a complete weather and climate observing system could address many more scientific unknowns and could provide many more benefits than are addressed here; however, given current budgetary constraints, the panel realized that such a complete system is untenable and therefore prioritized the objectives to be met and the measurements needed to meet them.

Societal Benefit

Examples of the societal benefits derived from the improved observations associated with the following objectives are detailed within the discussion of each objective; these benefits include the improved health and well-being of the world's populations and the world's ecosystems, and improvements in global economic and social infrastructure. Observations providing insights into variability and processes, and observations providing continued monitoring of the Earth system are both important for assessing the risks associated with climate variations and trends. As improved climate information becomes available, the advancement of knowledge about the Earth system and for reducing its uncertainties will allow improved detection of climate variations and trends. This can be translated into improved information for vulnerability, mitigation, and adaptation assessments—information that can be used in planning and decision making by stakeholders.

The information needed for the science and the associated societal advances will require continuity (over decades) in the space-based observations, complemented by critical surface and other in situ measurements. Critical analysis of the measurements as well as combining the data within a state-of-the-science reanalysis system will provide a comprehensive and quantitative picture of a broad suite of climate variables; using this information to evaluate and improve forecast models will in turn provide valuable predictions of important climate processes, variables, and risks.

It should be explicitly noted that socioeconomic scenarios that span the full range of possible futures (e.g., futures that depend on varying emissions trajectories for greenhouse gases and global mitigation policy implementation) will frame the context for the evaluation of the societal benefits. The range adds to the uncertainties that exist because of gaps in our current understanding of the physical system (e.g., range of climate sensitivities due to emissions of greenhouse gases, sensitivity of sea-level rise to thermal expansion of water, and ice-sheet dynamics due to changing ocean and air temperatures).

Prioritization Based on Scientific Importance and Societal Significance

All of the scientific questions that were discussed by this panel and reported here were deemed to be of high significance from the perspectives of both science and societal benefit; they are of value in improving predictions and reducing uncertainty across a wide variety of climate phenomena and processes, and should be the focus of climate observations over the coming decade.

Objectives framed by the panel are associated with science questions spanning the subjects listed here. As articulated by the Steering Committee, the range of questions in the context of this decadal survey has been partitioned into Most Important, Very Important, and Important categories.

The subjects that yielded Most Important objectives are as follows:

- *C-1*. Sea-level rise: ocean heat storage and land-ice melt
- *C-2*. Climate feedbacks and sensitivity

Other subjects that yielded Very Important and Important objectives are listed here:

- *C-3*. Carbon cycle, including carbon dioxide and methane
- *C-4*. Atmosphere-ocean flux quantification
- *C-5*. Aerosols and aerosol-cloud interactions
- *C-6 and C-7*. Seasonal-to-decadal predictions, including changes and extremes
- *C-8*. Causes and effects of polar amplification
- *C-9*. Ozone and other trace gases in the stratosphere and troposphere

C-1: Sea-level Rise: Ocean Heat Storage and Land-Ice Melt

Motivation

The rise of the global sea level represents an integrated response of the Earth system to the change of climate forced by increased heat stored on the planet. The two main contributors to sea-level rise are increased ocean heat storage, which causes thermal expansion, and melting of land ice (glaciers and ice sheets), which increases ocean mass. The projection of future sea-level rise, especially its geographic pattern in the coastal regions, is a grand challenge facing society. Before the satellite era, the rise of global sea level since the Industrial Revolution was measured using data from sparsely located tide gauges (Douglas, 2001). Over the 20th century, there was a total rise of ~20 cm, with an average rate of 1.7 mm/yr (IPCC WG1; Church et al., 2013). Since the 1990s systematic monitoring by satellite observations has enabled a more accurate assessment, indicating an acceleration in the rate of global sea-level rise to ~3.4 mm/yr over the past two decades (Figure 9.5). This rate is about one-third of the rate observed during the deglaciation some 10,000 years ago (IPCC, 2013).

Over the past 15 years, simultaneous global observations of the sea-surface height from satellite altimetry (e.g., Jason series and Cazenave et al., 2017), ocean mass from satellite gravimetry (Gravity Recovery and Climate Experiment [GRACE]), and ocean density from Argo floats have made it possible to measure and partition the global sea-level change in terms of ocean warming and mass changes. This data set provides an overdetermined system for cross-comparison of the closure of the sea-level budget to estimate its uncertainty (Leuliette and Willis, 2011). The Argo network provides estimates on the thermal expansion contribution to sea-level change for comparison with the difference of the altimetry and GRACE measurements. Such analysis has shown that we are able to determine the change of the rate of global sea-level rise

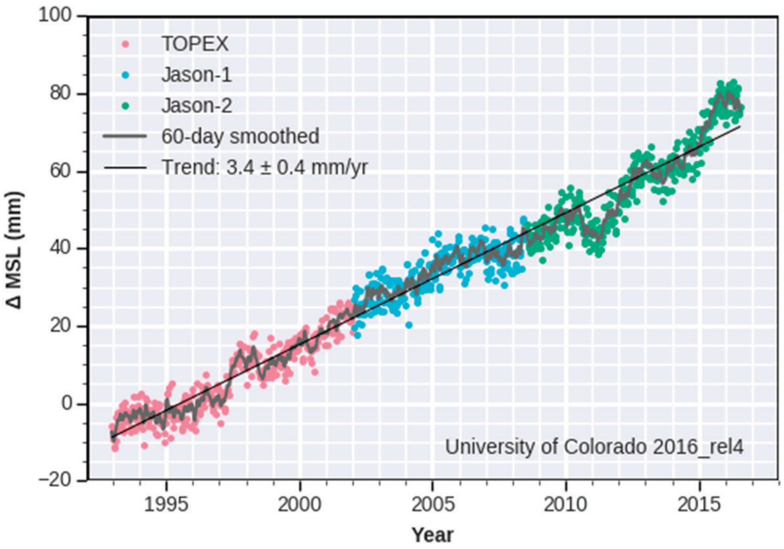

FIGURE 9.5 Global mean sea-level record from a series of satellite altimetry missions. This figure was based on precision altimetry missions covering 66 degrees N to 66 degrees S. New analysis (Ablain et al., 2017) has compared the rate of sea-level rise from these missions with that from high-inclination missions, arriving at 2.98 mm/year (the former) versus 2.36 mm/year (the latter) for the period 1993-2011. SOURCE: Adapted by Steven Nerem from Nerem et al. (2010). Reprinted by permission of the publisher, Taylor & Francis Ltd, http://www.tandfonline.com.

to within 1 mm/yr (1-sigma) evaluated over the course of one decade (NRC, 2015; Fu, 2016). A decade is considered a minimum duration over which an estimate of the rate of sea-level change is relevant to the effects of climate change. This rate of sea-level change over a decade is comparable to the level of sea-level acceleration over the past 50 years (Church and Clark, 2013), representing the benchmark of the signal of sea-level change resulting from climate change in the coming decades. Therefore, a priority measurement objective should be to determine the global mean sea-level rise to within 1 mm/yr over the course of a decade with 95 percent confidence. Assuming Gaussian statistics, 1 mm/yr corresponds to two standard deviations of the measurement uncertainty, so at the level of one standard deviation, a measurement accuracy of 0.5 mm/yr is needed. Note that the root-sum-square of the 0.4 mm/yr measurement error and the 0.3 mm/yr error from the seasonal/interannual variability is 0.5 mm/yr (Fu, 2016).[7]

More than 90 percent of the energy accumulated by the climate system since the Industrial Revolution is accounted for by a rise in ocean heat content (Cheng et al., 2017). The ability to determine the ocean heat storage change is of great importance to assess the state of climate and its future evolution. On global average the difference between the altimetric measurement of sea-level change and the part caused by melting land ice provides an estimate of the steric sea-level associated with thermal expansion, from which ocean heat storage can be estimated. Taking into account the vertical variation of thermal expansion, Wunsch and Heimbach (2014) estimated, based on global ocean climatologic conditions, the equivalence between the rate of sea-level rise and the rate of ocean warming: 1 mm/yr corresponds to 0.75 W/m^2. The uncertainty in estimating the ocean heat storage change, based on the present observing system of satellite and in situ measurements, is ~ 0.1 W/m^2 /decade (1-sigma) (Fu, 2016). The uptake of heat by the ocean is estimated to be 0.5-1 W/m^2 (Trenberth and Fasullo, 2010; Loeb et al., 2012; Trenberth et al., 2016b). Detection of its decadal change to within 0.1 W/m^2 represents 10-20 percent of the signal.

Much of the uncertainty in estimating the rate of the decadal change of sea level and ocean heat storage stems from the seasonal-interannual (SI) variability (Figure 9.5). Significant improvement in the estimation can be gained from a better determination and prediction of the SI variability. This issue becomes more serious for the estimation of regional sea-level change, as there is a great deal of geographic variability in the pattern of sea-level change over the past 20 years associated with the SI variability (Hamlington et al., 2016). Determination of regional sea-level change is particularly important for understanding the impacts of changes on coastal infrastructure and communities. An approximate estimate of the uncertainty in estimating regional sea-level change can be determined from the reduced degrees of freedom in spatial averaging of the SI variability. Given the one-standard-deviation uncertainty of the global estimate of 0.5 mm/yr/decade, the regional uncertainty ranges from 2.5 mm/yr/decade for a 4000 km × 4000 km region to 1.5 mm/yr/decade for a 6000 × 6000 km region. Note that the major contributor to the estimated uncertainty is SI variability. This indicates the challenge and gain associated with the understanding and prediction of the SI variability in terms of improving the estimate of global and regional sea-level change, as well as the global ocean heat storage change.

Further improvement in the estimation of sea level and ocean heat storage can be gained from enhancing the capacities of the Argo float array. The present array makes measurement of the heat storage in the upper 2000 m of the global oceans. The lack of deep ocean data (Purkey and Johnson, 2010; Johnson et al., 2015) has introduced uncertainty in estimating the ocean heat storage and compromised the calibration of the altimetry/GRACE system. Expanding the Argo array (or a subset of it) to the deep ocean (Johnson et al., 2015) will provide a better calibration of the altimetry/GRACE system and will facilitate a better understanding of the role of heat exchange between the upper and deeper ocean and a more accurate long-term prediction of oceanic heat uptake and expansion.

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[7] The accuracy noted here of 0.5 mm/yr is based on the required measurements accuracy for our scientific objective of determining the global mean sea-level rise to within 1 mm/yr over the course of a decade. Other objectives may require higher accuracies.

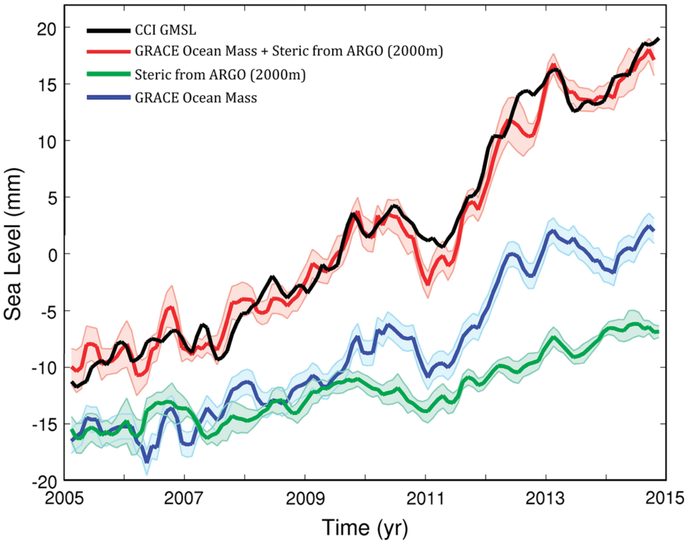

FIGURE 9.6 SL_cci-based global mean sea level (GMSL) (black); Argo-based steric sea level (green); and GRACE-based ocean mass (in equivalent of sea level, blue) over January 2005 to December 2014 (update from Dieng et al., 2015b). The red curve is the sum of the steric and ocean mass components. An arbitrary vertical offset was applied to the green and blue curves for clarity. SOURCE: Reprinted by permission from Springer Nature: Ablain et al. (2017).

Melting Land Ice

Melting of land ice (glaciers, ice caps, and ice sheets) accounts for around 50 percent of the current sea-level rise, a percentage that appears to be increasing in time. Since the 1990s the glaciers and ice caps (GIC) have contributed about 14 mm to global mean sea-level change, and the ice sheets have contributed nearly equally, because the mass loss from the ice sheets has been increasing faster than that from GIC (Shepherd et al., 2012) (Figure 9.6). While the remaining amount of ice stored in the GIC is only about 0.5 m of global sea-level rise (Church et al., 2013), the Greenland and Antarctic ice sheets account for 7 m and 56 m, respectively (Fretwell et al., 2013). Both ice sheets are melting sooner, faster, and more significantly than anticipated from climate warming, and predicting how fast the ice sheets will melt in the coming century and beyond remains a major scientific and societal challenge (IPCC AR5, 2013). Several studies have suggested that a collapse of the northern sector of West Antarctica may already be under way (Favier et al., 2014; Joughin et al., 2014; Rignot et al., 2014).

Detecting changes of the total surface mass balance at the 5 percent level is feasible and necessary to understand regional interactions of ice and climate with sufficient precision and to improve projections from physical models. Details of glacier dynamics need to be understood at the individual glacier level to take into account factors such as bed topography, exposure to warm ocean waters, subglacial hydrology, and surface runoff production. At present, the vast majority of the mass loss from Antarctica is caused by the acceleration of its glaciers, not by a change in precipitation or surface ablation; hence, the need to continuously observe ice dynamics. In Greenland and in a future, warmer Antarctica, surface mass balance processes, especially snow/ice surface melt, will play an increasingly important role. In areas not in contact with the ocean, the glacier and ice-sheet mass loss will be driven by surface mass balance processes, which must therefore be understood and modeled to better than 5 percent in the future. In areas where glaciers and ice shelves terminate in the ocean, the mass loss will be driven by the magnitude of thermal forcing from the ocean, by the shape of the seafloor and glacier bed, and by the rate at which ice breaks up into icebergs—that is, the glacier calving mechanics. Thermal oceanic forcing must therefore be measured along the periphery of ice sheets, using an extension of the Argo network with ice-avoiding capabilities, which is currently limited along the immediate periphery of the ice sheets, and bathymetry also must be measured in detail, in many places for the first time, using a variety of techniques such as multibeam echo sounding from ships, high-resolution airborne gravity combined with in situ seismic surveys, shipborne or air-dropped oceanographic sondes, in front of and beneath floating extensions of glaciers—or ice shelves—around Antarctica and northern Greenland. In Greenland NASA's Earth Venture Suborbital (EV-S) Ocean Melting Greenland airborne mission has initiated such an observation program. There is no Antarctic equivalent comparable in spatial scale and duration at this time that would provide critical information on ocean characteristics (temperature, salinity) in the proximity of Antarctic grounding lines and details about the seafloor topography around the continent and beneath its floating ice shelves. For calving dynamics short temporal resolution (daily to hourly), high-resolution (100 m) measurements are required to gain insights into the complex processes of ice fracturing, including hydrofracture under the action of meltwater, plastic fracture beyond a certain strain, and calving cliff failure beyond a threshold height of ice above hydrostatic equilibrium (Benn et al., 2007). The mechanisms of ice melting by the ocean and ice fracturing are most important to understand since they can increase the rates of glacier flow by one order of magnitude over the coming century, with concomitant effects on the rate of sea-level rise from ice sheets.

A glacier and ice-sheet observing system has already demonstrated its capability and its value to provide modern observations of ice-sheet mass balance and partitioning of the total loss using satellite/airborne altimetry (Ice, Cloud, and Land Elevation Satellite [ICESat], Operation IceBridge [OIB], CryoSat-2); airborne depth radar sounding (OIB); satellite radar interferometry (International Synthetic Aperture Radars [SARs]); and satellite gravity (GRACE). These techniques have also been applied successfully to the more challenging sampling of the world's GIC, which were estimated from sparse in situ data in the past, with large uncertainties. These satellite/airborne techniques provide complementary and essential information about the glacier and ice-sheet mass loss and the processes controlling it, but instruments need to acquire data continuously, with improved calibration and data access, for decades to come. This must happen in combination with development of a network of novel ocean observations along the ice-sheet periphery. The probability of success of these techniques is high given prior heritage from existing/past missions and advances in technology.

Ice-sheet melting remains the largest uncertainty in estimating future sea level. Projections for the turn of the century range from 30 cm, with a more than 96 percent chance of being exceeded, to 2.5 m, with a 0.1 percent chance of being exceeded (NOAA, 2017), depending on the range of climate scenarios (Representative Concentration Pathways, or RCPs) and on the range of acceleration in ice-sheet loss (from none, to linear, to highly nonlinear; Figure 9.7). Over time the uncertainty grows in part due to the uncertainty in future emissions, particularly for the most threatening higher tail of the distribution of future emissions, and so the estimates for 10- and 30-year time horizons are more robust because they can be informed by past local sea-level rise trajectories and real-time refinements in the accuracy borne from more precise measurement of global trends. Projections range from 0.5 m to 10 m global sea-level rise by 2200 (Ritz et al., 2015; DeConto and Pollard, 2016). Evidence of paleo-sea levels meanwhile indicate unequivocally that in prior warm periods with polar temperatures comparable to those expected in the next centuries, sea level rose 6-9 m (Dutton et al., 2015).

The societal benefits that would arise from meeting these initiatives are some of the most obvious in the entire spectrum of climate change risks. Rising seas are creating and will continue to create hazards for human and natural systems along coastlines worldwide. Threats of flooding amplified by storm surges from extreme storms and hurricanes come to mind easily, but evidence is growing that even routine storms create hazards that in turn create profound vulnerabilities and strongly test the abilities of communities to maintain tolerable levels of risk (e.g., Yohe et al., 2011). Improved information from the next generation of remote sensing devices in space and atmospheric missions about the distributions of sea-level rise across a wide range of possible futures will certainly provide more rigorous footing for response decisions—not only for "immediate scale" responses that are routine in most coastal communities, but also for short-, medium-, and long-term investments in protective adaptation as well as coastal infrastructure (in the pri-

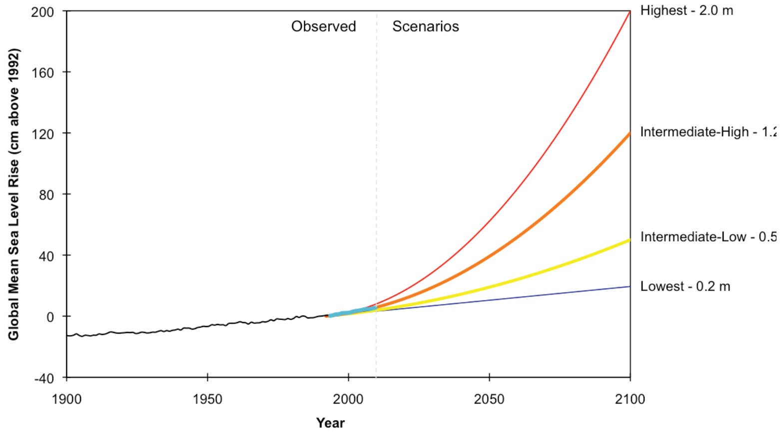

FIGURE 9.7 Global mean sea-level rise scenarios ranging from 0.2 m to 2 m by 2100. These are based on the range of possible scenarios from different scientific studies and reflect different degrees of ocean warming and ice-sheet loss. SOURCE: Parris et al. (2012).

vate and public sectors of our society). Paying attention to using the output of these missions to sustain (1) a series of distributions that span time increments from now through 2100 and beyond (say, for decadal increments from as soon as possible to well into the future) with (2) particular attention paid to the upper tails of those distributions where impacts can be catastrophic will be particularly important. While the proposed missions will certainly improve projections up to 2100, it is in the nearer term where adaptation and investment decisions will be made; it follows that it is perhaps the near to medium time scales (~10-30 years) wherein their values may be the most significant.

Science Question and Application Goals

Question C-1. How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?

In order to make substantial improvement in the ability to predict sea-level rise, several objectives have been identified by the panel:

- *C-1a*. Determine the global mean sea-level rise to within 0.5 mm/yr over the course of a decade (Most Important).
- *C-1b*. Determine the change in the global oceanic heat uptake to within 0.1 W/m^2 over the course of a decade (Most Important).
- *C-1c*. Determine the changes in total ice-sheet mass balance to within 15 Gton/yr over the course of a decade and the changes in surface mass balance and glacier ice discharge within the same accuracy over the entire ice sheets, continuously, for decades to come (Most Important).
- *C-1d*. Determine regional sea-level change to within 1.5-2.5 mm/yr over the course of a decade (1.5 corresponds to a ~6000 km^2 region, 2.5 corresponds to a ~4000 km^2 region) (Very Important).

These objectives are formulated based on the assessment of the measurement capabilities of the observing system established over the last decade. These capabilities are deemed adequate to address the impact of the change of the measured quantities on Earth system science and societal issues. These capabilities must be maintained indefinitely to monitor and predict the continuing change expected in the future from climate change.

Measurement Objectives and Approaches

The measurements needed to achieve these objectives are outlined in the Science and Applications Traceability Matrix (SATM; see Appendix B) for optimal resolutions and approaches. Here, we highlight those priority measurements that are needed to achieve the objective as noted earlier.

- *Sea-surface height*. This is the most fundamental measurement for addressing the sea-level objectives. Satellite altimetry measurement with the accuracy and precision of the Ocean Topography Experiment (TOPEX)/Poseidon mission and the Jason series is required. High-resolution altimetry like the CryoSat-2, Sentinel-3, or Surface Water and Ocean Topography (SWOT) mission is required for measuring sea-surface height close to the coasts. The sea-level change of impact to the coastal population and infrastructure is the sea-level change relative to the land motions. The measurement of precise land motions requires local geodetic network via Global Positioning System (GPS). The impact of sea-level change is manifested via storm surges and long-term change of the local wind field. Measurement of waves and winds with high-spatial resolution over a long period of time is required to address the long-term change of coastal sea level.
- *Ocean mass distribution*. This is essential for determining the part of sea-level change caused by the change of ocean mass, from which the difference with the total sea-surface height, the steric sea level caused by ocean heat storage change, can be derived. The steric sea level is used to determine the change of ocean heat storage. Spaceborne gravity measurement with the accuracy and sampling of GRACE and GRACE-Follow On (GRACE-FO) is required.
- *Ice-sheet mass*. Measurement of the change of the mass of major ice sheets is key to determining the rate of sea-level change caused by the melting of land ice, which is potentially the largest source of future global sea-level rise. Among the processes driving total mass change of the ice sheets, the most significant vector of rapid change is ice dynamics, because glaciers could potentially speed up by one order of magnitude in response to climate forcing. Spaceborne gravity measurement with the accuracy and sampling of GRACE and GRACE-FO is required. Measurements of ice dynamics with interferometric SAR (NASA-ISRO Synthetic Aperture Radar [NISAR] Follow on, Sentinel-1, and others) and optical sensors (Landsat series) are essential on the ice sheets, along with detailed monitoring of ice-sheet grounding lines (within 100 m) using interferometric SAR and detailed measurements of the thickness of the glaciers to constrain their mass flux into the ocean. Improved observational constraints on reconstructions of surface mass balance is also of fundamental importance for projections of future changes. These measurements should be complemented with detailed glacier ice thickness measurements via airborne platforms or a novel satellite mission, especially Antarctica; seafloor bathymetry in fjord and beneath ice shelves; along with a novel network of ocean measurements at the ice-sheet periphery. Measurements of the thickness and thinning rate of Antarctic ice shelves and ice shelves in northern Greenland are critical to understand the role of these ice shelves in buttressing the flow of glaciers, their evolution in a warmer climate, and their subsequent impact on glacier flow and sea-level change.

> The ice sheets account for one-third of the current trend in global mean sea level. Currently, Greenland and Antarctica lose about 300 Gt/yr, with an acceleration of 30 Gt/yr/yr over the time period 1992-2010 (Rignot et al., 2011). We need an observation system that detects changes at the 5 percent level of the total surface mass balance—that is, 15 Gt/yr per decade or 1.5 Gt/yr/yr (NRC, 2016). The GRACE mission is able to detect acceleration at the 3 Gt/yr per decade at present, and combining this with Interferometric Synthetic Aperture Radar (InSAR) and radar measurements of ice fluxes with regional climate model estimates of snowfall accumulation detect changes at the 2 Gt/yr per decade. To understand the processes responsible for mass loss, we need to partition the total mass loss between surface mass balance and ice dynamics, so both need to be known with the same level of accuracy. This requires detailed observations of ice thickness (via airborne radar sounding), surface elevation (via polar satellite altimetry), ice motion (via InSAR and Landsat), grounding lines (via InSAR), and changes in these variables with time. Critical supporting information comes from weather observations (ground network and satellite, reanalysis data) to support regional atmospheric climate model development and evaluation.

Connections to Other Panels and Integrating Themes

The scientific objectives discussed in this section and many of the measurement requirements are also reflected in Chapter 10 on the Solid Earth Panel. Improved estimates of ocean heat storage and changes in land and ocean mass are crucial components of understanding and predicting variability and trends in the global cycles of energy and water. A greater understanding of changes in regional sea level will also provide critical inputs to changes in ecosystems as coastal regions become inundated and saltwater intrusions to local groundwater systems change. Changes to coastal shorelines and ecosystems will significantly impact the effect of extreme weather events as hurricane-induced storm surge and flooding. Improved estimates of climate sensitivity, thermal expansion, and ice-sheet mass balance, as well as improved understanding of the carbon cycle and polar ice amplification proposed in the sections on climate sensitivity, carbon cycle, and decadal-scale atmosphere and ocean circulation, respectively, will progressively help decision makers respond more effectively to what will be a growing challenge for coastal communities.

C-2: Climate Feedbacks and Sensitivity

Motivation

The amount of warming of the global Earth system due to a given level of greenhouse gases is governed by the radiative forcing exerted and climate feedbacks, with climate sensitivity providing a convenient metric to ascertain the total response of the climate system to a given level of forcing. Climate sensitivity is defined as the amount of global average surface temperature change per change in effective radiative forcing (IPCC, 2013). (Surface-air temperature, rather than surface temperature, is used in some data sets.) Several of the key processes contributing to feedbacks that then impact climate sensitivity are addressed in the following objectives sections. The quantitative evaluation of the processes, and thus the feedbacks, are integral to the estimates and physical interpretation of climate sensitivity and to the ensuing climate response to a given forcing. Climate sensitivity is defined in terms of the global-mean impact; however, its utility extends to hemispheric and even continental scales, as the changes tend to be generally correlated with the global-mean, at least in a qualitative sense. Equilibrium climate sensitivity (ECS) describes the Earth system response to radiative forcing on longer time scales (centuries) and is composed of a wide range of feedback processes involving clouds, water vapor, temperature lapse rate, surface albedo, and the carbon cycle. Transient climate response (TCR) describes the response on shorter time scales (decades) and includes only part of the feedback response associated with ECS. Paleo-climate observations are used to estimate climate sensitivity on even longer time scales of thousands of years when feedbacks from ice sheets and geological weathering processes can exert a significant effect. In the near term ECS and TCR are the most relevant quantities for societal decisions, but the two quantities and their uncertainties are closely related (IPCC, 2013). We use ECS to simplify discussion here, but the discussion applies to either TCR or ECS. Note that the discussions here are related to the sensitivity with regard to surface temperature; sensitivity with regard to precipitation is not considered.

To first order, ECS from feedbacks in the physical climate system in combination with carbon cycle feedback yields estimates of the response of the Earth system to future greenhouse gas emissions, as has been deliberated in international climate policy negotiations/agreements. The current uncertainty in ECS is a factor of 4 at 73 percent confidence level with a range of 1.5°C to 6°C for the radiative forcing caused by a doubling of CO_2 in the atmosphere. Figure 9.8 summarizes the range of ECS estimates from climate models and climate observations (IPCC, 2013, Box 12.12). The factor of 4 uncertainty at 73 percent confidence is chosen as intermediate between results shown in Figure 9.8 for a factor of 6 uncertainty (1°C to 6°C) at 85 percent confidence and a factor of 3 uncertainty (1.5°C to 4.5°C) at 66 percent confidence shown.

A large uncertainty in ECS leads to a large uncertainty in the amount of CO_2 that can be emitted to hold warming below specific temperature threshold levels. The large uncertainty in ECS is also one of the largest uncertainties in predicted future economic impacts of any given scenario of future emissions (Interagency Working Group on Social Cost of Carbon Memo, 2010, or SCC, 2010). The economic impacts are driven by sea-level rise, changing agricultural productivity, human health, energy use, and changes in natural ecosystem services (SCC, 2010; NRC, 2017).

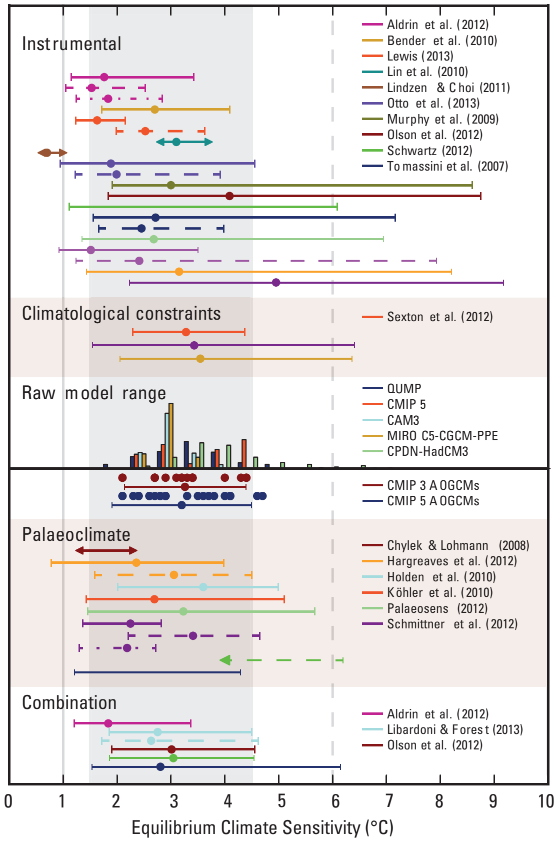

FIGURE 9.8 Probability density functions, distributions, and ranges for equilibrium climate sensitivity based on climate observation and modeling studies. The gray shaded range marks the *likely* (>66 percent probability) 1.5°C to 4.5°C equilibrium climate sensitivity (ECS) range; the gray solid line the *extremely unlikely* (<5 percent probability) ECS less than 1°C; and the gray dashed line the *very unlikely* (<10 percent probability) ECS greater than 6°C. SOURCE: Collins et al. (2013, p. 1110, Box 12.2, Figure 1).

As a rough approximation, the long-term economic impacts vary as the square of the amount of global temperature increase (SCC, 2010; Kopp et al., 2012). As a result an ECS uncertainty of a factor of 4 leads to a factor of 16 uncertainty in long-term economic impacts, and is the largest single scientific uncertainty in estimating the impacts due to carbon emission scenarios (SCC, 2010). A factor of 2 reduction in ECS uncertainty would lead to a large reduction in the uncertainty of future climate change economic impacts, in the social cost of carbon, and in societal plans for future emissions reductions needed to limit climate change to an agreed upon maximum warming level. Reducing the uncertainty in climate sensitivity has been estimated to have an economic value of roughly $10 trillion U.S. dollars to global society at the Net Present Value discount rate of 3 percent used as the nominal value by the SCC 2010 (Cooke at al., 2014, 2016; Hope, 2015). The panel determined that narrowing the uncertainty in ECS, including quantified understanding of the feedback processes, should be one of the highest priorities of climate science.

Science Question and Application Goals

Question C-2. How can we reduce the uncertainty in the amount of future warming of Earth as a function of fossil fuel emissions, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?

The following key objectives have been identified and are discussed in detail in the following sections:

- *C-2a*. Reduce uncertainty in low and high cloud feedback by a factor of 2 (Most Important).
- *C-2b*. Reduce uncertainty in water vapor feedback by a factor of 2 (Very Important).
- *C-2c*. Reduce uncertainty in temperature lapse rate feedback by a factor of 2 (Very Important).
- *C-2d*. Reduce uncertainty in carbon cycle feedback by a factor of 2 (Most Important).
- *C-2e*. Reduce uncertainty in snow/ice albedo feedback by a factor of 2 (Important).
- *C-2f*. Determine the decadal average in global heat storage to 0.1 W/m^2 (67 percent confidence) and interannual variability to 0.2 W/m^2 (67 percent confidence) (Very Important).
- *C-2g (see also Question C-9)*. Quantify the contribution of the upper troposphere and stratosphere (UTS) to climate feedbacks and change by determining how changes in UTS composition and temperature affect radiative forcing with a 1-sigma uncertainty of 0.05 W/m^2/decade (Very Important).
- *C-2h (see also Question C-5)*. Reduce the IPCC AR5 total aerosol radiative forcing uncertainty by a factor of 2 (Most Important).

In order to address the science question, the quantitative linkage from process-level Earth system understanding to evaluation of feedbacks to ECS has to be considered. Reducing uncertainty in ECS has proven difficult since the first IPCC report (IPCC, 1990). What has been learned over the last 25 years of climate model and climate data analysis, however, are the sources of uncertainty in the estimation of ECS, and their relative magnitudes (Bony et al., 2006; Soden et al., 2008; IPCC, 2013). Considering these uncertainty sources, we choose as a realistic and critical goal the reduction of the IPCC AR5 uncertainty in ECS by a factor of 2. This type of goal has the advantage of not presupposing the actual value of ECS, but instead of reducing the uncertainty in its estimation. This in turn will greatly reduce uncertainty in societal decisions about the economic value of greenhouse gas emission reductions using current economic resources when compared to savings from reduced adaptation costs in the future.

Climate sensitivity can be quantified as the sum of individual climate feedbacks (Roe and Baker, 2007; Soden et al., 2008; IPCC 2013). Of these feedbacks, cloud feedbacks have been shown to be the largest uncertainty in determining ECS in both observations and climate models (IPCC, 2013), particularly low cloud feedbacks. The process-level understanding involves the quantitative determination of how clouds affect circulation and vice versa (WCRP Grand Challenge). Uncertainty in the cloud feedback and the difficulty in estimating it arises partly from the fact that the spatial scales over which the processes have to be determined span several orders of magnitude (micrometers to kilometers; both horizontally and vertically; e.g., cloud microphysics to mesoscale convective complexes to spatially extensive cirrus shields). This poses an enormous challenge for observational strategies; however, spaceborne measurements offer the best coverage over the entire globe and represent the best opportunity to monitor all the global cloud regimes. The second largest uncertainty is the determination of the combined water vapor feedback and temperature lapse rate feedback. These two feedbacks have a strong negative correlation and are therefore normally considered as a combined feedback uncertainty even though uncertainty in each component can be much larger than the two in combination (IPCC, 2013). Indeed, the water vapor and cloud feedback processes together constitute the interplay between the elements of hydrologic cycle and energy. The lowest uncertainty in the climate sensitivity estimate is surface albedo feedback, which includes vegetation, soil characteristics, and snow/ice influences on the sunlight reflected off the planetary surface. Each of these physical climate system feedbacks is considered in this science question. Figure 9.9 shows a summary of the current understanding of uncertainty in climate feedbacks (from IPCC, 2013, Figure 9.23).

The most recent IPCC report included an extensive discussion of carbon cycle feedbacks and concluded that the uncertainty of these feedbacks, especially over land surfaces, can rival those of the physical climate system (IPCC WG1, 2013). The dominant feedback is the so-called concentration-carbon response

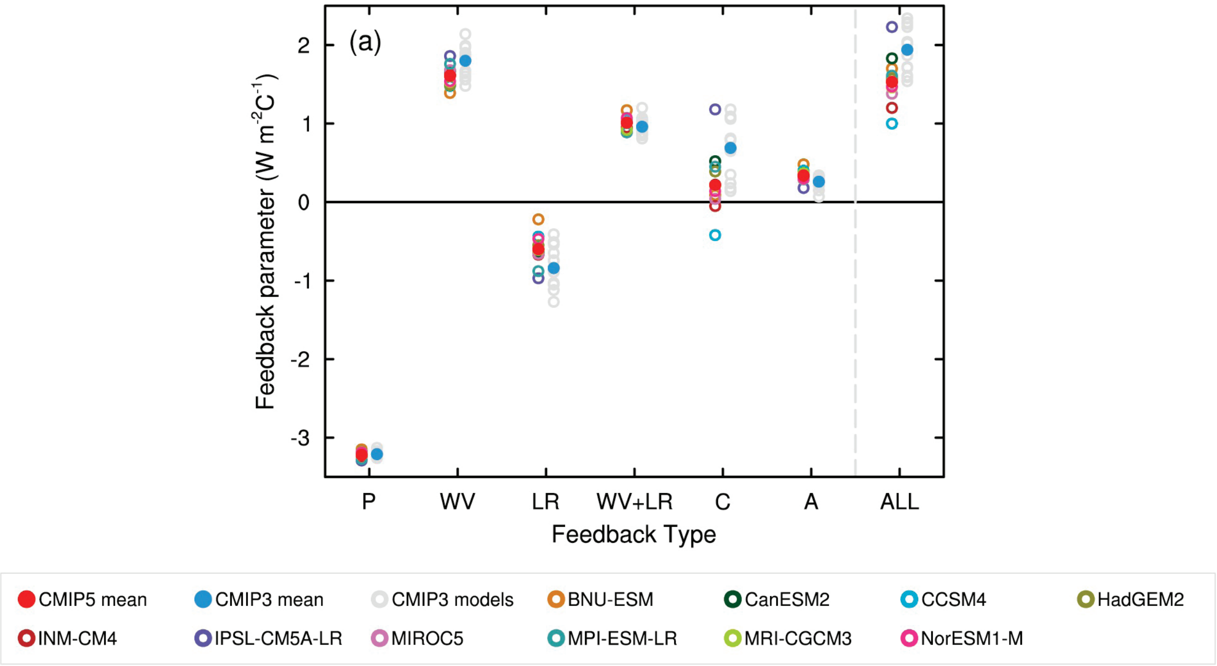

FIGURE 9.9 Strengths of individual feedbacks for a range of IPCC climate models. Feedbacks are Planck (P), water vapor (WV), temperature lapse rate (LR), combined water vapor/lapse rate (WV+LR), cloud (C), surface albedo (A), and total of all feedbacks (ALL). SOURCE: Flato et al. (2013, p. 819, Figure 9.43).

that describes the dependence of carbon storage in ocean and land reservoirs on the changing concentration of CO_2 in the atmosphere (Gregory et al., 2009; IPCC, 2013). The Coupled Model Intercomparison Project Phase 5 (CMIP5) spread in the concentration-carbon response is greater for the land than for the ocean, and important processes are missing from many or all CMIP5 models, such as the role of nutrient cycles, permafrost, fire, and ecosystem acclimation to changing climate (IPCC, 2013). There is a second carbon cycle feedback that results from temperature change, but it is of much smaller magnitude and is similar in uncertainty to surface albedo feedback (IPCC, 2013). Carbon cycle processes and feedbacks are discussed briefly in the following section and treated in more detail by the Ecosystems Panel.

Similarly, aerosol forcing is considered separately in the following sections in terms of the processes governing their direct effect and their interactions with clouds, but here we note briefly two considerations of relevance for ECS. First, one of the key methods to estimate climate sensitivity from observations is to compare the time series of radiative forcing with that of temperature increase. In these types of comparisons the largest uncertainty is not the temperature record but is instead the poorly known levels of direct and indirect aerosol radiative forcing (IPCC, 2013). Reducing uncertainty in aerosol radiative forcing is therefore one method that can assist in reducing uncertainty in climate sensitivity. Second, while the largest feedback uncertainty as part of ECS is cloud feedback, the same clouds we would observe to examine cloud feedback could also be getting impacted by aerosols through the aerosol indirect effect. For both of these reasons the panel decided to include aerosol radiative forcing in this science question although the factors affecting these interactions are dealt with in a separate objective. The panel chose a similar factor of 2 reduction of uncertainty as the science goal.

Last, natural variability of the climate system provides the major “noise” against which anthropogenic climate change must be detected (Weatherhead et al., 1998; Leroy et al., 2008). This noise primarily increases the climate record length needed to clearly see anthropogenic climate signals, including those of climate feedbacks. Most of this noise is internal nonlinear variability of the ocean-atmosphere coupled system (IPCC, 2013). Transient variations in the climate system can arise due to temporary large loadings of stratospheric aerosols from explosive volcanic eruptions such as the 1982 El-Chichon and 1991 Mount Pinatubo eruptions (IPCC, 2013). Other natural factors that can potentially introduce variability, although with smaller amplitudes, include variations in solar irradiance and in naturally occurring tropospheric aerosols (e.g., dust). Knowledge of both natural variability and heat storage variations are required in order to understand and quantify the climate response to anthropogenic radiative forcing—namely, the “signal” above the internal/natural “noise.” Ascertaining natural variability is one prime reason for requiring sustained monitoring of the planet. Typically, variability of the climate system over century time scales is currently obtained from unforced climate model integrations, but long-term observations are required to verify and make these estimates robust.

The panel determined that achieving the objectives related to this science question will produce enormous benefit to both U.S. and global society. It will advance both the understanding of how humankind is forcing the climate system and thus climate responses for a given level of emissions against the backdrop of natural variations, as well as the ability to predict more accurately the future impact of those emissions on human society.

Society’s ability to see current climate forcing and climate change, as well as to predict future climate change, occurs through what can be thought of as three “fuzzy” lenses (Weatherhead et al., 2017). The first fuzzy lens is a result of the noise of natural variability. The second fuzzy lens is a result of the many limitations of our observing system. The third fuzzy lens is a result of limitations and uncertainties in the climate models used for understanding climate and for making climate predictions and projections. Aspects of each of these challenges are addressed in this critical science question.

Measurement Objectives and Approaches

The overarching science question, motivation, and goals lead to a set of quantified objectives involving the observation of physical climate system feedbacks, carbon cycle feedbacks, aerosol radiative forcing, and naturally driven variability of the climate system. The relative importance of each of these goals is based on uncertainties in recent major assessments such as the IPCC WG1 (2013). The largest of these uncertainties are (1) cloud feedback, (2) water vapor-plus-lapse rate feedback, (3) carbon cycle feedback, and (4) aerosol radiative forcing. The remaining quantified objectives are also important, but at a level significantly below these four.

As indicated in the "Introduction and Vision" section at the start of this chapter, solutions to climate science challenges require combined advances in climate process observations, climate modeling, and long-term monitoring observations. Figure 9.10 provides an example of how these elements work together. While the examples in the figure are most relevant to studies of clouds and aerosols, the overall approach is applicable to most climate science challenges.

Similar to the question of sea-level rise, high confidence in the understanding of climate system feedbacks and forcings requires both a measurement of the integrated effect of these long-term (interannual to decadal) changes in the radiation balance of Earth as well as measurement of the underlying physical variables driving the changes in energy balance. Achieving both measurements with consistent results provides a top-down and bottom-up independent verification of results and their uncertainties.

Long-term observations alone, however, are unlikely to be sufficient to improve the underlying process physics in climate models. Many of the uncertain modeling processes such as clouds and aerosols occur at short time and space scales (hours to days) and are often dominated by convection and large-scale dynamics rather than the radiation energetics that drives longer time scale global-mean forcings and feedbacks (Bony et al., 2015). Thus, additional observations specifically targeted at improving climate model processes are needed to enable improved accuracy of climate prediction (seasonal to decadal time scales) and climate projection (decade to century time scales). While modeling studies have enabled an understanding of the quantitative observing requirements for long-term climate feedbacks (Soden et al., 2008; Shea et al., 2017), equivalent observing requirements do not yet exist for cloud or aerosol process studies. This makes selection of new process study observations much more challenging. For example, what level of improvement is needed in measurements of cloud updrafts/downdrafts and mesoscale circulations; higher vertical resolution water vapor profiles; improved high vertical resolution boundary layer temperature, water vapor, and wind profiles; liquid and ice particle size distributions (cloud, rain, and snow); cloud condensation and ice nuclei concentrations; and improved vertical aerosol profiles? Which of these advances would be more important to understand and quantify cloud-climate interactions? While currently uncertain, it should be possible to develop quantitative objectives for process observations. In addition a range of new technologies have the potential to address some of these cloud and aerosol process observations. Table 9.3 provides some examples of potential improvements in cloud process measurements and potential technologies that might be used to address them.

Fortunately, cloud process models at very high spatial resolution of 10 meters to 1 km (Large Eddy Simulation to Cloud Resolving Model) can now run on domains of hundreds to thousands of kilometers, sizes large enough to capture cloud and larger scale dynamics as a system, and sizes that overlap the 30 km to 10 km grid resolution of global climate models. Nested global models that can run simulations on as fine a scale as ~1 km over limited areas of the globe are also under development (e.g., NOAA and NASA). This suggests that field experiments (e.g., EV-S selections) and their more complete data sets from surface, satellite, and aircraft might be used to more rigorously test cloud and aerosol process models on a global scale. It also suggests that high-resolution cloud model Observing System Simulation Experiments (OSSEs),

TABLE 9.3 Example Improved Cloud Process Measurements and Relevant Potential Space Technologies

Example Cloud Process Measurement	Example Space Technology
Convective cloud updrafts and downdrafts	Doppler radar
High vertical resolution accurate water vapor profiles (~100 m, <5% accuracy)	Differential absorption (DIAL) lidar, water vapor absorption line microwave radio occultation
High vertical resolution boundary layer profiles of temperature, water vapor, wind speed/direction	Surface scatterometer winds, wind lidar, DIAL lidar, water vapor radio occultation, temperature lidar using molecular oxygen density
High time resolution (e.g., 15-minute sampling)	Smallsat constellations, geostationary satellites
High-accuracy precipitation and drop size distribution	Multiwavelength doppler radar, multifield of view lidar
Multilayer cloud vertical profiles	Radar, lidar
Thin cirrus vertical distribution, optical properties	High spectral resolution lidar
Surface pressure	Molecular oxygen lidar, Molecular oxygen A-band, numerical weather prediction (NWP) assimilation
Large-scale vertical velocities (50 km and larger)	No current candidate

including global-mesoscale-nested models, might ultimately be capable of more rigorous definition of field experiment and satellite observations needed to test key uncertainties in the process models. While field experiment observations can provide a more complete set of relevant process variables, satellite observations can provide tests on global scales with large statistical sampling. This dichotomy suggests that field experiments and high-resolution cloud models as well as emerging high-resolution global models with nesting capabilities (~1 km resolution over the continental United States) that maintain a physical consistency between large-scale and mesoscale processes might be gainfully used to determine observing system requirements for later global observations from space. In parallel with the field experiments NASA technology programs can be maturing the next generation measurement capabilities. Last, as process models reach higher resolutions and begin to resolve cloud physical processes, existing observations such as from the Afternoon Constellation (A-Train) can be used in new ways to constrain the advancing model capabilities.

Following the earlier discussion, the Climate Panel SATM related to climate sensitivity is focused primarily on long-term observations required to constrain uncertainty in Earth's forcings and feedbacks. From an observations standpoint, the ECS quantification is a less difficult proposition than the comprehensive approach centered on the quantification of each relevant process. As examples of the difficulty, the processes shaping low and high clouds are significantly different, involving various facets of the tropospheric large-scale circulation and convection. Also, precipitation becomes a key element in the understanding of cloud feedbacks, since it affects the lifetime and energy exchanges.

There is less discussion here of the observations that might enable improved process models because of the current difficulty in relating those observations to quantified objectives, and the difficulty of prioritizing which observations are more critical than others or which ones will yield greater dividend earlier. This should not be interpreted as any lack of importance of process observations, nor does it imply that important process-level observations of some relevant aspects of feedbacks are not occurring or are not possible. (For example, cloud radar observations have pointed to an important feedback involving drizzle in clouds that does not appear to be simulated by climate models or well understood.) Instead, the preceding statement should be interpreted as an uncertain balance between the value of field experiments, satellites, and the key variables to measure for each. It is expected that some of the short time scale weather and hydrology science questions will be relevant for process studies of forcings and feedbacks, as will some of

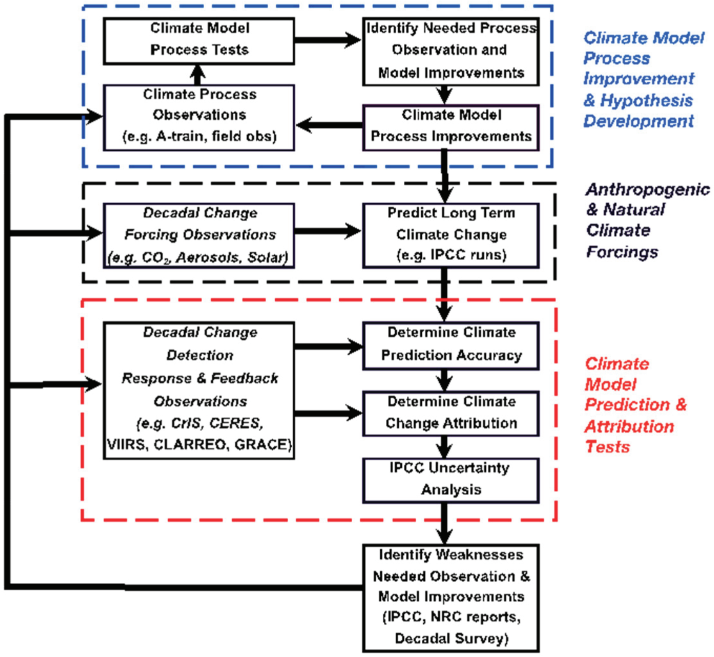

FIGURE 9.10 Schematic showing the role of process and monitoring observations for climate model improvements (blue dashed box), observations of anthropogenic and natural climate forcings (black dashed box), and climate monitoring observations used for detection, attribution, and testing the uncertainty of past and future climate predictions and projections (red dashed box). Narrowing uncertainty in ECS requires an integrated approach of modeling, process, and monitoring observations. SOURCE: Adapted from Springer Nature: Trenberth et al. (2013, Figure 5).

the observations required for long-term observations of forcings and feedbacks, in addition to the existing satellite process observations such as the 10-year A-Train record. We also note that the World Climate Research Programme (WCRP) Grand Challenge on climate sensitivity is focused on several cloud and general circulation modeling studies, along with studies of past observations to move toward improved cloud process models.[8] Ultimately, development and testing of improved cloud and aerosol process models will require advanced short time scale process observations (say, from weather to seasonal time scales), while climate model projection accuracy using the new processes must be verified using sufficiently accurate and complete long-term decadal observations, as shown in Figure 9.10.

A high-level summary of the quantified science objectives and potential measurement approaches is given in this section. Further details can be found in the Climate Panel SATM (see Appendix B).

Objective C-2a. Reduce uncertainty in low and high cloud feedback by a factor of 2 (Most Important).

The largest uncertainty in ECS is caused by low cloud feedback (IPCC, 2013). Climate models vary from negative to positive feedback for low clouds. Studies to separate feedbacks using radiative kernels (Soden et al., 2008; IPCC, 2013) suggest that multidecadal records of shortwave cloud radiative effect (SWCRE) can be used to determine cloud feedback. A similar method is used in analysis of climate model simulations. Verification that the SWCRE is caused by the correct cloud property (cloud fraction, optical

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[8] See https://www.wcrp-climate.org/gc-clouds-circulation-activities/gc4-clouds-initiatives.

depth, phase, particle size) requires observations by CALIPSO-like lidar (cloud fraction, phase) and Visible Infrared Imaging Radiometer Suite (VIIRS)-like global imager (cloud fraction, optical depth, phase, and particle size). Progress has been made in unscrambling cloud feedbacks by cloud property (Zelinka et al., 2012, 2017). These studies suggest that the largest feedbacks occur from changes in cloud fraction, followed by cloud height, and finally cloud optical depth. The optical depth feedback in turn is dominated by changing cloud droplet phase from larger ice crystals to smaller water droplets in high southern latitudes (Zelinka et al., 2012). As a result even cloud particle phase is important to consider as a cloud feedback measurement. To date, the satellite record of SWCRE and cloud properties has lacked sufficient climate record length and accuracy to directly observe low cloud feedback at the required uncertainty level (Dessler, 2010, 2013; IPCC, 2013). The suggested measurement approach to resolve this issue is to continue the climate record of global radiation budget observations by Cloud-Earth Radiant Energy System (CERES)/Radiation Budget Instrument (RBI) and VIIRS to achieve the long record length, but augmented for greater accuracy by intercalibrating CERES/RBI and VIIRS radiometers to a reference SI traceable transfer spectrometer at the required 0.15 percent (k = 1) accuracy level as proposed in the 2007 Decadal Survey Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission (NRC, 2007; Wielicki et al., 2013; Shea et al., 2017).

High cloud feedback is large and positive in all major climate models and results primarily from a change in high cloud height, and therefore in a change between high cloud temperature and surface temperature. The Fixed Anvil Temperature (FAT) hypothesis affords an explanation of the basic large-scale physics of this feedback in the tropics (Hartmann and Larson, 2002). The key radiative fluxes for high cloud feedback are longwave fluxes, while the key cloud physical properties are cloud amount, cloud height, and cloud top temperature. It is noted though that these governing properties are themselves affected by atmospheric dynamics and microphysical (mixed-phase and solid ice) processes. Unfortunately, sufficiently accurate decadal time scale cloud height, temperature, and flux observations from space have not yet been available to directly observe this feedback (IPCC, 2013). For ice clouds, the challenge is even more daunting than for water clouds owing to serious gaps in knowledge of dynamics and microphysics. There are two suggested ways to provide the required accuracy in the observations to verify high cloud feedback: (1) long-term space-based atmospheric lidar similar to at least CALIPSO capability for more accurate cloud height; and (2) much higher accuracy (0.03 k = 1) SI traceable infrared observations from visible/infrared imagers similar to VIIRS, and higher accuracy broadband radiation measurements. One method to achieve this higher accuracy using the operational NOAA VIIRS and NASA CERES/RBI sensors is to intercalibrate each against a reference SI traceable infrared transfer spectrometer at this accuracy level as proposed in the 2007 Decadal Survey CLARREO mission (NRC, 2007; Wielicki et al., 2013; Shea et al., 2017). The requirement for a multidecade record is determined by natural variability of tropical and global average cloud amount, height, and radiative fluxes.

Objective C-2b. Reduce uncertainty in water vapor feedback by a factor of 2 (Very Important).

While cloud feedback is by far the largest uncertainty in ECS, the combination of water vapor feedback and temperature lapse rate feedback (Objective C-2c) are the second largest uncertainties in the physical climate system sensitivity. Current uncertainties are determined from climate model agreement, the Clausius Claperyon relationship of specific humidity increase with temperature at constant relative humidity (7 percent/K) and observations of column water vapor decadal changes (IPCC, 2013). Further observational constraint of water vapor feedback requires decadal time series of temperature profiles and water vapor profiles at higher accuracy than current satellite or surface instruments provide (Xu et al., 2017). In addition, the far-infrared spectrum (longwave radiation at wavelengths beyond 15 micron) has not been observed spectrally, yet this is half of the thermal infrared radiation and the dominant portion of the water vapor greenhouse effect and the dominant source of water vapor feedback. The far-infrared has been observed by broadband radiation instruments such as CERES but only for the integrated longwave radiation across all infrared wavelengths. As a result, there is a marginal observational constraint on changing temperature profile, water vapor profile (especially upper troposphere), and far-infrared spectral radiation trends. One method to achieve such an advance is to utilize decadal trends from the current NOAA Cross-track Infrared Sounder (CrIS) mid-infrared sounder and CERES/RBI broadband radiometer calibrated against a higher accuracy SI traceable standard at the 0.03K (k = 1) accuracy requirement indicated for anthropogenic climate trends by recent studies (Xu et al., 2017). A high-accuracy infrared reference spectrometer including the far-infrared spectrum was proposed by the 2007 Decadal Survey CLARREO mission (NRC, 2007). Global Navigation Satellite System Radio Occultation (GNSS RO) systems such as Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) and COSMIC-2 can provide high-accuracy trends for vertical temperature profiles between 5 and 20 km altitude, but only lower level water vapor profiles. Accuracy of commercial radio occultation systems has yet to be demonstrated. High-accuracy, high vertical resolution water vapor profiles have been proposed using radio occultation signals at new wavelengths in varying strength microwave water vapor absorption lines, and by differential absorption lidar.

Objective C-2c. Reduce uncertainty in temperature lapse rate feedback by a factor of 2 (Very Important).

The logic for this objective is similar to that in Objective C-2b, but without the requirement of water vapor profile or far-infrared spectra observations. Meeting this objective would therefore rely on a combination of CrIS spectrometer observations with GNSS RO systems such as COSMIC and COSMIC-2, or with CrIS combined with intercalibration to a high accuracy (0.03K, k = 1) SI traceable infrared spectrometer such as the 2007 Decadal Survey CLARREO mission (NRC, 2017).

Objective C-2d. Reduce uncertainty in carbon cycle feedback by a factor of 2 (Most Important).

The uncertainty on the carbon cycle is of comparable magnitude to the uncertainty arising from physical climate processes (Gregory et al., 2009; IPCC WG1, 2013), and the panel recognizes the critical and obvious need for measurements to reduce this uncertainty with the designation of Objective C-2d as Most Important. Due to the complexity of measuring and predicting carbon cycle processes, we devote a separate section of this chapter to the topic "C-3: Carbon Cycle, Including Carbon Dioxide and Methane." Note that the Question C-3 objectives are defined with granularity required to derive mission requirements, and consequently no individual C-3 objective is sufficiently broad to receive a rating of Most Important by the Climate Panel. Carbon cycle feedbacks are also treated in Chapter 8.

Objective C-2e. Reduce uncertainty in snow and ice albedo feedback by a factor of 2 (Important).

Surface albedo is the smallest uncertainty feedback, both because of its smaller magnitude and because of the fact that seasonal cycles of snow and ice and sea-ice albedo change have been shown to be a very accurate proxy for the long-term feedback of snow and ice albedo (IPCC, 2013). There are no new observational requirements beyond the operational NOAA VIIRS instrument and a longer accurate climate record to achieve this objective. This observation does not require intercalibration of VIIRS to the high accuracy of the CLARREO reference spectrometer mentioned for cloud feedback or temperature and water vapor feedback to achieve.

Objective C-2f. Determine the decadal average in global heat storage to within 0.1 W/m^2 (67 percent confidence), and interannual variability to 0.2 W/m^2 (67 percent confidence) (Very Important).

This objective overlaps with Objective C-1b at decade and longer time scales. But it adds an interannual component to identify shorter term natural variability of ocean heat storage that Argo sampling cannot achieve. This interannual capability is currently provided by combining Total Solar Irradiance (TSI) observations from Solar Radiation and Climate Experiment (SORCE) and broadband radiation observations from CERES (Von Schuckmann et al., 2016; Hansen et al., 2017). While net radiation alone cannot determine climate sensitivity (due to uncertainty in ocean vertical mixing rates), it does provide a very useful constraint when combined with other observations such as reduced uncertainty aerosol forcing and improved cloud feedback observations.

The panel also notes the importance of monitoring the interannual and decadal variations of the natural radiative forcings of volcanic eruption aerosols and of Total/Spectral Solar Irradiance variability (Hansen et al., 2005; IPCC WG1, 2013; NRC, 2013, 2015) to an accuracy of 0.05 W/m^2 per decade. In the context of naturally occurring aerosols and their plausible interactions with clouds, there will be a need to also monitor the influence of dust emissions from surfaces globally, which can vary on a year-by-year and decadal basis (Prospero et al., 2002; Ginoux et al., 2012; IPCC WG1, 2013). These measurements are important for a wholesome determination of the ECS.

Connections to Other Panels and Integrating Themes

For a given forcing of the system, feedbacks determine the amplitude of the climate system response. In this sense climate forcings and feedbacks link to the Hydrology, Weather and Air Quality, and Ecosystems Panels through the long-term changes in all of these Earth systems. In the same sense climate feedbacks also link closely to the Water and Energy Integrating Theme, the Water Cycle Integrating Theme, and the Carbon Cycle Integrating Theme, as well as the Natural Hazards and Extreme Events Integrating Theme. In some cases the linkage is obvious, as for the carbon cycle climate feedback objective, which overlaps with the Ecosystems Panel as well as the Carbon Cycle Integrating Theme. Another major example is the linkage of the energy cycle and the water cycle through Earth's energy system. Changes in climate forcings and feedbacks modify Earth's energy cycle, which in turn modify the latent heat and precipitation water cycle. Latitudinal changes in the energetics of forcings and feedbacks (e.g., polar amplification) can also drive circulation changes that then lead to changes in the mean hydrologic cycle as well as the frequency of extremes.

C-3: Carbon Cycle, Including Carbon Dioxide and Methane

Motivation

Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas (GHG). The dry air mole fraction of CO_2 has risen from a preindustrial value of ~280 parts per million (ppm) to a contemporary value that exceeded 400 ppm in 2016 (Figure 9.11). Early in the 20th century the rise in atmospheric CO_2 was driven by the clearing of forests for agriculture. Over the past 70 years this rise has been driven by increasing combustion of fossil fuels (IPCC, 2013).

Methane (CH_4) is the second most important GHG emitted by human society. CH_4 has risen from a preindustrial level of 700 ppb to a contemporary value of more than 1800 ppb (Figure 9.11). The radiative forcing (RF) of climate driven by rising CH_4 is about 30 percent of the RF caused by rising CO_2. Weighted

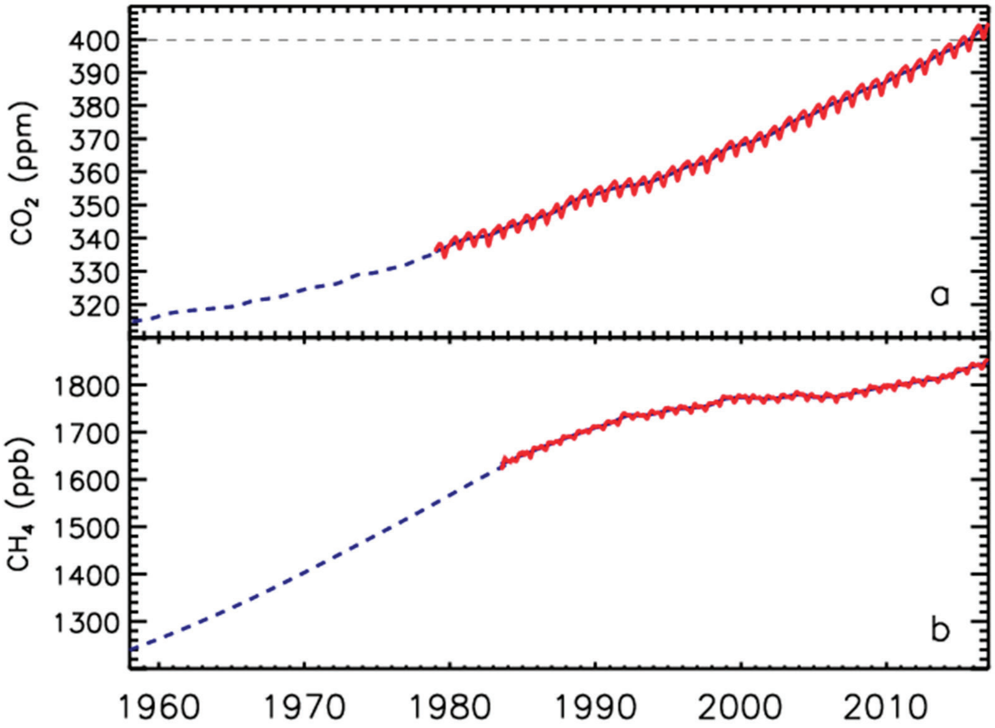

FIGURE 9.11 *Top panel:* Global mean atmospheric CO_2 (red) and seasonally corrected trend (black). Data prior to 1980 (dashed curve) are from Scripps Institute of Oceanography, and data after 1980 are from NOAA's Cooperative Global Air Sampling Network (Ed Dlugokencky and Pieter Tans, www.esrl.noaa.gov/gmd/ccgg/). The dashed gray horizontal line indicates 400 ppm. *Bottom panel:* Same as earlier but for CH_4. Data after 1984 are from NOAA's Cooperative Global Air Sampling Network (Dlugokencky et al., 2009). Data prior to 1984 (dashed curve) are from firn and ice core samples (Etheridge et al., 1998) and have been multiplied by 1.0124 for compatibility with the NOAA X2004A CH_4 scale. SOURCE: Ed Dlugokencky, NOAA GMD.

by mass, the release of a pulse of CH_4 has a global warming potential that is 84 times that of CO_2 over a two-decade time horizon, and 28 times CO_2 over a century. These estimates of global warming potential (GWP) of CH_4 rise to 86 and 34 for the two time horizons, respectively, when allowance is made for carbon cycle feedback (IPCC, 2013). Anthropogenic emissions of CH_4 occur for many sectors of a modern economy, including fossil fuel extraction and use, ruminants (i.e., mammals such as cattle and sheep that acquire nutrients from food via fermentation prior to digestion), agriculture (particularly crops that prefer wet anaerobic conditions such as rice), landfills, and sewage treatment, whereas natural sources are dominated by emissions from tropical and northern wetlands (i.e., seasonally or perennially flooded regions), biomass burning, termites, lakes, and geological sources.

There presently exists considerable uncertainty in the recent carbon budget and in projections of how atmospheric CO_2 will respond to climate change (Ciais et al., 2013). Recent studies have reported increasing terrestrial sinks due to CO_2 fertilization (Zhu et al., 2016; Los et al., 2013; Schimel et al., 2015; Keenan et al., 2016). Meanwhile, other studies covering diverse regional ecosystems suggest reduced carbon uptake due to droughts and other extreme events (e.g., Ma et al., 2012; Reichstein et al., 2013; Zhou et al., 2014; Brienen et al., 2015). Friedlingstein et al. (2014) evaluated simulations of end of century CO_2 from 11 atmospheric, oceanic general circulation models with an interactive carbon cycle. Variations of CO_2 in 2100 ranged from 795 to 1145 ppm for the same fossil fuel emission scenario, with differences mainly attributable to the response of the land carbon cycle. Booth et al. (2012) found even larger differences (a range of 461 ppm) using a single coupled climate-carbon cycle model and perturbing key land carbon cycle parameters over ranges consistent with their uncertainties. Using a price of $13/ton of atmospheric CO_2, 400 ppm of CO_2 has a present-day economic value of $40 trillion.[9]

Projections of future atmospheric CH_4 are also highly uncertain. The scenarios for future GHG abundance developed for IPCC (2013), termed Representative Concentration Pathways (RCPs), project that CH_4 could be as high as 3750 ppb (RCP 8.5) or as low as 1250 ppb (RCP 2.6) in year 2100 (Riahi et al., 2011; van Vuuren et al., 2011). This uncertainty is driven by disparate assumptions regarding whether, and how effectively, human emission of CH_4 will be managed and curtailed. Furthermore, the mechanisms driving recent methane trends are not well understood. The observed stabilization of methane levels between 1996-2006 and renewed increase after 2006 may be attributable to a slowdown in fossil fuel emissions followed by an increase in biogenic emissions such as from tropical wetlands or increased agricultural sources (Kirschke et al., 2013; Nisbet et al., 2016; Schaefer et al., 2016). An alternative hypothesis to explain recent increases in CH_4 is a decrease in concentration of the hydroxyl radical, the largest methane sink (Rigby et al., 2017; Turner et al., 2017). Schwietzke et al. (2016) used methane isotope data to show that fossil sources of methane are higher than previously estimated and that there is no significant trend in fossil sources, but their analysis could not distinguish between emissions from fossil fuel industrial activity versus natural geologic seepage. Conversely, Wolf et al. (2017) suggest that changes in livestock management and practices may account for 50 to 75 percent of the recent rise in atmospheric CH_4. This lack of consensus reflects the current state of knowledge, and additional measurements are needed that can differentiate among the various hypotheses.

Projections for CH_4 are complicated by possible alteration of wetland sources due to climate-change induced changes in the hydrologic cycle (i.e., floods and droughts), release of possible large amounts of CH_4 upon thawing of the Arctic permafrost (Schuur et al., 2015), and leakage from the extraction or transportation of natural gas (Karion et al., 2013). To date, the release of CH_4 from the thawing of permafrost is small on a global scale (Walter Anthony et al., 2016).

Science Question and Application Goals

Question C-3. How large are the variations in the global carbon cycle and what are the associated climate and ecosystem impacts in the context of past and projected anthropogenic carbon emissions?

To advance understanding of the global carbon cycle (i.e., CO_2 and CH_4), the panel has suggested the following objectives:

- *C-3a.* Quantify CO_2 fluxes at spatial scales of 100-500 km and monthly temporal resolution with uncertainty <25 percent to enable regional-scale process attribution explaining year-to-year variability by net uptake of carbon by terrestrial ecosystems (i.e., determine how much carbon uptake results from processes such as CO_2 and nitrogen fertilization, forest regrowth, and changing ecosystem demography) (Very Important).

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[9] See Climate Policy Initiative, "California Carbon Dashboard," http://calcarbondash.org.

- *C-3b*. Reliably detect and quantify emissions from large sources of CO_2 and CH_4, including from urban areas, from known point sources such as power plants, and from previously unknown or transient sources such as CH_4 leaks from oil and gas operations (Important).
- *C-3c*. Provide early warning of carbon loss from large and vulnerable reservoirs such as tropical forests and permafrost (Important).
- *C-3d*. Provide regional-scale process attribution for carbon uptake by ocean to within 25 percent (especially in coastal regions and the Southern Ocean) (Important).
- *C-3e*. Quantify CH_4 fluxes from wetlands at spatial scales of 300 km × 300 km and monthly temporal resolution with uncertainty better than 3 mg CH_4 m^{-2} day^{-1} in order to establish predictive process-based understanding of dependence on environmental drivers such as temperature, carbon availability, and inundation (Important).
- *C-3f*. Improve atmospheric transport for data assimilation/inverse modeling (Important).
- *C-3g*. Quantify the tropospheric oxidizing capacity of OH, critical for air quality and dominant sink for CH_4 and other GHGs (Important).

Quantification of greenhouse gas (GHG) fluxes at continental, regional, and local scales is needed (1) to assess the efficacy of policies included in international climate agreements, and (2) to understand the processes controlling the natural components of the carbon cycle, which in turn will lead to models with better predictive abilities under changing climate conditions. Satellite observations of CO_2, such as those provided by the Orbiting Carbon Observatory-2 (OCO-2) and Greenhouse Gas Observing Satellite (GOSAT) and from potential future missions such as GOSAT-2 and the recently announced Geostationary Carbon Cycle Observatory (GeoCARB), have the potential to play a pivotal role, if systematic errors are identified and remedied.

The panel also identified numerous other Important goals (see Appendix B) focused on quantification of CH_4 fluxes from wetlands at high spatial resolution as well as the development of a reliable predictive capability for future change in this source, quantification of CO_2 and CH_4 emissions from urban areas and point sources, early warning of the loss of carbon from vulnerable ecosystems, as well as understanding how climate change will alter the oxidative capacity of the troposphere (i.e., how tropospheric mean [OH] will respond to global warming). Large contemporary uncertainties in all these areas limit our confidence in the representation of carbon cycle feedbacks within global models (IPCC, 2013).

Measurement Objectives and Approaches

The predominant approach for satellite-borne CO_2 and CH_4 sensors such as OCO-2, GOSAT, and the Tropospheric Monitoring Instrument (TROPOMI) measures absorption of reflected near-infrared light. Passive sensors measure reflected sunlight, while proposed active sensors such as the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission recommended by the ESAS 2007 and the planned French-German Methane Remote Sensing Lidar Mission (MERLIN) would employ lasers. Passive satellite observations of X_{CO2} are unevenly distributed across the globe and may have aerosol, thin-cloud, albedo, surface-type, solar zenith angle, or other coherent space- and time- dependent biases. Passive sensors are limited to sunlit conditions and so do not provide data for nighttime or for high-latitude winter scenes, limiting sensitivity to possible increasing emissions from vulnerable Arctic reservoirs (see Objective C-3c). Retrievals from passive sensors are limited to cloud-free conditions and hence have a fair-weather bias. Active sensors are uniquely capable of providing nighttime data and are arguably less susceptible to biases associated with aerosols and clouds, but active sensors have increased complexity and power requirements and provide limited spectral information. The recently announced GeoCARB mission is an

OCO-2-like passive sensor in a geostationary orbit that will provide dense data over temperate and tropical North and South America with additional spectral channels for CH_4 and CO. The dense sampling will be especially useful for monitoring urban emissions and emissions from large point sources (C-3b). GeoCARB is expected to provide new constraints on estimates of fluxes from tropical wetlands and insights into how wetland fluxes respond to changes in environmental drivers such as temperature and inundation (C-3e).

Both passive and active techniques provide a column-integrated measurement, with limited information about the structure of the vertical profile. The signal of regional sources/sinks is typically diluted in the full column to 20 to 30 percent of its strength in the boundary layer. Day-to-day variability in X_{CO2} is strongly influenced by synoptic weather patterns, obscuring signatures of surface fluxes. Kulawik et al. (2016) have recently developed a method for separately estimating lower and upper tropospheric partial column CO_2 with GOSAT data, and comparisons with aircraft measurements demonstrate the potential for this approach. Midinfrared sensors are already in orbit on weather satellites and can potentially provide additional information about midtropospheric CO_2 and CH_4 abundance. However, midinfrared sensors have little to no sensitivity to the surface layer, where signatures of emission and uptake are strongest. The combination of near- and midinfrared spectral information should enable some separation of boundary layer and midtropospheric signals. However, in practice, this requires extremely careful characterization of the sensors, and a consistent retrieval strategy. Future satellite sensors may employ a variety of combined approaches, including active/passive, geostationary versus low-Earth orbit, high spatiotemporal resolution over targeted areas versus broad-area mapping, and combined near-IR/mid-IR spectroscopy.

For flux estimation, systematic biases in retrievals are more problematic than random errors and can be reliably detected and quantified only if sufficiently informative ground truth data are available. The OCO-2 and GOSAT science teams have worked diligently to identify and mitigate systematic biases in retrievals (Wunch et al., 2011a; Lindqvist et al., 2015; Wunch et al., 2016; Crisp et al., 2017; Eldering et al., 2017), but even small biases in X_{CO2} can cause significant errors in estimated fluxes. Quantification of subtle signals resulting from changes in emissions and from climate-induced biological flux anomalies will require the ability to sense gradients and detect trends with long-term stability (i.e., over periods of months to years) of ~0.2 ppm in X_{CO2} maintained over many years (Wofsy and Harris, 2002; NRC, 2010). Measurement requirements to detect important flux signatures at local to continental scales are discussed in a report on the notional CarbonSat mission that was proposed to ESA and are consistent with the requirements in the SATM (ESA, 2015). The systematic error goal for CarbonSat is 0.2 ppm for CO_2, a factor of 2 or more better than what has been demonstrated so far for OCO-2. The CarbonSat systematic error goal for CH_4 is 2.5 ppb, compared to 2 percent (or roughly 40 ppb) for the planned TROPOMI sensor.

The current strategy for evaluating OCO-2 retrievals relies on the Total Carbon Column Observing Network (TCCON). TCCON uses ground-based spectrometers similar to OCO-2 and GOSAT but with higher spectral resolution. TCCON retrievals have been linked to the World Meteorological Organization CO_2 and CH_4 scales via infrequent overflights by research aircraft (Wunch et al., 2010; Messerschmidt et al., 2011). The aircraft profiles typically have a maximum altitude between 10 and 12 km and so the stratospheric contribution to the column has to be approximated. Starting in 2012 the balloon-borne AirCore sampling system (Karion et al., 2010) has been routinely deployed over certain TCCON sites and provides profiles of calibrated in situ CO_2 and CH_4 up to ~28 km. Wunch et al. (2015) estimate that systematic biases of 0.2 percent for X_{CO2} (0.8 ppm) and 0.4 percent (7 ppb) for X_{CH4} could exist with the TCCON network. Site-to-site comparability of X_{CO2} of 0.2-0.56 ppm and X_{CH4} at the level of 1.5- 4.6 ppb for CH_4 has recently been demonstrated across four TCCON sites in the United States during a 5-week campaign using a pair of mobile spectrometers (Hedelius et al., 2017). Comparisons between TCCON and OCO-2 show a median difference of less than 0.5 with root-mean-square differences typically less than 1.5 ppm (Wunch et al., 2016).

Strategic investments in infrastructure for additional ground truth are needed that will enable identification and mitigation of remaining systematic biases and that will serve a variety of emerging measurement concepts. Ongoing evaluation will be necessary, since satellite sensors may drift or degrade over time, and any seasonally or spatially varying retrieval biases would not be revealed by limited validation experiments. Frequent vertical profile data covering a range of latitudes and conditions have been crucial for correcting biases in satellite ozone retrievals and enabling trend detection across missions. Profile data are equally necessary for X_{CO2} and X_{CH4}, but are currently limited. NOAA performs biweekly to monthly aircraft sampling at 14 sites over North America and from the island of Raratonga up to altitudes of ~8 km, and intensive campaigns such as the Atmospheric Carbon and Transport—America (ACT-America) and the Atmospheric Tomography (ATom) experiments also provide vertically resolved validation data. Internationally, the National Institute for Environmental Studies of Japan has implemented a commercial aircraft CO_2 sampling program (Machida et al., 2008), and the European In-service Aircraft for a Global Observing System (IAGOS) program will begin measuring CO_2 and CH_4 from commercial aircraft later this year. Expanded commercial aircraft sampling is a promising mechanism for obtaining a large volume of crucial validation data needed to realize the potential of current and future greenhouse gas emissions and to establish continuity across missions. Ongoing site-to-site comparisons with portable spectrometers are needed to establish and track comparability across the global TCCON network, while continued routine AirCore overflights at key sites are needed to maintain the link between TCCON and the in situ network.

In addition to their value for evaluating satellite retrievals, ground-based, airborne, and shipboard in situ data have independent value for estimating carbon fluxes and are necessary for resolving flux signals that are too subtle for satellites to detect, such as gradients and trends resulting from ocean fluxes in critical regions such as coastal fluxes and Southern Ocean fluxes (see Objective C-3d; see also Objective C-4a for more discussion of air-sea fluxes of CO and CH_4). The main advantage of satellite sensors is their global vantage point. GOSAT and OCO-2 are providing new information in regions where other types of atmospheric data are sparse, and they provide information about spatial patterns of flux that will drive improvements in process-based models. Conversely, the usefulness of point measurements is limited by sparseness in space and time. Consequently, the best flux estimates will come from a combination of remote-sensing and in situ measurements from a variety of platforms.

Connections to Other Panels and Integrating Themes

Ecosystems Panel

Carbon cycle-climate feedbacks are also addressed by the Ecosystems Panel, and discussion of measurements such as vegetation indices, biomass, and solar-induced fluorescence are described in Chapter 8. This panel has focused on carbon-climate questions related to predicting future radiative forcing, whereas the Ecosystems Panel also considers how changing atmospheric CO_2 and future climate may affect ecosystems (CO_2 fertilization, ocean acidification, changing ecosystem demography in response to changing climate).

Weather and Air Quality Panel

This panel is focusing on the co-benefit, for air quality, of slowing down or stopping the rate of growth of methane. Methane is a precursor of tropospheric ozone, and increases since preindustrial time have played an important role in driving a rise of ozone throughout the global troposphere. While the primary societal benefit for limiting the growth of methane will be to reduce the rate of global warming, the air quality co-benefit has been noted in many papers (e.g., Fiore et al., 2002).

The extent to which surface fluxes of CO_2 and CH_4 can be inferred from measurements of atmospheric abundance depends on the fidelity of atmospheric transport models used in data-assimilation systems. Question C-3 addresses this need, but the measurement requirements are not well defined. This is an important linkage with the Weather Panel, and it is important to note that certain considerations that are critical for trace constituent transport (e.g., dry air mass conservation) are not typically taken into account for weather prediction. Measurements and model improvements that lead to improved simulation of atmospheric transport would have far-reaching benefits across atmospheric science, including for air quality and general atmospheric composition questions.

C-4: Atmosphere-Ocean Flux Quantification

Motivation

A key component in the dynamics of the Earth system is the interaction between the atmosphere and the ocean. This interaction, which occurs through transfers (or fluxes) of heat, momentum, and mass (e.g., water vapor, sea spray, CO_2, and DMS), provides feedbacks through the boundary layers of the atmosphere and oceans to modulate ocean and atmospheric circulations, the ocean heat content, the global water and energy cycles, the concentration of CO_2 in the atmosphere by sequestration in the ocean and subsequent evasion, and the modulation and production of low-level clouds through oceanic aerosol production of cloud condensation nuclei. These interactions occur across a wide range of time and space scales, from the relatively fast weather exchanges at storm scales to centennial global variability. Thus, measuring these fluxes is imperative to understanding the processes leading to variability of the Earth system. For example, understanding how much heat and carbon the ocean absorbs is vital to understanding sea-level rise and to predicting how much, how fast, and where the atmospheric temperature will change, as the ocean stores more than 90 percent of the excess heat that has been added to the climate system over recent decades (e.g., Cheng et al., 2017) and roughly 30 percent of the excess carbon (Mikaloff Fletcher et al., 2006; Le Quéré et al., 2010).

It is also essential to understand the partitioning of the global energy imbalances between the atmosphere and ocean, as this is critical to defining the climate response to anthropogenic forcings. Currently, the surface energy and water budgets do not close, to a large extent due to imbalances between the radiative and turbulent heat fluxes and the evaporation and precipitation across the ocean surface (e.g., Stephens et al., 2012; L'Ecuyer et al., 2015). As can be seen in Figure 9.12, the evaporation from the ocean to the atmosphere represents the single largest term in the global water budget, and current estimates of the total magnitude require significant adjustment to bring balance to the budget. Other components of the water budget (precipitation in particular) are of roughly the same magnitude and uncertainty, but given the connection of the evaporation to the energy cycle, bringing balance to both appears to require larger adjustments to ocean evaporation than precipitation (L'Ecuyer et al., 2015; Rodell et al., 2015). The warming of the upper ocean tends to be reflected in trends of increasing ocean evaporation (i.e., water vapor flux) and precipitation in the hydrologic cycle, all of which can be and have been observed by evaluating the upper ocean salinity over time (e.g., Durack and Wijffels, 2010). These variations in the global hydrologic cycle are not restricted to over-ocean locations but affect precipitation patterns across land surfaces as well. The movement of water from the ocean to the atmosphere, where it then becomes available as precipitation to fall over both the ocean and land surfaces, is vital to life on land. However, our ability to predict the timing and magnitude of these variations is due in part to the uncertainties in the current global air-sea flux products, which prevent them from being used to quantify the trends in either the heat or the moisture budget (IPCC, 2013), as uncertainties are on the order of 10 to 20 percent (e.g., Gulev et al., 2011).

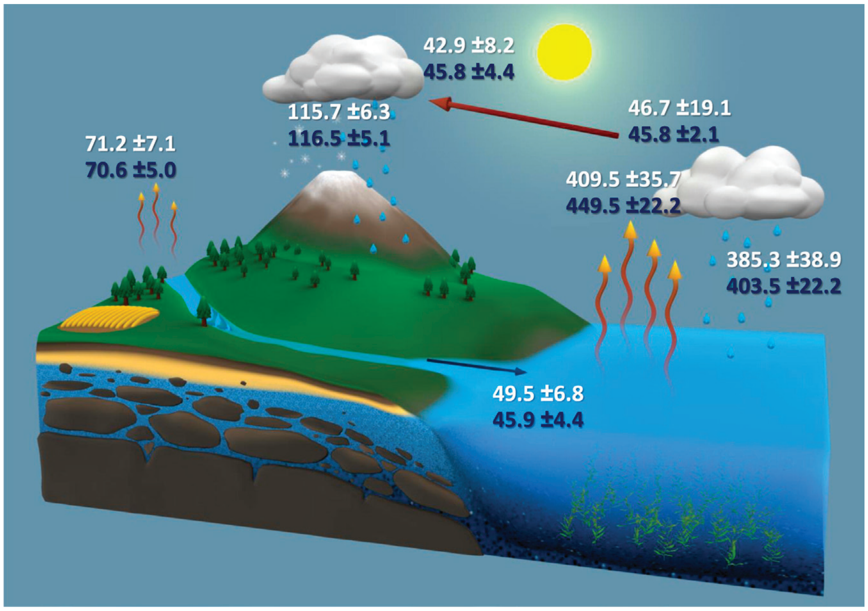

FIGURE 9.12 Mean annual fluxes (10^3 km^3/yr) of the global water cycle, and associated uncertainties, during the first decade of the millennium. White numbers are based on observational products and data integrating models. Blue numbers are estimates that have been optimized by forcing water and energy budget closure, taking into account uncertainty in the original estimates. SOURCE: Rodell et al. (2015). © American Meteorological Society. Used with permission.

The exchange of momentum in addition to heat and moisture through the ocean surface drives the ocean circulation, upper ocean mixing, and surface wave fields, and provides a drag on the atmosphere. The overturning circulation in high latitudes, which helps drive the larger scale thermohaline circulation, is highly dependent on air-sea fluxes. In addition, the momentum flux to the ocean and resulting breaking wave fields provide a significant fraction of the aerosols that form the basis in the lower atmosphere for cloud formation, particularly in remote areas of the ocean. Uncertainties in how sea spray is generated by breaking waves limit our understanding of the transfer of heat and momentum between the ocean (e.g., Mueller and Veron, 2014), as well as limiting our ability to accurately reproduce the feedbacks between the upper ocean surface, aerosols, and low-level clouds. A number of analyses using combinations of satellite-based data sets, in situ observations, and reanalysis products have shown varying changes in wind-stress trends at decadal to centennial time scales; however, the variability between these analyses is large, and thus our knowledge of the actual change in time of these fields is low (IPCC, 2013). Increases in wind-stress fields from the tropical Pacific and Southern Ocean regions have been noted (e.g., Merrifield et al., 2012; Swart and Fyfe, 2012), but variations due to interannual variability are large and poorly understood (IPCC, 2013), and are complicated by Sun-synchronous observations of a variable with substantial diurnal and semidiurnal variability (Wentz et al., 2017).

Similarly, the scientific community lacks a robust understanding of how to estimate the exchange of CO_2 between the ocean and atmosphere given the few variables that can be measured and the significant uncertainties surrounding other key variables (e.g., wind speed and thermal stratification) that are needed to calculate this exchange. On centennial time scales, basic scientific principles dictate that the ocean CO_2 amount will equilibrate with atmosphere CO_2, but an open question remains as to the rate at which this ocean uptake will occur, and our understanding of some key processes that control the carbon distributions in the ocean is still limited. Due to the dearth of observations, it is still unclear whether the rate at which the ocean is taking up CO_2 is changing, with some analyses indicating a decline in the ocean uptake rate of total CO_2 (Le Quéré et al., 2007; Schuster and Watson, 2007; McKinley et al., 2011), and others finding a lack of evidence for a decrease (e.g., Knorr, 2009; Gloor et al., 2010; Sarmiento et al., 2010). Future estimates are even more uncertain, with recent studies suggesting that the Southern Ocean might increase carbon uptake, possibly enough to change the global net uptake to increasing rather than decreasing (Doney, 2010). Current observation-based estimates of the climate response of the global air-sea CO_2 flux do not include feedbacks from ocean warming and circulation variability, which could make a difference of 20 to 30 percent in the ocean response (IPCC, 2013). Given that the ocean stores roughly 50 times as much inorganic carbon as the atmosphere (Sabine et al., 2004c), variations in the exchanges between the ocean and atmosphere can affect the atmospheric concentration of CO_2, while also impacting the rate and magnitude of the ocean acidification (Doney et al., 2009).

Therefore, satellite observations of these air-sea fluxes are a crucial component of the measurement system given that in situ measurements are costly and difficult to implement, and we are currently unlikely to attain the needed temporal and spatial resolution and global coverage through these measurements. However, as many of the questions raised here require process-level understanding, investment in in situ measurements should also be a top priority for the atmospheric and oceanic communities. In addition, the full realization of the potential of the satellite observations requires improved atmospheric and oceanic boundary layer models, which should also be a key priority of the atmospheric modeling community. Some questions in climate science may best be addressed through a combination of in situ, satellite, and model simulations, in which satellite fluxes are used for assimilation, for comparison, or as a constraining parameter. Gridded satellite flux products are also useful metrics for evaluation of the quality of a coupled model. Ocean reanalysis products (e.g., Valdivieso et al., 2017) may also be useful for constraining total heat, moisture, or mass exchanges as estimated from satellites, and close collaborations between these communities will likely also produce scientific dividends.

Science Question and Application Goals

Question C-4. How will the Earth system respond to changes in air-sea interactions?

In order to make progress in our understanding of this question, four key objectives have been identified:

- *C-4a*. Improve the estimates of global air-sea fluxes of heat, momentum, water vapor (i.e., moisture), and other gases (e.g., CO_2 and CH_4) to the following global accuracy in the mean on local or regional scales: (1) radiative fluxes to 5 W/m^2, (2) sensible and latent heat fluxes to 5 W/m^2, (3) winds to 0.1 m/s, and (4) CO_2 and CH_4 to within 25 percent, with appropriate decadal stabilities (Very Important).
- *C-4b*. Better quantify the role of surface waves in determining wind stress; demonstrate the validity of Monin-Obukhov similarity theory and other flux-profile relationships at high wind speeds over the ocean (Important).
- *C-4c*. Improve bulk flux parameterizations, particularly in extreme conditions and high-latitude regions reducing uncertainty in the bulk transfer coefficients by a factor of 2 (Important).
- *C-4d*. Evaluate the effect of surface CO_2 gas exchange, oceanic storage, and impact on ecosystems, and improve the confidence in the estimates and reduce uncertainties by a factor of 2 (Important).

Of these four key objectives, the first, improving the estimates of the fluxes themselves, has been identified as Very Important, with the other three constituting Important objectives but clearly related to the first. In addition, these three priorities also require substantial modeling and in situ observation approaches in order to achieve these goals; thus, the focus here will be on the first objective of improving the estimates of global air-sea fluxes. However, better understanding of the remaining three objectives will affect the uncertainties in the first objective. For instance, there are relatively few measurements of the fluxes under extreme conditions like high-wind speeds, including hurricanes, and in difficult to reach locations, such as the Southern Ocean, where very few direct observations of the air-sea exchanges of heat and moisture have ever been taken (Bourassa et al., 2013). Because of this lack of measurements, open questions still remain about the influence of waves, sea spray, bubbles, and other properties of the air-sea interface on these exchanges, and the parameterizations used to convert measurements of winds, air temperature, and other variables to the actual fluxes remain somewhat more uncertain in these regimes.

Measurement Objectives and Approaches

The measurements needed to achieve these objectives are outlined in the SATM (see Appendix B) for optimal resolutions and approaches. Here, we highlight those measurements that are needed to achieve the Very Important priority objective as noted earlier. In order to determine the turbulent fluxes of heat, moisture, momentum, and gasses from satellite observations, accurate measurements of the state variables associated with the associated flux need to be made, and then the flux is calculated from these measurements using a bulk flux parameterization. For instance, for latent and sensible heat flux, the state variables are near-surface winds and surface currents, near-surface temperature and specific humidity (or mixing ratio), and sea-surface temperature. The surface radiative fluxes can be inferred from satellite measurements using radiative transfer models. Here, we list the state variables and caveats about these measurements:

- *Surface vector winds*. Surface winds are key for all of the turbulent fluxes. If the vector winds are measured relative to Earth, then current, atmospheric stability, and perhaps wave information are needed for accurate estimation of the surface fluxes. However, it should be noted that scatterometers measure backscatter from surface roughness elements that are produced by wind stress. The wind stress is most closely related to the equivalent neutral wind speed measured relative to the ocean surface (e.g., Plagge et al., 2016). Therefore, if future scatterometers are tuned to equivalent neutral winds or stress equivalent winds measured relative to the ocean surface, then surface current and stability information is not needed for stress estimates, and the uncertainty of relating the wind speed to the momentum flux is substantially eliminated. As such, this is a highly recommended approach. Information on surface currents, waves, and stability would be useful for model validation and development.
- *Near-surface air-temperature and humidity over the ocean*. These measurements are less-well established than the surface vector winds, and require continued investment in higher resolution measurements approaches. In addition, increased in situ observations in key regimes will be needed in order to evaluate the uncertainty of these new measurements. As with surface winds, a significant time series exists that is used for calculation of global data sets of evaporation and turbulent momentum and heat fluxes from the passive microwave Special Sensor Microwave Imager (SSMI) and Special Sensor Microwave Imager/Sounder (SSMIS) sensors through the Defense Meteorological Satellite Program (DMSP) that are to be discontinued. Even the current passive microwave sensors, including JAXA's Advanced Microwave Scanning Radiometer-2 (AMSR2), are past their nominal lifetimes. A series of replacement sensors in the microwave is urgently needed, preferably at higher temporal and spatial resolutions in order to achieve the goals listed here.
- *Sea-surface temperature (SST)*. For calculation of the fluxes, the skin temperature with full diurnally varying resolution is required in order to attain the desired accuracy (e.g., Fairall et al., 1996; Ward et al., 2004; Clayson and Bogdanoff, 2013).

- *Radiative fluxes*. Measurement techniques are the same as for over-land observations; however, there is still a need for more ocean radiative in situ direct observations to help constrain the error budgets.
- *Carbon and methane fluxes*. Measurements useful for calculating carbon and methane fluxes over the ocean are particularly challenging to make, and current methods involve the use of some combination of satellite data, models, and in situ measurements. Several alternatives include using satellite-derived winds in combination with in situ measurements of the trace gases, using relationships between sea-surface carbon dioxide fugacity and sea-surface temperature and chlorophyll to calculate the flux from remotely sensed SST and ocean color, and through satellite measurements of column CO_2 and CH_4 using techniques similar to OCO-2 or lidar profiles. All of these methods require either continued investment in in situ, modeling, or more technological developments to achieve the desired goals.

Connections to Other Panels and Integrating Themes

Measurement of air-sea fluxes are key needs for accurate predictions of many weather-related phenomena, where improved observations of both the surface and the lower atmospheric boundary layer will have substantial impacts (along with improved modeling) of key weather events including extreme events like tropical cyclones. Fluxes of carbon and methane are also of high importance to the Ecosystem Panel. Variability in the air-sea heat and moisture fluxes are key to the Hydrologic Cycle Panel goals of improved understanding and representation of the global energy and water cycles, as the largest source of uncertainty in closing these budgets is the air-sea flux of latent heat (water vapor; e.g., L'Ecuyer et al., 2015). The ocean-atmosphere interactions occurring during extreme events like hurricanes are one of the important factors in predicting the track and severity of these storms (Glenn et al., 2016).

C-5: Aerosols and Aerosol-Cloud Interactions

Motivation

Humans have been increasing the emissions of small airborne particles (called "aerosol") and their precursors in many ways (energy generation, transportation, agriculture, biomass burning, and others), and the association of human activities with tropospheric aerosols is well established from orbital (e.g., Streets et al., 2013) and suborbital observations. Most aerosols exert a negative (cooling) radiative forcing (RF) by scattering sunlight back to space that would otherwise warm the planet. Some aerosol species absorb sunlight, producing a warming effect. Aerosols also affect the planet's energy indirectly by influencing the hydrologic cycle—that is, clouds and precipitation. While the best current estimate of the net radiative effect of anthropogenic aerosols is negative, as discussed in IPCC AR5 and Boucher et al. (2013; IPCC WG1, 2013), the single greatest source of uncertainty in estimating humans' effect on the current surface temperature of the planet arises from limited understanding of aerosol direct and indirect radiative impacts.

Aerosol production, lifetime, and losses are controlled by a complex set of processes, including meteorological features (winds, temperatures, clouds, condensate phase, cloud updraft velocities, and precipitation), microphysics and chemistry (governing aerosol formation, growth, and composition, size evolution and morphology, as well as aerosol volatility, and solubility that makes them susceptible to cloud scavenging), and emission of aerosols and their gaseous precursors (both natural, and man-made; e.g., Seinfeld et al., 2016). Cloud liquid and primary ice form on aerosol particles, so the number and composition of aerosols influence cloud properties. These components of the Earth system interact continuously with each other, with precipitation being the major sink of fine particles that leads to particle lifetimes on the order of days or less. As a result aerosols vary at small spatial and temporal scales, and are controlled by processes operating at even smaller scales, making it challenging to measure properties relevant to their production and loss, and their roles, via their optical properties and their impacts on clouds and precipitation, on the global energy budget, from space. Very high resolution (in space and time) nearly coincident measurements of multiple variables have proven useful in constraining estimates of aerosol indirect effects, and the processes that control aerosol-cloud interactions. These observations have often been provided by satellites operating in a constellation formation.

Uncertainties in how much aerosols are cooling the planet also confound estimates of the sensitivity of the planet to increasing greenhouse gases (i.e., aerosols have offset some portion of historical GHG-induced warming, but the magnitude of this offset is highly uncertain; IPCC WG1, 2013). The climate record can be fitted nearly equally well by assuming a large aerosol cooling (and a large climate sensitivity to CO_2, from large positive feedbacks), or a small aerosol cooling (and a low climate sensitivity, with small feedbacks). In addition, aerosols likely counteract the tendency of greenhouse gases to increase global-mean precipitation (Bollasina et al., 2011; Z. Li et al., 2011; Polson et al., 2014).

Smith and Bond (2014) developed a wide range of estimates of future changes in total RF due to aerosols, but all of these scenarios show diminishing future aerosol influences on climate, because of global efforts to control aerosols and their precursors due to public health concerns (Bell et al., 2007; see Figure 9.13). Because aerosol lifetimes are much shorter than those of greenhouse gases, atmospheric loadings of anthropogenic aerosol will diminish much more rapidly when emissions are controlled, compared to greenhouse gases, and Earth's temperature will effectively be determined by the climate sensitivity to CO_2 (Levy et al., 2013), providing divergent projections of future global warming (Salawitch et al., 2017).

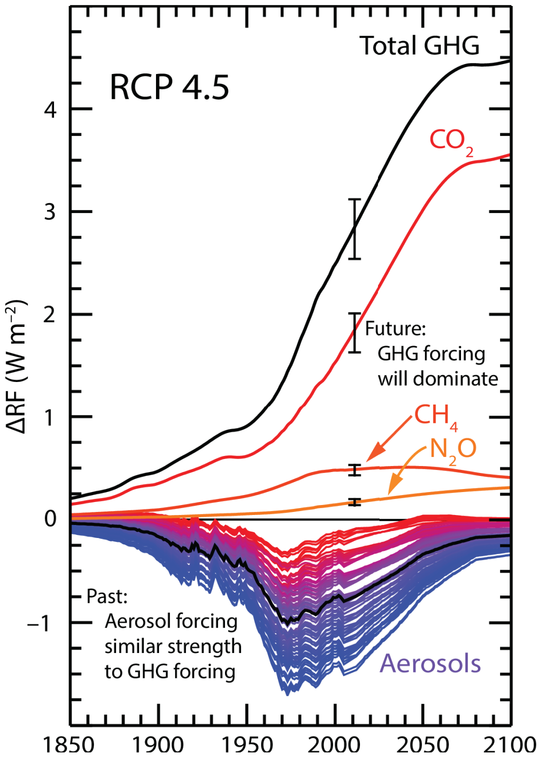

FIGURE 9.13 *Top:* Time series of change in radiative forcing of climate (ΔRF) due to CO_2, CH_4, N_2O, and all anthropogenic GHGs, from 1850 to 2100, based on the RCP 4.5 scenario (Meinshausen et al., 2011). *Bottom:* 71 plausible scenarios for total ΔRF due to anthropogenic aerosols (combination of the aerosol direct effect and the aerosol-cloud interaction) from Smith and Bond (2014). Blue colors are used to denote the high end of the range of aerosol cooling (i.e., more overall cooling of climate), and red colors denote the low end (less overall cooling). SOURCE: Salawitch et al. (2017, Figure 1.10).

Hence, identifying aerosol's influence on past and present climate is critical to establishing the potential future warming.

Current uncertainties in projecting future responses of the Earth system to rising levels of GHGs represent a quantifiably huge economic and societal liability. Investments in resilient infrastructure will depend strongly on the magnitude and rate of the planet's response to increasing greenhouse gases (e.g., infrastructure commitments to accommodate sea-level rise). Hence, the panel identified as a Very Important priority continuing and new measurements aimed at obtaining the information needed on aerosol radiative forcing to substantially reduce this uncertainty. Prior work (e.g., IPCC WG1, 2013) indicates that the radiative forcing uncertainty by aerosols (about 1 W m^{-2}) is approximately twice that of any other single factor contributing to the estimated total forcing uncertainty (IPCC WG1, 2013). The IPCC report indicates the total forcing uncertainty to be approximately the same magnitude as the aerosol forcing uncertainty. IPCC WG1 Figure 8.16 and surrounding text indicate total forcing uncertainty is dominated by aerosol forcing uncertainty. Hence, at least a factor of 2 reduction in the uncertainty of radiative forcing of climate due to aerosols would be required to achieve a factor of 2 reduction in total forcing uncertainty, assuming contributing errors add in quadrature. This reduction would contribute to narrowing the estimate of the ECS, and hence results in tangible economic and societal benefits as noted in the subsection "C2: Climate Feedbacks and Sensitivity."

Science Question and Application Goals

The overarching science questions for this subsection feed into Objective C-2h of the "C:2: Climate Feedbacks and Sensitivity" subsection.

Question C-5. A. How do changes in aerosols (including their interactions with clouds, which constitute the largest uncertainty in total climate forcing) affect Earth's radiation budget and offset the warming due to greenhouse gases? B. How can we better quantify the magnitude and variability of the emissions of natural aerosols, and the anthropogenic aerosol signal that modifies the natural one, so that we can better understand the response of climate to its various forcings?

In this subsection, we address the fundamental aspects of these questions that are related to aerosols—naturally and anthropogenically derived—the processes that govern their atmospheric burdens, and their interactions with clouds. For this subsection, there are four closely related objectives:

- *C-5a*. Improve estimates of the emissions of natural and anthropogenic aerosols and their precursors via observational constraints (Very Important).
- *C-5b*. Characterize the properties and distribution in the atmosphere of natural and anthropogenic aerosols, including properties that affect their ability to interact with and modify clouds and radiation (Important).
- *C-5c*. Quantify the effect that aerosol has on cloud formation, cloud height, and cloud properties (reflectivity, lifetime, cloud phase), including semidirect effects (Very Important).
- *C-5d*. Quantify the effect of aerosol-induced cloud changes on radiative fluxes (reduction in uncertainty by a factor of 2) and impact on climate (circulation, precipitation) (Important).

What Are the Largest Uncertainties in Aerosol Direct Radiative Forcing?

The Earth observing missions that have been carried out over the past two decades have provided a wealth of data on global aerosol emissions, transport, and distributions, from anthropogenic pollution to sea spray, volcanic emissions, smoke, and dust. These observations have been used to refine regional to global-scale models, and aerosol forecasts that assimilate such data show a remarkable ability to predict the locations and even surface concentrations of particulate matter in many cases (Al-Saadi et al., 2005). Spaceborne measurements have provided global distributions of aerosol optical depth (Remer et al., 2008) and some information on aerosol types (R. Kahn et al., 2007), complemented by comparison with Aerosol Robotic Network (AERONET) surface-based observations, as well as yielded an estimate of direct radiative forcing of climate due to aerosols (R. Kahn, 2012). However, the vertical distributions of aerosols are not constrained by column measurements of aerosol optical depth, yet these have an impact on the radiation budget. This is especially true of absorbing aerosols, for which large uncertainties dominate current overall understanding of the direct effect (Bond et al., 2013). Lidar measurements (Winker et al., 2009) have proven helpful in providing information that locates aerosol layers, but the lidar retrievals rely on a priori estimates of the aerosol type and properties. Further, better sensitivity is needed for accurate lidar retrievals near the surface, under conditions of low aerosol loadings, and in cloudy atmospheres. Last, improved retrieval of aerosol absorption (e.g., single scattering albedo), a significant climate parameter, is necessary. A possible pathway is combining optical depth measurements with advanced lidar techniques (e.g., High Spectral Resolution Lidar [HSRL]) and algorithms to yield a more accurate physical interpretation of the aerosol characteristics.

What Are the Largest Uncertainties in Aerosol Indirect Radiative Forcing?

Understanding aerosol-cloud-precipitation interactions from space is a complex problem, as it is fundamentally challenging or impossible to observe both the aerosol and the clouds in the same column. Adding to the complexity are the spatial scales in the problem, with an extent from micrometers to kilometers in terms of the totality of the effect and with variations across different meteorological conditions. Despite this, progress has been made in understanding how the properties of low warm clouds—generally considered to be the most susceptible to changes in available cloud-nucleating particles, and to have the largest impact on albedo due to their persistence and extent—are modified by increases in boundary layer aerosol concentrations (IPCC WG1). With the ability to detect drizzle (Stephens et al., 2008), the connections between aerosol, cloud properties, and precipitation can also be made (Suzuki et al., 2011, 2013), key to developing a better understanding of several of the indirect effects beyond simply albedo changes. Understanding of aerosol-cold cloud impacts is poorer, largely because of gaps in the knowledge on ice nucleation and the ability to identify the precise role of aerosols—for example, initial ice formation in relatively warmer cold clouds may hinge upon the presence of ice nucleating particles (Lohmann and Diehl, 2006; Storelvmo et al., 2011) and the ability to detect and quantify them. Further, current methods do not accurately detect the onset of precipitation (ice crystals or light snow) in low cold clouds (Skofronick-Jackson et al., 2013).

Effects of particles on convective clouds have also been hypothesized using models (Morrison and Grabowski, 2011; Song and Zhang, 2011). Observable outcomes of such effects include changes in updraft strength, modified precipitation, and changes in cloud anvil properties and extent (Koren et al., 2005, 2010; Wang and Feingold, 2009; Saleeby et al., 2015), and thus a strategy targeted at indirect effects in convective clouds must include these as observable variables (Seinfeld et al., 2016).

For all aerosol indirect effects, the environmental conditions under which the cloud forms are also key to shaping the aerosol impacts (Comstock et al., 2005; Fan et al., 2009; VanZanten et al., 2011) and must be characterized close to simultaneously with the aerosol and cloud fields.

Measurement Objectives and Approaches

- *Aerosol direct radiative effects*. The POR will include instrumentation (VIIRS) that continues the record of radiometer measurements that can be used to derive aerosol optical depths. Further, new instruments such as Geostationary Orbit Environmental Satellite-R Series (GOES-R) provide similar, high-resolution geostationary data with high time resolution. The addition of capabilities for vertical distribution of the aerosol column, and for improving estimates of spectral aerosol absorption, is required to address the science objectives. At a minimum CALIPSO-like lidar and polarimeter will be needed. These observations, combined with other continuing or new instruments, will be useful in addressing the objectives.
- *Aerosol indirect effect*. Since atmospheric aerosols serve as the nuclei for cloud particles and hence exert a strong influence on cloud formation, microphysics, and precipitation—that is, the hydrologic cycle—aerosol indirect effects are manifest in a continuous arc that begins with how, when, and where aerosol are ingested into clouds, and ends with their removal to the surface in precipitation or resuspension in the atmosphere after processing, along with the changes to the atmospheric state induced that then feed back into subsequent cloud cycles. Clearly, this highly coupled system is too complex and operates on too many scales to permit direct observation of all individual processes. The panel defined an approach to knowledge generation that prioritizes an observational strategy emphasizing the characterization of cloud microphysics and precipitation, especially properties that have been hypothesized to respond to changes in the nature and amount of atmospheric particulate matter. Importantly, the observations of clouds and precipitation must be put into the context of the ambient aerosol and environmental state conditions. Hence, the observational strategies put into place to address aerosol direct radiative effects (Objectives C-5a and C-5b) will serve the dual purpose of providing important observations addressing Objectives C-5c and C-5d. Inevitably, some information about the aerosol properties and three-dimensional (3D) distribution that is relevant to aerosol-cloud interactions must be provided by models. The observational strategy that places an emphasis on better characterization of emissions (Objective C-5a) will serve to improve our ability to model the atmospheric aerosol with greater fidelity and hence to provide the needed links between the aerosol environment and cloud formation and evolution.

The required observations of clouds and precipitation include a combination of the measurements indicated under “C-2: Climate Feedbacks and Sensitivity” (Question C-2) for clouds, together with the instruments named earlier for the aerosol radiative effect. While the precipitation issue, including drizzle effects as diagnosed recently from CloudSat observations (e.g., Suzuki et al., 2013), could be considered from an observational strategy perspective as an element separate from the measurement of the aerosol-induced cloud albedo changes, it is nevertheless important to synthesize the composite picture emerging from both sets of measurements for the complete description and quantification of the aerosol-cloud interactions. Cloud radars form a key component to fully document the cloud properties especially for precipitation onset, light drizzle, which would complement the other platforms providing precipitation data. The lidar capabilities outlined earlier will be useful for quantifying anvils and other thin, high clouds, as well as obtaining estimates of the coverage of low clouds, many of which are missed by the spaceborne radars currently operating or envisioned. We need better information on cloud phase so that we can better describe the overall microphysical processes at play in both stratiform and convective clouds, and then make a link back to the aerosol that affects these. We need to characterize anvil and other thin-cloud prevalence and properties because of their radiative effects, and also because there are hypothesized indirect effects manifested in the anvil and thin-cloud characteristics. Cloud fraction responses to absorbing aerosol could also be examined, when the aerosol environment is known or modeled well, as suggested here. Effects of aerosol on microphysics and in turn, on the strength of convection can be studied if observations of in-cloud vertical motion are available.

There needs to be a very strong linkage to suborbital programs such as DOE ARM and NASA AERONET. Venture-class missions can also be helpful in filling observational gaps. Dedicated field campaigns that augment space-based observations would strengthen the quantification of the aerosol indirect forcing and thus the net anthropogenic forcing. In addition, the combination of models (high-resolution global climate models [GCMs], cloud resolving models [CRMs], and large eddy simulations [LESs]), and in situ observations, together with the space-based observations, will be needed to quantify this effect globally. It is likely that only such a combination of platforms would resolve the roles of the naturally occurring and anthropogenic aerosols on clouds.

Connections to Other Panels and Integrating Themes

Weather and Air Quality Panel

Aerosols are a huge public health issue. Improved detection closer to the surface has relevance to health as well as to safety issues surrounding the transportation sector. Other related effects include aerosol effects on aviation and tourism.

Ecosystems Panel

Some sources of aerosols cause acid rain, which damages ecosystems. This is under control in the United States and most of Europe, but a growing problem in the developing world. Deposition of dust and black carbon is believed to accelerate melting of ice and snowpack.

Water and Energy Cycle

Effects on precipitation will directly impact these cycles.

C-6 and C-7: Seasonal-to-Decadal Predictions, Including Changes and Extremes

Motivation

Variations in the climate system on the scale of seasons to decades have substantial impacts on human life and on the economic and infrastructural health of society. Precipitation deficits that lead to droughts, for example, affect water and food supplies. Floods, arising from precipitation excess, lead to immense destruction. Coastal regions experience severe inundation from storm surges occurring amid rising sea levels and high tides (see also Question C-1, under “Relevant Climate Topics,” earlier). Abnormally hot summers laden with heat waves can have detrimental impacts on human mortality and on ecosystems (e.g., forests), while abnormally wet periods can foster the spread of mosquito-borne disease. Arctic sea-ice cover varies from year to year with large amplitudes, affecting transportation, commerce, and local ecosystems. On the longer (decadal) time scales, oceanic variations can imprint themselves on atmospheric weather patterns, leading to seasonal- and decadal-scale regional shifts and changes in the occurrence of good weather, drought, and so on. Meteorological patterns such as the stagnation of high-pressure systems can give rise to continental-scale heat waves, and the El Niño cycle can induce rainfall excesses or deficits across the globe. Oceanic currents along coasts, which cause disruptions in coastal activities and fisheries, are driven both by natural variability and by forcing of the Earth system.

If we could predict such variations ahead of time—either specific, transient anomalies at the seasonal-to-interannual scale or, at the decadal scale, shifts or trends in the nature of the atmospheric and oceanic circulation and the associated probabilities of extremes—we could prepare and plan for them sufficiently early and could adapt to or mitigate their ill effects, leading to reduced damages and enhancing significantly economic and health benefits. As an example, predicting Arctic ice conditions in a given year can guide local storm risk assessments, planning for village resupply, and so on, and learning about the Arctic being generally ice-free during summer in coming decades would present unprecedented opportunities in a variety of economic and commerce sectors. In general, across the globe, skillful predictions of fair or problematic weather and climate, and associated risks of weather and climate extremes, would substantially support short-term and long-term planning in agriculture, the military, aviation, tourism, water and land management, and so on. Over the past decade significant advances have been made in the observation of the important variables and in the development of modeling and assimilation systems, all key to improved prediction systems.

To fully realize the benefits, however, we must address a number of currently unanswered questions. For example, have we adequately tapped all relevant sources of predictability in the Earth system, and are our modeling systems realistic enough to translate this information into forecast skill? Regarding longer time-scale variability, how will the Hadley and Walker weather circulations change in the coming decades? Will the monsoon systems in different regions of the world exhibit a shift in amplitude and spatial extent? Is the character of the Atlantic Meridional Overturning Circulation (AMOC) changing? Such circulation patterns can vary naturally on long time scales but may also respond to imposed external forcing (e.g., increases in $CO_{2,}$ methane, nitrous oxide, halocarbons, and aerosols). The decadal-scale aspect of the prediction problem indeed represents a new challenge to both science and societal planning. Scientists recognize it as both an initial value problem (forecasted decadal-scale anomalies partly reflect the state of the system at the start of the forecast) and a boundary value problem (the decadal-scale anomalies also reflect the evolution of CO_2, methane, aerosols, and other forcings that are anthropogenic in origin; IPCC WG1, 2013). Figure 9.14 illustrates hindcast simulations using a coupled climate model and a data assimilation system to demonstrate the significance of both observed initial conditions and radiative forc-

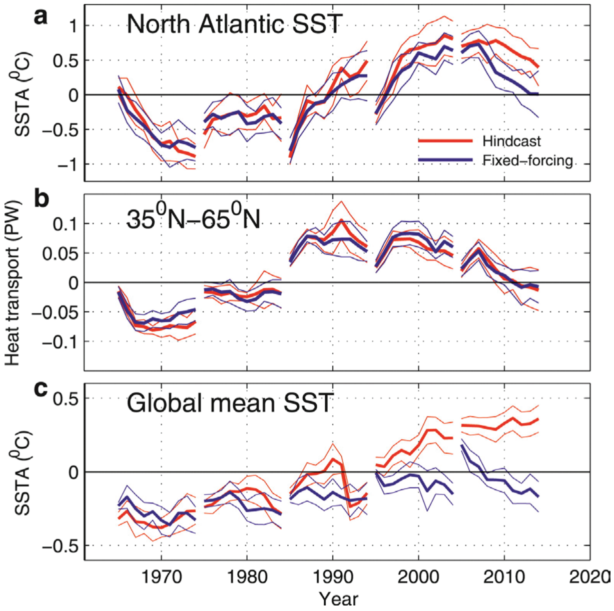

FIGURE 9.14 Decadal hindcast simulations (NOAA/GFDL CM2.1 global climate model with the Ensemble Coupled Data Assimilation system, used in WCRP/CMIP3 project). *Panel A:* The ensemble mean (thick) and spread (thin) time series of the SST anomalies in the North Atlantic subpolar gyre region as a function of forecast lead time for the decadal hindcast (i.e., decadal evolution based on initial climate state and time-evolving climate forcings; red) and fixed-forcing (i.e., decadal evolution based on initial climate state only; blue) experiments, initialized every 10 years from 1965 to 2005. *Panel B:* As in (A), but for the anomalous oceanic heat transport averaged over the latitude belt between 35 degrees and 65 degrees N in the North Atlantic. *Panel C:* As in (A), but for the anomalous global mean SST. SOURCE: Yang et al. (2014, Figure 8). © American Meteorological Society. Used with permission.

ing of climate on decadal predictions (Yang et al., 2013). While the global SST is driven by the radiative forcings, the decadal-scale North Atlantic SST and heat transport in the midlatitudes are driven primarily by the initial conditions.

The decadal problem is in fact new ground for consideration in the sustained monitoring of the Earth system, since it extends beyond both traditional weather forecasting (almost exclusively an initial-value challenge, at least to weekly and perhaps even to subseasonal time scales) and studies of decadal-to-centennial-scale climate change (boundary value problem). Societal planners and decision makers recognize the decadal scale problem as affecting infrastructural planning; such planning constitutes large resource investments and thus demands accurate, credible predictions. Planners are interested in knowing the potential for extremes (e.g., temperature, precipitation) as much as the mean trends.

The chief tools currently used for seasonal-to-decadal prediction are numerical models of the climate system—models that simulate the coupled behavior of the ocean, biosphere, cryosphere, and atmosphere (see Figure 9.1). The coupled models act to translate the information content of the initial state of the system into predictions of, for example, seasonal temperature and precipitation in continental regions or the extent of sea ice. Figure 9.15 provides an example of skill levels achieved with such a forecasting system. The coupled models can also simulate the impact of the boundary forcing (CO_2 concentrations, aerosols, etc.) on circulation patterns. In addition to the deployment of coupled global general circulation model prediction systems, some problems will require additional tools to estimate the physical impacts. For example, in the risk analysis of coastal inundation due to sea-level rise, tides, and storm surges, well-documented tools such as wave and tidal models, along with fine-grained regional coastal models, will be additionally needed.

A measurement program that includes satellites and that is complemented by adequate surface-based and other in situ observational platforms will contribute comprehensively to the initialization of Earth system models and thus to the skill of forecasts. In addition, sustained monitoring of variables that describe the evolution of the external forcing would allow us to better characterize the evolution of Earth's general circulation patterns and thereby enable tackling both the initial and boundary value aspects of the seasonal-to-decadal forecast problem.

In essence, the seasonal-to-decadal problem involves the quantification and prediction of "weather" anomalies, including extremes, superposed on a changing climate that is itself governed by natural and

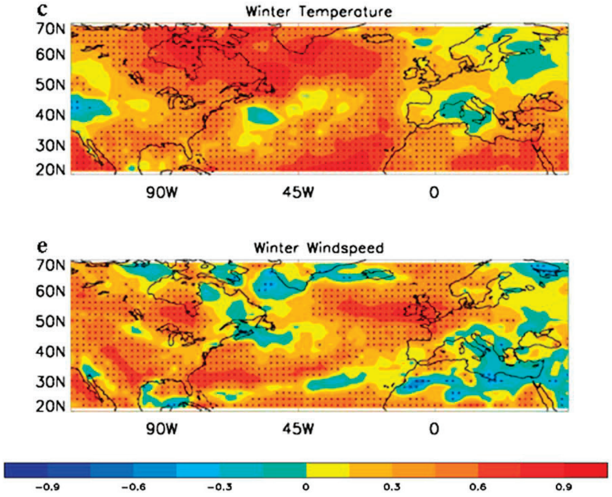

FIGURE 9.15 Evaluation of forecasts produced by the UK Met Office GloSea5 seasonal forecast system. Ensemble seasonal forecasts covering 20 years were initialized near November 1 during each year of 1993-2012; forecasted temperatures and wind speeds were then compared to observations. The ability to reproduce the observations, as measured by correlation score, is plotted. Stippling indicates that the skill levels are statistically different from zero at the 90 percent confidence level. SOURCE: Scaife et al. (2014, Figure 4, panels C and E). © 2014 American Geophysical Union.

anthropogenic forcings on the Earth system. The present maturity of the science and of existing measurement and instrumentation techniques provides confidence in meeting this challenge over the next decade.

Science Questions and Application Goals

Question C-6. Can we significantly improve seasonal to decadal forecasts of societally relevant climate variables?

Question C-7. How are decadal-scale global atmospheric and ocean circulation patterns changing, and what are the effects of these changes on seasonal climate processes, extreme events, and longer term environmental change?

The SATM (see Appendix B, Questions C-6 and C-7) describes the overarching and most societally relevant questions in the seasonal-to-decadal prediction challenge. These questions relate to the prediction of climate variations seasons to decades ahead, the identification and prediction of variations and trends in large-scale weather and ocean patterns that could lead, for example, to regime shifts in temperature and precipitation, and the determination of associated shifts in the occurrence and character of extreme events.

The SATM lists the specific goals associated with these questions. For seasonal-to-decadal prediction, the goals are to produce improved initial ocean states (including cryospheric components), land states (including cryospheric components), and stratosphere states for forecasts, as follows:

- *C-6a*. Decrease uncertainty (by a factor of 2) in the quantification of surface and subsurface ocean states for initialization of seasonal-to-decadal forecasts (Very Important).
- *C-6b*. Decrease uncertainty, by a factor of 2, in quantification of land surface states for initialization of seasonal forecasts (Important).
- *C-6c*. Decrease uncertainty, by a factor of 2, in quantification of stratospheric states for initialization of seasonal-to-decadal forecasts (Important).

Initializing ocean states is critical because these states impart the greatest predictability to the Earth system. Ocean heat content, particularly in the subsurface, has substantial memory and underlies our hopes for reliable decadal scale prediction and for most facets of seasonal-to-interannual prediction. The phases of the El Niño Southern Oscillation cycle (ENSO; a coupled mode of the atmosphere-ocean system), for example, can be predicted months or more in advance if the ocean is properly initialized; recent model experiments suggest (X. Yang, personal communication) that initializations that utilized observed subsurface oceanic profiles prove crucial for hindcasting of the 2015-2016 El Niño. (Note that the arbitrary specificity of the phrase "by a factor of 2" reflects the unique character of the seasonal-to-decadal [S2D] prediction problem, for which precise skill improvements cannot be specified; see the following.)

For questions regarding the atmospheric circulation, the SATM lists several objectives, as follows:

- *C-7a*. Quantify the changes in the atmospheric and oceanic circulation patterns, reducing the uncertainty by a factor of 2, with desired confidence levels of 67 percent (likely in IPCC parlance) (Very Important).
- *C-7b*. Quantify the linkage between natural (e.g., volcanic) and anthropogenic (greenhouse gases, aerosols, land use) forcings and oscillations in the climate system (e.g., MJO, NAO, ENSO, QBO). Reduce the uncertainty by a factor of 2. Confidence levels desired: 67 percent (Important).

- *C-7c*. Quantify the linkage between global climate sensitivity and circulation change on regional scales, including the occurrence of extremes and abrupt changes. Quantify the expansion of the Hadley cell to within 0.5 degree latitude per decade (67 percent confidence desired); changes in the strength of AMOC to within 5 percent per decade (67 percent confidence desired); changes in ENSO spatial patterns, amplitude, and phase (67 percent confidence desired) (Very Important).
- *C-7d*. Quantify the linkage between the dynamical and thermodynamic state of the ocean upon atmospheric weather patterns on decadal time scales. Reduce the uncertainty by a factor of 2 (relative to decadal prediction uncertainty in IPCC, 2013). Confidence level: 67 percent (likely) (Important).
- *C-7e*. Provide observational verification of models used for climate projections. Are the models simulating the observed evolution of the large-scale patterns in the atmosphere and ocean circulation, such as the frequency and magnitude of ENSO events, strength of AMOC, and the poleward expansion of the subtropical jet (to a 67 percent level correspondence with the observational data)? (Important).

The two Very Important objectives address the aspects of decadal-scale variability in atmospheric circulation most relevant to society: how changes in the circulation affect mean weather conditions and, just as important, how they affect the probability of weather extremes such as droughts, floods, and hurricanes. Existing research has demonstrated the importance of observations combined with state-of-the-art modeling and assimilation systems to the analysis of such extremes; Murakami et al. (2015), for example, describe successful hindcast simulations of hurricanes in the world's ocean basins over the past ~3 decades, including the most destructive Category 4 and 5 storms. With expected advances in observations, the science is well poised to address decadal-scale changes in the character of circulation and extremes.

Measurement Objectives and Approaches

The S2D prediction problem is best addressed by evaluating and improving the predictions made with forecast modeling systems and through climate studies utilizing state-of-the-art decadal-centennial climate models. These models should indeed provide the best, and most relevant, S2D forecasts of extremes and shifts in climate patterns, particularly if initialized with continuous space-based measurements in conjunction with complementary in situ and airborne measurements.

For S2D prediction (Question C-6 in the SATM), the measurement objectives targeted here are associated with forecast model initialization, which in the coming years will rely on the IESA framework. As discussed earlier, the IESA is a coupled model data assimilation system that ingests and optimally combines a wide variety of data sets into a single consistent and comprehensive picture of atmospheric, ocean, cryospheric, and land states. (This comprehensive modeling framework will indeed serve as a basis for much of NASA Earth science in the coming years.) The IESA can thereby provide estimates of ocean, land, and stratosphere states (including cryospheric components) that are critical for initializing forecasts extending beyond the ~10-day scale of weather prediction. Among the measurements that should be ingested into IESA systems for the S2D prediction problem are the following:

- Tropospheric quantities (temperature, water vapor, cloud properties, tropospheric winds, surface pressure);
- Stratospheric quantities (polar vortex winds, ozone, temperature, water vapor);
- Ocean quantities (sea-surface height, sea-surface salinity, sea-ice thickness, sea-ice fraction, sea-surface temperature, surface vector winds, subsurface temperatures and salinity, surface currents, ocean mass, ice-shelf slope); and

- Land-surface quantities (soil moisture at the surface and in the root zone, freeze-thaw state, total water storage, vegetation phenology, snow water amounts, surface albedo).

The SATM provides information on optimal resolutions and approaches.

Characterizing decadal-scale shifts in climate patterns (Question C-7 in the SATM) requires continuous space-based measurements examined in the context of the new generation of global numerical models that couple together the atmosphere, oceans, biosphere, and cryosphere. Needed measurements include the following:

- Climatological averages and anomalies in weather patterns (e.g., Arctic wintertime winds, midlatitude jets, surface and subsurface ocean currents, water vapor transport, cloud distributions) and surface meteorological variables (e.g., precipitation, air temperature, soil moisture).
- Natural (volcanic, solar) and anthropogenic (greenhouse gases, aerosols, land use) forcings. For the short-lived forcers in particular, the precursor emissions together with a self-consistent meteorology would be needed to obtain accurate global distributions and thus the spatially dependent forcings.
- Atmospheric circulation on regional scales including the occurrence of extremes and abrupt changes.
- Dynamic and thermodynamic state of the ocean.
- Evolution of the large-scale patterns in the atmosphere and ocean circulation (e.g., ENSO, AMOC, poleward shift of the subtropical jet).

For both questions, a large variety of measurement types are listed here. This underlines the unique character of these questions and their associated objectives: because the variety of measurements far exceeds what can reasonably be expected from a single NASA mission, answering either question is probably best viewed *not* as the motivation for a specific mission. Instead, it is best considered as benefiting (e.g., via integration through the IESA) from a very wide range of measurements collected in response to missions designed for other science objectives (e.g., the measurement of sea-surface height for the study of sea-level rise or the measurement of cloud information needed for determining climate sensitivity). Another motivation for this viewpoint is the fact that the limits of predictability on seasonal to decadal time scales are currently difficult to quantify (NRC, 2010), so quantitative promises cannot be made regarding skill improvements associated with any specific measurement. Note, however, that the consensus in the scientific community is that current forecast systems fall short of the predictability limits due in part to deficiencies in forecast model initialization and in the models themselves, and that an improved measurement program would significantly mitigate the first deficiency. Quantitative reduction of uncertainties along with the desired confidence levels indicated in the objectives stated earlier serve as markers to be attained in the S2D challenge.

Given the use of the IESA for forecast initialization, two aspects of the listed measurement objectives for the S2D forecast problem require consideration:

1. The absence of any particular measurement is not a "deal-breaker," since some value is still derived from the others through the IESA's integration. Note, however, that sea-surface height, sea-surface temperature, subsurface temperatures, surface vector winds, and surface currents in the ocean and root zone soil moisture and snow at the land surface are considered by some to be most important for seasonal prediction, whereas for decadal prediction (and seasonal sea-ice prediction), important variables also include salinity, sea-ice thickness, sea-ice fraction, and ocean mass.

2. While the particular spatial resolutions listed for this objective in the SATM, which were compiled through discussion with experts in the field, can be considered optimal targets, coarser resolutions than those listed would also not be deal-breakers, since useful information that advances understanding and prediction could still be extracted from the coarser data.

The key point is that the accuracy of the model assimilation product (for initialization of the forecasts and for the analysis of seasonal-to-decadal variations) should improve as the variety of the data sets employed increases and as the resolution of each data set used increases. Such a pathway from improved measurements to improved data assimilation products (both through the direct ingestion of the measurements into the data assimilation system and through their use in improving the system's underlying models) has been demonstrated extensively—for example, in the context of initializing numerical weather forecasts (e.g., Dee et al., 2014). The S2D problem should benefit, to varying degrees, from newly captured measurements obtained in a number of NASA missions.

Because of the continuum of time scales—from seasonal to interannual to decadal—being dealt with for questions C-6 and C-7, and given the urgent need for the U.S. weather and climate communities to tackle and successfully address "seamlessness" in weather-to-climate forecasting (e.g., NRC, 2012), continuity in observations and sustained measurements are essential. This is particularly true given the need to address not only "average" weather but also its extremes (the "tails" of the probability distribution function of atmospheric and ocean states).

While many of the needed measurements are amenable to satellite-based remote sensing (and are in fact covered by the Program of Record), some are not; subsurface ocean temperature distributions, for example, must presumably be measured with in situ buoy systems or through the Argo array (including Deep Argo). Field campaigns may be needed to characterize relevant processes related to well-mixed and short-lived greenhouse gases, aerosols, clouds, and wind fields. For the boundary-value component of the decadal problem, it will also be necessary to quantify relevant external forcings (CO_2 concentrations, etc.). While satellite data can contribute to estimates of, for example, precipitation and land use, supplementary ground-based measurements can significantly bolster such estimates. Of the satellite-based measurements needed, the measurement type not addressed within the POR is ocean surface currents, which would require the development of a Doppler scatterometer. Importantly, reanalysis (IESA) will be needed to assemble a comprehensive time series of states for complete Earth system determination.

A key aspect to consider in the seasonal-to-decadal forecasting problem is the joint requirement of accurate initial conditions (as provided by the IESA) and a model for evolving the initial states forward in time. Forecast models are far from perfect, and thus model physics development would be valuable in conjunction with improved initial conditions. Such model development (particularly, improvements in process parameterizations) would presumably benefit from a wide variety of NASA measurements.

The need for an IESA is part of an overall need here for coupled data assimilation, initialization, reanalyses, and reforecasts. There has been exceedingly good progress in IESA development, particularly involving the physical climate system, over the last decade. Addressing the S2D problem correctly, however, will require more than making routine accurate forecasts based on sustained observations of climate parameters around the globe. In the future modeling the coupled physical climate system in isolation will be increasingly insufficient; the coupling will need to be expanded to include biogeochemical cycles (carbon, nitrogen, etc.) and terrestrial and marine ecosystems. The challenge then becomes more complex given the corresponding expansion of the catalog of variables to be observed. However, the resultant outcomes should provide powerful and gainful benefits for multiple societal sectors.

Connections to Other Panels and Integrating Themes

The seasonal-to-decadal forecasting problem and the weather-climate interface challenge it entails has a strong tie to the subseasonal, regional forecasting objectives of the Weather Panel (Questions W-2 and W-4); the drought and water-related forecasting objectives of the Hydrology Panel (Questions H-1 to H-3) and sea-level-related coastal impacts (Question H-4); and the weather/climate-driven cycling of key constituents (e.g., water, carbon) among the priorities of the Ecosystems Panel (Question E-2). Also, an external forcing mechanism that can affect circulation patterns is solar irradiance changes and the loading of the stratosphere with sulfate aerosols following explosive volcanic eruptions. The occurrence of explosive eruptions has a potential link with Earth's surface dynamics priority of the Solid Earth Panel (Questions S-1 and S-4); coastal loss due to sea-level rise (SLR) has a potential link with Question S-3. The prediction of temperature and precipitation and sea-ice anomalies at seasonal and longer time scales ties in directly to the Water and Energy Cycle Integrating Theme, and the prediction of changes in the character of extremes has an obvious linkage with the Integrating Theme on Extremes.

C-8: Causes and Effects of Polar Amplification

Motivation

Polar amplification refers to the potential for greater warming in polar regions compared to the rest of the globe due in part to strong positive feedbacks between ice cover and albedo decreases and air temperature increases in these regions causing additional warming. In the Arctic amplification is already observed, while for the Antarctic amplification does not seem to be in effect yet due to the presence of dampening processes. While polar amplification is largely driven by changes in sea ice and snow cover, changes in atmospheric and ocean circulation, including changes in prevailing winds driven by ozone depletion, have also contributed. Understanding these processes and their impacts on the global climate is critical to understanding climate sensitivity. Changes in the polar regions may affect global climate through changes in ice coverage, clouds, winds, carbon pools and fluxes, bottom water formation, and sea-level rise.

While polar regions are remote, they are relevant to global climate and human systems. Polar regions are generally covered by snow and ice most of the year, helping to keep the planet cooler than it otherwise may be. These regions are key in the formation of deep ocean water that drives global ocean circulation patterns, as well as driving large-scale atmospheric circulation between the warm tropics and the cold poles. Today, we are seeing pronounced changes in the polar regions, which climate models have struggled to accurately simulate. In most cases models have been too conservative in their projections of cyrospheric change, especially in regard to the Arctic sea-ice cover (Stroeve et al., 2007, 2012), but also in regard to changes in northern hemisphere snow cover (Derksen and Brown, 2012) and ice-sheet flow (Pollard et al., 2015). This is due to a range of key processes that are not fully understood or not accurately represented in the models, resulting in considerable model deficiencies.

Arctic temperatures have continued to rise at two to three times the rate of global temperature increase, with the average annual surface air temperature anomaly over land north of 60°N for October 2015-September 2016 being 3.5°C above preindustrial levels (Richter-Menge et al., 2016). In response to this rapid warming, Arctic sea-ice cover in the month of September has declined by nearly 14 percent per decade, as documented by nearly four decades of satellite observations (IPCC AR5, 2013). Earlier ship and aircraft observations, whaling log reports, and ice charts reveal that today's sea-ice loss in the Arctic is unprecedented in the last 150 years, while sea-ice reconstructions from terrestrial proxies suggest it is unprecedented in at least 1450 years (Kinnard et al., 2011). Similarly, long satellite records have documented a significant reduction in seasonal snow cover extent over recent decades (Derksen and Brown, 2012); the rapid loss of land ice from Greenland (Shepherd et al., 2012) and glaciers and ice caps from Alaska, Canadian Arctic, Russian Arctic, Svalbard, Iceland (Jacob et al., 2012); and an increase in coastal erosion along Arctic permafrost shores (Jones et al., 2009). These changes have already affected Earth's radiation budget, raised sea level, and affected land water hydrology, coastal erosion, marine ecosystems, the Arctic atmosphere, and the carbon cycle.

There has also been rapid warming of the Antarctic Peninsula and rapid melt of West and East Antarctic ice. The Antarctic Circumpolar Current has warmed faster than the global ocean as a whole, which plays an important role in the carbon budget. On the other hand, warming for the Antarctic continent has been much slower than Arctic warming. Ozone depletion from human activities is part of the explanation, leading to intensification of the polar vortex and strengthening of the westerly winds. This has effectively isolated Antarctica from warming elsewhere on the planet, leading to little change in surface temperature over much of the Antarctic continent. Changes in the winds have also largely driven the slight expansion of Antarctic sea ice over the satellite data record, although the last 2 years have seen record low, or near record lows, highlighting the large interannual variability in the Antarctic sea-ice cover. Uncertainty remains as to the role of natural versus forced climate variability in explaining the expansion (NASEM, 2017). Hence, unlike in the Arctic, where temperatures are increasing at 2-3 times the global average, the Antarctic has not warmed as fast as the rest of the world. Both climatic trends have, however, impacted the Earth system beyond the polar regions and have both contributed to sea-level rise from melting land ice.

Given these rapid changes taking place at the poles, there is an urgent need to observe and understand the changes taking place at high latitudes, especially in the Arctic, in order to help and protect human systems and support decision making, but also in the Antarctic, to understand its impact on global climate and sea-level change.

While anthropogenic influences have very likely contributed to Arctic sea-ice loss since 1979 (IPCC, 2013; Notz and Stroeve, 2016), the thinning and shrinking of the Arctic sea-ice cover combined with reductions in northern hemisphere snow cover in June has contributed to amplification of the warming in the northern polar regions (Serreze et al., 2009; Brown and Robinson, 2011; Derksen and Brown, 2012; Najafi et al., 2016). Changes in atmospheric and oceanic circulation, heat-trapping water vapor and clouds, and the lapse rate feedback, have also contributed, although uncertainty remains as to the relative contributions of each to the observed warming (Pithan and Mauritsen, 2014). The importance of the factors driving Arctic amplified warming is relevant in improving an understanding of whether and how continued Arctic change will impact midlatitude weather extremes or, at the very least, if the two phenomena are correlated. The chaos of the atmospheric circulation makes it difficult to determine whether or not amplified warming in the Arctic is already impacting midlatitude weather extremes. This topic is a major research challenge, yet continued monitoring Arctic changes, such as sea-ice loss and snow cover retreat, together with better characterization of the atmosphere can help to answer this question.

Much of the understanding and documentation of these changes come from decades of satellite observations. Continuation of these long-term satellite observations are essential for understanding the role of natural climate variability versus anthropogenic forcing on the long-term decline of sea ice, its impact on midlatitude weather, the impact of melting land ice on global sea level, and quantifications of hydrological and biogeochemical fluxes.

Science Question and Application Goals

Question C-8. What will be the consequences of amplified climate change already observed in the Arctic and projected for Antarctica on global trends of sea-level rise, atmospheric circulation, extreme weather events, global ocean circulation, and carbon fluxes?

In order to make progress on this science question, the panel has identified the following objectives:

- *C-8a*. Improve our understanding of the drivers behind polar amplification by quantifying the relative impact of snow/ice-albedo feedback versus changes in atmospheric and oceanic circulation, water vapor, and lapse rate feedback (Very Important).
- *C-8b*. Improve understanding of high-latitude variability and midlatitude weather linkages (impact on midlatitude extreme weather and changes in storm tracks from increased polar temperatures, loss of ice and snow cover extent, and changes in sea level from increased melting of ice sheets and glaciers) (Very Important).
- *C-8c*. Improve regional-scale seasonal to decadal predictability of Arctic and Antarctic sea-ice cover, including sea-ice fraction (within 5 percent), ice thickness (within 20 cm), and location of the ice edge (within 1 km), timing of ice retreat and ice advance (within 5 days) (Very Important).
- *C-8d*. Determine the changes in Southern Ocean carbon uptake due to climate change and associated atmosphere/ocean circulations (Very Important).
- *C-8e*. Determine how changes in atmospheric circulation, turbulent heat fluxes, sea-ice cover, freshwater input, and ocean general circulation affect bottom water formation (Important).
- *C-8f*. Determine how permafrost thaw-driven land cover changes affect turbulent heat fluxes, above- and belowground carbon pools, resulting greenhouse gas fluxes (carbon dioxide, methane) in the Arctic, as well as their impact on Arctic amplification (Important).
- *C-8g*. Determine the amount of pollutants (e.g., black carbon, soot from fires, and other aerosols and dust) transported into polar regions and their impacts on snow and ice melt (Important).
- *C-8h*. Quantify high-latitude, low-cloud representation, feedbacks, and linkages to global radiation (Important).
- *C-8i*. Quantify how increased fetch, sea-level rise, and permafrost thaw increase vulnerability of coastal communities to increased coastal inundation and erosion as winds and storms intensify (Important).

The panel also determined that improving and continuing to characterize land-ice melt, accumulation of snowfall and ice flow dynamics of the ice sheets, mountain glaciers and ice caps and the physical processes (surface melt from warm air temperatures, basal melt from warm ocean temperatures, calving mechanisms, basal sliding) that drive these changes and how they relate to global climate variables are also important (see Question C-1 for requirements).

Few field observations are collected in the polar regions, which remain the least well explored parts of the planet. All the preceding stated objectives are important and require substantial investments in field and remote sensing observations as well as modeling.

Measurement Objectives and Approaches

The measurements needed for these objectives are listed in the SATM (see Appendix B). Here, we highlight the measurements that are needed to achieve the Very Important objectives listed earlier. For land-ice monitoring (ice sheets, glaciers), a range of active and passive microwave instruments, lidars, and gravimetric sensors will be needed to continue existing time series of land-ice volumes and fluxes (see Question C-1).

- *Sea-ice concentration/extent/ice type/thickness.* These measurements are key for air-sea fluxes, radiation budget, biological feedbacks, regional-scale S2D variability and midlatitude weather forecasts. In the Arctic this information is also required by coastal managers, shipping companies, and extractive industries. Thus, there is a strong need to ensure continuity of the multichannel passive microwave observations started in October 1978 as part of the Defense Meteorological Satellite Program but to be discontinued. The existing satellites are aging, including JAXA's AMSR2, which now exceeds its nominal lifetime, and currently the United States is not planning any follow-on missions to ensure the continuity of this historical data set. These sensors are important for other climate variables, including rainfall, snow cover, ice-sheet melt, sea-surface temperatures, wind speed, and soil moisture, which are critical measurements for Very Important priority climate variables such as air-sea fluxes, sea-level rise, and seasonal to decadal predictability. There is also a strong need to improve upon the resolution of these instruments (25 km for SSMI and 10 km for AMSR2) to better delineate the ice edge and for marine applications such as ship routing. Sea-ice thickness will require a combination of laser altimetry (e.g., ICESat) and high-frequency radar interferometry topographic mapping (Ku-/Ka-band, e.g., SWOT) to provide data at 1 km resolution with a vertical precision of 3 cm or better. Combining sensors will allow for both retrieval of snow depth and ice thickness, which one sensor alone cannot achieve. CryoSat, AltiKa, and Sentinel-3 are already providing standard sea-ice thickness products with greater precision (albeit lower spatial resolution), and SMOS is providing thin-ice thickness.
- *Snow cover extent/thickness/snow water equivalent.* While continuity of the multichannel passive microwave series is desirable, other approaches combining radar interferometry mapping (Ku-/Ka-band) or laser and radar altimetry should be pursued to provide higher resolution data and precision measurements of the temporal variability in surface height. Snow thickness and water equivalent are critical for land hydrology and permafrost studies. Snow depth on sea ice is currently not retrieved with satellites, although there is the potential to retrieve it using dual radar Ka- and Ku-band radar topographic mappers, combined laser and radar altimetry (i.e., collocated ICESat-2 and CryoSat-2), L-band radiometers, or radar interferometry techniques.
- *Changes in ice sheets, glaciers, and ice caps.* See Question C-1 for additional details.
- *Atmospheric boundary layer (surface temperatures, temperature profiles, surface-air fluxes, water vapor, clouds).* Daily at 25 km spatial resolution, 200 m vertical resolution in the planetary boundary layer (PBL) using IR and microwave sounders (e.g., AIRS, AMSU, ATMS), GNSS-RO.
- *Sea-surface temperature, wind speed.* For calculation of air-sea fluxes, the skin temperature of the sea surface is required at diurnal resolution and a few kilometers spatial resolution, within 0.1 K accuracy. The temporal and spatial variability should be similar for wind speed at a few kilometers spatial resolution, daily, 2 m/s uncertainty, via scatterometers (e.g., QuikSCAT).
- *Freeze/thaw state of the nonglacierized circumpolar land surface.* Observation of this state is important for quantifying carbon, energy, and water fluxes and how they affect land cover change. This variable is best addressed with passive microwave radiometers or synthetic aperture radars. There are no current operational measurements of active layer thickness from space; however, observations of seasonal freeze-thaw cycles and the range of associated thaw subsidence and frost heave due to water-ice phase transitions allows indirect assessments of active layer thickness. Permafrost cannot be directly observed with current spaceborne sensors, and quantifying the state of permafrost across regions requires relation of environmental surface variables (air and skin temperature, land

cover, snow cover and density, freeze/thaw state) with models of subsurface temperatures and validation data from boreholes (Pastick et al., 2015; Westermann et al., 2017). Long-term land surface subsidence due to permafrost thaw can already be observed with spaceborne InSAR—TerraSAR-X (X-band), Radarsat, Sentinel-1, ERS (C-Band), PALSAR (L-Band)—and the full range of lidar instruments from terrestrial to airborne to spaceborne (ICESat; Jones et al., 2015), and observations need to be continued and expanded to larger spatial domains. Monitoring of erosion along permafrost coasts requires annual high-resolution optical and SAR image data sets with submeter to several meters ground resolution.

- *Bottom water formation, carbon update.* Required is information on wind speed (see earlier), sea-surface temperature (see earlier), polynya formation using passive microwave and synthetic aperture radar (km spatial resolution, daily temporal resolution), ocean subsurface temperature via Argo network with ice-avoiding capability and seal data, autonomous underwater vehicles (AUVs), and gliders, and rate of thinning of Antarctic ice shelves (via CryoSat and ICESat-2 polar altimetry, interferometric synthetic aperture radar, km spatial resolution, monthly resolution).

Connections to Other Panels and Integrating Themes

Snow extent, thickness, and water equivalent are relevant to the water and energy cycle. Thawing permafrost is relevant to high-latitude terrestrial ecosystems, affects water resources in the terrestrial Arctic, and can be a hazard to northern communities. Measurements of ice melt are relevant to sea-level rise and coastal impacts worldwide. Understanding of high-latitude climate and connection to midlatitude climate, improved seasonal sea-ice forecasts, and a better characterization of the atmospheric boundary layer in polar regions is relevant to improving weather forecasts. Sea-ice forecasts are also relevant for coastal communities, shipping companies and extractive industries. Sea ice, permafrost and active layer state, as well as snow extent and thickness are relevant for managing northern transportation infrastructure and ecosystems. Permafrost thaw and mobilization of previously frozen carbon is directly contributing to carbon cycle changes and observation strategies for monitoring greenhouse gas release on global scales thus also apply for permafrost regions.

C-9: Ozone and Other Trace Gases in the Stratosphere and Troposphere

Motivation

Earth's ozone layer shields the surface from harmful ultraviolet (UV) radiation. The global ozone layer is in the process of a slow, long-term recovery from human release of CFCs and other harmful ozone-depleting substances (ODSs; WMO, 2014; Solomon et al., 2016). As the atmospheric levels of CFCs and ODSs decline, levels of stratospheric column ozone will be controlled in a rather complex manner by future atmospheric levels of CO_2, CH_4, and N_2O (Eyring et al., 2013; Revell et al., 2015; see Figure 9.16). The possible future intensification of the strength of the Brewer Dobson circulation due to rising levels of greenhouse gases (GHGs; Butchart, 2014) will also be a key factor in determining the future thickness of Earth's ozone layer and the resulting levels of UV radiation reaching the surface (WMO, 2014).

In addition to controlling the transmission of UV radiation, stratospheric ozone is radiatively active and impacts atmospheric temperatures and circulation. The global radiative forcing (RF) by stratospheric ozone from 1750 to 2011 is estimated as –0.05 (–0.15 to +0.05) W m^{-2} (IPCC, 2013). But effects on climate arising from ozone-depletion-induced changes in atmospheric circulation can be much more significant. For example, the past decline of Earth's ozone layer has been associated with changes in surface tem-

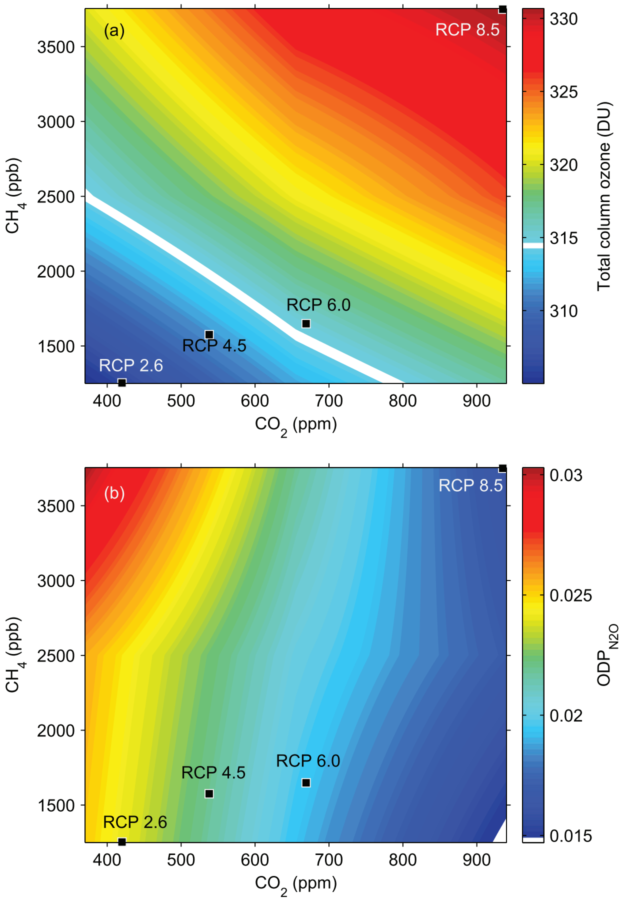

FIGURE 9.16 Projections of total ozone and ozone depletion potential of N_2O for year 2100. *Upper panel;* Calculation of global-mean total column ozone in 2100 as a function of CO_2 and CH_4, found using constraints from RCP 6.0 for all other quantities (i.e., ODSs, N_2O). *Lower panel:* Ozone depletion potential of N_2O in 2100 as a function of CO_2 and CH_4, found using constraints from RCP 6.0 for other quantities. The white contours show the values of total column ozone (314 DU) and ODP of N_2O (0.015) for year 2000, provided to give an indication of how these quantities could evolve over the next century. The black squares in both panels show values corresponding to the appropriate CO_2 and CH_4 surface concentrations for the different RCPs in 2100. SOURCE: Revell et al. (2015, Figure 1). © 2015 American Geophysical Union.

peratures, clouds, and precipitation in the southern hemisphere due to the Antarctic ozone hole (Previdi and Polvani, 2014). It has been suggested that the future recovery of the ozone layer will enhance surface warming globally in the first half of this century (Hu et al., 2011).

The stratosphere and troposphere are tightly coupled via the upper troposphere and lower stratosphere (UT/LS) region, commonly considered to be the region within ±5 km of the tropopause (Gettelman et al., 2011). The UT/LS plays a key role in controlling Earth's radiative and thermal balance and climate (Gettelman et al., 2011; Riese et al., 2012; Coffey et al., 2014). But radiatively active species such as water vapor and ozone exhibit steep vertical gradients and substantial spatial and temporal variability in the UT/LS, leading to large uncertainties in quantifying their effects. The composition of this region is controlled by transport from the troposphere and stratosphere, and meridional exchange between the tropical UT and extratropical LS. Key issues involve the control of RF of climate due to changing levels of humidity (Solomon et al., 2010), aerosols (Kaufmann et al., 2011), and the response of temperature in this region to rising levels of GHGs (Gettelman et al., 2011).

Tropospheric ozone also exerts considerable control on climate. Human release of CO, NO_x, and volatile organic chemicals (VOCs) has led to a buildup of tropospheric O_3 (Shindell et al., 2006), which increased the global RF of climate by +0.4 (0.2 to 0.6) W m^{-2} between 1750 and 2011; this is almost equal to the RF of climate by CH_4 (+0.48 Wm^{-2}) over this same period of time (IPCC, 2013). The largest contribution to the climatic influence of tropospheric O_3 is from enhancements in the tropical troposphere (Stevenson et al., 2013). Elevated surface O_3 adversely affects human health and agriculture (Avnery et al., 2011). Legislation enacted to protect public health has significantly reduced emissions of O_3 precursors from automobiles, factories, and power plants throughout much of the industrialized world, resulting in a steady decline of tropospheric O_3 levels in the extra-tropics (Cooper et al., 2014). It is unclear whether these will reduce the climatic impact of O_3, since the largest radiative influence of O_3 is in the tropics, where elevated O_3 has been linked to biomass burning (Jacob et al., 1996; Anderson et al., 2016).

Science Question and Application Goals

Question C-9. How are the abundances of ozone and other trace gases in the stratosphere and troposphere changing, and what are the implications for Earth's climate?

This can be answered with the following quantified objectives:

- *C-9a*. Quantify the amount of UV-B reaching the surface, and relate to changes in stratospheric ozone and atmospheric aerosols (Important).
- *C-2g*. Quantify the contribution of the upper troposphere and stratosphere (UTS) to climate feedbacks and change by determining how changes in UTS composition and temperature affect radiative forcing with a 1-sigma uncertainty of 0.05 W/m^2 over the course of the decade (Very Important).

The goal here is to improve prediction of the ozone layer, as well as atmospheric and surface radiative forcing and its associated consequences for climate. Achieving this goal requires measurements of the temperature and changing composition in the UTS, including ozone and other radiatively active gases such as H_2O, CO_2, CH_4, and N_2O, as well as aerosols and aerosol precursors released by a wide variety of industrial processes, volcanoes, and biomass burning (aerosols are discussed in Question C-5). Distributions of O_3 and other constituents that are key to climate predictability are controlled by chemical transformations, dynamical processes ranging from planetary and gravity waves to the Hadley Cell and Brewer Dobson Circulation, and the interaction of chemistry and transport (e.g., transport of pollutants in monsoonal circulations). Therefore, achieving this goal also requires knowledge of these processes, which means observing a suite of chemically reactive constituents such as NO_x, HO_x, and halogens, as well as transport tracers. It is also critical that existing suborbital assets such as (but in no way limited to) the Brewer Dobson Network, the Network for Detection of Atmospheric Composition Change, various programs that launch ozonesondes and watersondes, as well as routine (e.g., piggyback on commercial flights) and campaign observations by aircraft and balloons all be maintained. This will ensure that future spaceborne observations can be evaluated, eventually validated, and ultimately tied in a quantitatively meaningful manner to a wide variety of existing measurements. The ultimate, long-term goal is provision of climate data records that will allow the next generation of scientists to reliably assess, and confidently predict, the role of human activity on Earth's protective ozone layer and consequences for surface UV, the consequences for climate of changes in Earth's ozone layer, and the importance of the UT/LS region for climate change.

Measurement Objectives and Approaches

As detailed in the SATM (see Appendix B), improving predictability of the ozone layer and how changes in atmospheric trace gas concentrations will affect climate requires a complete set of measurements that can be used to determine the vertically resolved distribution of stratospheric O_3 and other trace gases from the upper troposphere through the stratosphere. These profiles must be measured with accuracy sufficient to quantify the decadal radiative forcing with a 1-σ uncertainty of better than 0.05 W/m^2. The SATM also includes an objective on quantifying the amount of UV-B radiation reaching the surface, since this is a quantitative measure of the impact of changing stratospheric ozone on the surface, even though this impact is not expected to be measured from space. For prognostic capabilities it is necessary to characterize the processes that control the UT/S temperature and constituent distributions, which requires measurements of relevant chemically reactive constituents and transport tracers. Observations of temperature and key radiatively active gases in the UT/LS must have sufficient precision, vertical resolution, and geographic coverage to quantify radiative forcing; the SATM requirements are specified to meet this requirement. In addition, diagnostics of the processes that control the temperature and distributions of O_3 and other radiatively active constituents must be measured with a precision, vertical resolution, and geographic coverage appropriate for the scales on which the processes occur. As specified in the SATM, the observations must be global in nature, comprehensive, and with high vertical resolution (~1 km or better) because of steep vertical gradients in the UT/LS.

These measurement requirements can be met with a number of different approaches, each with advantages and disadvantages. For example, UV, visible, and infrared solar occultation (e.g., Mauldin et al., 1985; Russell et al., 1993; Lucke et al., 1999; Bernath et al., 2005) lend themselves to measurements with high-precision, sub-km vertical resolution, and climate-quality data; global coverage requires a constellation. Lunar (Amekudzi et al., 2005) and stellar (Kyrölä et al., 2004) occultation provide better horizontal coverage, but are less well-proven. Infrared (Fischer et al., 2008) and microwave (Waters et al., 2006) limb emission instruments provide global coverage with night and daytime sampling; obtaining fine vertical resolution is a challenge. Limb scattering of visible solar radiation (McPeters et al., 2000) is another technique that yields global coverage. Nadir-viewing instruments measuring emitted (Beer et al., 2001) or scattered (Bhartia et al., 1996) radiation can provide global coverage with very high horizontal resolution, but limited vertical resolution. Radio occultation measurements (Kursinski et al., 1997) have proven useful for tropospheric temperature and water vapor. Because of the rich spectrum of molecular lines, infrared sounders are typically capable of detecting more trace gas species than other instruments. All of these approaches have been used to measure ozone, temperature, or other trace gas species in the troposphere or stratosphere, and would be plausible candidates for contributing to the measurement objectives described earlier. The long-term plan in the United States for measuring vertical profiles of stratospheric ozone is to use the Ozone Mapper and Profiler Suite-Limb Profiler (OMPS-LP), but whether a succession of such instruments will be suitable for measuring ozone trends is not yet clear (Jaross et al., 2014).

Connections to Other Panels and Integrating Themes

Weather and Air Quality Panel

State-of-the-art operational forecast centers rely on models that assimilate satellite radiances. It has been shown that the stratosphere exerts a strong influence on tropospheric weather (Baldwin and Dunkerton, 2001; Kidston et al., 2015), and that medium and longer range weather forecasts exhibit quantitative improvement in accuracy when a realistic stratosphere is included in the forecast models (Baldwin et al., 2003; Charron et al., 2012; Sigmond et al., 2013). Also, downward transport of stratospheric O_3 has been implicated in surface O_3 violations, particularly during winter in mountainous regions such as the U.S. Midwest (Lin et al., 2015). Finally, poor air quality is known to occur during hot, stagnant conditions. Were stratospheric O_3 recovery to accelerate global warming, then it would require even further reductions in the emission of O_3 and aerosol precursors to achieve a particular air quality standard.

Societal Benefits

Earth's O_3 layer protects humans, animals, and plants from harmful ultraviolet radiation released by the sun, particularly in the UV-B spectral region (280 to 315 nm). The thickness of the global O_3 layer was reduced by about 5 percent due to anthropogenic halogens in the early 1990s, which has and will continue to lead to excess skin cancer fatalities throughout the world (Slaper et al., 1996). The ban on the manufacture of ozone depleting substances brought about by the Montreal Protocol limited global O_3 depletion at the ~5 percent level, thereby avoiding runaway increases in skin cancer due to a severely damaged ozone layer that could have otherwise resulted (Longstreth et al., 1998). The need to understand the effect of GHGs such as CH_4 and N_2O on the O_3 layer is motivated by the societal importance of not reversing the great success of the Montreal Protocol.

The need to understand the radiative budget of the UT/LS is motivated, in part, by the fact that the RF of climate due to the rise in tropospheric O_3 over the Industrial Era rivals that due to the rise in CH_4 (see Figure 9.16), with most of this climate driver due to O_3 increases in the tropical UT/LS. Simply put, it is unclear whether policy measures currently enacted or planned for the near future will reverse the trend of rising O_3 in this climatically important region of the atmosphere. The tropical UT/LS has long been characterized as a nexus for the interaction of climate and atmospheric composition, and the conduit in the exchanges between stratospheric and tropospheric thermodynamical states. In addition, climate models poorly represent the processes that control the vertical distribution of radiatively active constituents in the UT/LS, even though changes in these constituents have a strong influence on the global climate (SPARC, 2010). The measurements described earlier are designed to provide data-driven policy options to address radiative forcing of climate that occurs in the UT/LS.

RESULTING SOCIETAL BENEFIT

Earth's climate shapes the nature of societies, the characteristics of ecosystems and the performance of economies across the globe through its wide-ranging influence on natural and human systems (Carleton and Hsiang, 2016). What grows well, what prospers, where, and for how long depends on climate. Where it is more or less hazardous to live, whether because of risks of disease or natural hazard, depends on climate. The type of infrastructure needed to protect against natural hazards and ensure provision of energy, food, water, and transportation connectivity all depend on the climate.

As a result, many societal decisions—for financial investments, infrastructure design, natural resource management, and planning and policy making—are based in part on information, or assumptions, about expected climatic conditions. By improving our understanding of the current and future states of our climate, including climate sensitivity (see "C-2: Climate Feedbacks and Sensitivity"), improving our ability to predict fluctuations in climate, and improving our ability to detect important changes in our climate system, the priorities proposed here would enhance and strengthen society's basis for decision making, thereby benefiting people and communities across the nation.

Like weather forecasts, anticipatory information about near-term climate has value for a wide range of decisions. Seasonal, interannual, and extending to decadal climate prediction (see "C-6 and C-7: Seasonal-to-Decadal Predictions") are rapidly evolving areas of scientific research that rely on measurements of current ocean, land surface, sea-ice, and atmosphere conditions. Using these initial conditions, model predictions can be made for the phase and amplitude of many modes of variability in the climate system, including the El Nino Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO); monsoons; departures from normal patterns; as well as the risk of extremes such as heat waves, hurricanes, floods, drought, or severe storms around the nation. These regionally and locally specific climate predictions, built in part upon improved atmosphere-ocean flux exchanges (see "C-4:

Atmosphere-Ocean Flux Quantification"), can be used for national-scale decisions about risk sharing (e.g., insurance or asset diversification), resource distribution (e.g., by energy companies in anticipation of altered patterns of energy demand for heating and cooling), capital investment decisions regarding seasonal recreation, disaster-response staging (NRC, 1999; AMS, 2003), and natural resource planning and management in specific locations (e.g., drought early warning, water resource management; Lettenmaier et al., 2003; NOAA/NIDIS, 2017). Improved regional seasonal-decadal prediction of Arctic and Antarctic sea-ice cover (see "C-8: Causes and Effects of Polar Amplification") can inform planning by the shipping and fishing industries, while better quantification and projection of variability and changes in regional sea level can help coastal communities better predict their near- and longer-term risks of coastal erosion (see "C-1: Sea-level Rise").

Information about what to expect, locally, as climate continues to change, including the possibility of rapid changes, is in increasing demand. At a global scale the current large uncertainties in climate change projections lead to a factor of 10 or more uncertainty in the magnitude of future long-term economic impacts (NRC, 2017). More locally, communities and businesses seek geographically targeted information to inform climate change risk and vulnerability assessments and decisions about short-, medium-, and long-term investments in protective adaptation and other climate change responses (Bierbaum et al., 2014). Planners, engineers, and natural resource managers facing decisions with long-term consequences desire improved information about the conditions expected over the lifetime of their project. For example, where, when, and for which health stressors or disease vectors should health departments design monitoring systems? How long can a city expect existing sources to supply sufficient drinking water for its citizens? How big must a reservoir be to ensure adequate irrigation water for new orchards? At what height must an interstate freeway be constructed to protect against increasing flood risk, and with which type of asphalt should it be constructed to withstand increasing heat (Iowa State University Institute for Transportation 2015, USDOT)? Coastal communities and infrastructure managers desire better estimates of the upper bound of sea-level rise for local risk assessments, infrastructure design, ecosystem protection and potential investment in relocation (e.g., *Miami Herald*, 2017,[10] and *San Francisco Chronicle*, 2016[11]). The fishing and aquaculture industry seeks improved information about future rates and hotspots of ocean acidification to inform hatchery and growing operations already tied to these conditions and early warning of other potential problem locations. Uncertainty about internal and naturally induced climate variations, and about the timing and magnitude of changes and their duration, are clear challenges to adaptation strategies with accompanying investment and risk considerations: urgent and unplanned-for adaptation incurs significant extra cost, while an investment in physical capital is largely irreversible, so investing too soon is also a cost that could be averted with reduction in uncertainties.

Improved climate change projections in general, and projections of sea-level rise, ocean acidification, and ozone in particular, will be supported by proposed work (see previous sections) on polar processes, aerosols, clouds and ozone, climate feedbacks and sensitivity, carbon cycle, atmosphere-ocean flux, sea-level rise, and ocean heat storage and glacier-ice. Improved understanding and prediction of climate changes from seasonal to centennial scales can be used to support decisions in nearly all sectors of society, with consequences on a wide spectrum of space and time scales. For example, it could be about when and how to manage planetary and regional climatic impacts, adaptation, and mitigation. Improved carbon-cycle monitoring (see "C-3: Carbon Cycle") could help monitor accurately globe-wide sources (the development of an Integrated Global GHG Information System [IG^{3}IS][12]), and better quantify the emissions from all

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[10] See J. Flechas, 2017, "Miami Beach to Begin New $100 Million Flood Prevention Project in Face of Sea Level Rise," *Miami Herald,* January 28, http://www.miamiherald.com/news/local/community/miami-dade/miami-beach/article129284119.html.

[11] See J. King, 2016, "A Regional Response to the Bay's Encroaching Waters," *Rising Reality*, May, http://projects.sfchronicle.com/2016/sea-level-rise/part1/.

[12] See P. DeCola, O. Tarasova, J. Butler, R. Duren, S. Reimann, K. Gurney, A. Manning, and the IG3IS Team, 2016, "Integrated Global GHG Information System (IG3IS): Evidence Based Policy Support and Evaluation: Paris Agreement on Climate Change," September

sources. Improved understanding of the ongoing effects of atmospheric gases on atmospheric ozone will help the nation ensure that the valuable gains in UV-protection afforded by the recovery of the ozone layer are maintained (see "C-9: Ozone and Other Trace Gases in the Stratosphere and Troposphere"). Improved monitoring of global and regional aerosol pollution together with information on meteorological conditions (see "C-5: Aerosols and Aerosol-Cloud Interactions") is capable of yielding early warning information on heat waves and air quality, and the likely impacts to health and regional climates.

Observations of Earth's climate system from space provide important real-time "nowcasts" of current conditions that inform weather forecasting, provide insight into evolving environmental threats or opportunities, and enable detection and early warning of severe climatic events. Ongoing measurements of atmospheric and oceanic conditions from space can improve midlatitude weather forecasts, in particular for extreme events. Information derived from enhanced monitoring of arctic sea-ice cover can help alert vulnerable arctic communities to near-term dangers of coastal inundation and flooding. Concomitant improved understanding of the connection between polar processes and global climate could help improve prediction and better calibrate the Arctic and Antarctic as "first indicators" of global climate change. Proposed measurements of biomass change, especially in the Arctic, are important for identifying release of carbon stored in permafrost, a potentially significant positive feedback to warming.

Full realization of these benefits will require concomitant advances in several related efforts to ensure that the observations, results, and products of the program described here are fully utilized across relevant arenas of science and society. Attention to measurement continuity and climate-quality measurements and data sets, including appropriate data archiving and metadata, is essential for understanding and predicting long-term changes in Earth's climate. Continued investments in modeling are needed for observation assimilation, analysis, and evaluation, and for the crucial step of connecting these observations to information about changes in variables or systems of direct importance to society. Last, connecting the climate observing program described here to societal efforts to better anticipate, plan for, and adapt to climate fluctuations will require an effective information delivery system and robust forums. This will enable iterative interaction between the Earth-system observing community and the prospective scientific *and* public users of information derived from space-based climate-related observations (Miles et al., 2006).

REFERENCES

Ablain, M., J.F. Legeais, P. Prandi, M. Marcos, L. Fenoglio-Marc, H.B. Dieng, J. Benveniste, and A. Cazenave. 2017. Satellite altimetry-based sea level at global and regional scales. *Surveys in Geophysics* 38(1):7-31.

Abraham, J.P., M. Baringer, N.L. Bindoff, T. Boyer, L.J. Cheng, J.A. Church, J.L. Conroy, et al. 2013. A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. *Reviews of Geophysics* 51(3):450-483.

Al-Saadi, J., J. Szykman, R.B. Pierce, C. Kittaka, D. Neil, D.A. Chu, L. Remer, et al. 2005. Improving national air quality forecasts with satellite aerosol observations. *Bulletin of the American Meteorological Society* 86(9):1249-1261.

Amekudzi, L.K., A. Bracher, J. Meyer, A. Rozanov, H. Bovensmann, and J.P. Burrows. 2005. Lunar occultation with SCIAMACHY: First retrieval results. *Advances in Space Research* 36(5):906-914.

AMS (American Meteorological Society). 2003. *Report of a Policy Forum: Improving Responses to Climate Predictions*. https://www.ametsoc.org/ams/assets/File/Climate_response_2003.pdf.

Anderson, D.C., J.M. Nicely, R.J. Salawitch, T.P. Canty, R.R. Dickerson, T.F. Hanisco, G.M. Wolfe, et al. 2016. A pervasive role for biomass burning in tropical high ozone/low water structures. *Nature Communications* 7:10267.

Anderson, T.L., R.J. Charlson, S.E. Schwartz, R. Knutti, O. Boucher, H. Rodhe, and J. Heintzenberg. 2003. Atmospheric science: Climate forcing by aerosols—A hazy picture. *Science* 300(5622):1103-1104.

Avnery, S., D.L. Mauzerall, J. Liu, and L.W. Horowitz. 2011. Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. *Atmospheric Environment* 45(13):2284-2296.

Baldwin, M.P., and T.J. Dunkerton. 2001. Stratospheric harbingers of anomalous weather regimes. *Science* 294(5542):581-584.

Baldwin, M.P., D.B. Stephenson, D.W.J. Thompson, T.J. Dunkerton, A.J. Charlton, and A. O'Neill. 2003. Stratospheric memory and skill of extended-range weather forecasts. *Science* 301(5633):636-640.

22, http://carbon.nasa.gov/pdfs/DeCola_CMS_Policy_Sept22_16.pdf.

Beer, R., T.A. Glavich, and D.M. Rider. 2001. Tropospheric emission spectrometer for the Earth Observing System's Aura satellite. *Applied Optics* 40(15):2356-2367.

Bell, M.L., F. Dominici, K. Ebisu, S.L. Zeger, and J.M. Samet. 2007. Spatial and temporal variation in PM2.5 chemical composition in the United States for health effects studies. *Environmental Health Perspectives* 115(7):989-995.

Benn, D.I., C.R. Warren, and R.H. Mottram. 2007. Calving processes and the dynamics of calving glaciers. *Earth-Science Reviews* 82(3-4):143-179.

Bernath, P.F., C.T. McElroy, M.C. Abrams, C.D. Boone, M. Butler, C. Camy-Peyret, M. Carleer, et al. 2005. Atmospheric chemistry experiment (ACE): Mission overview. *Geophysical Research Letters* 32(15).

Bhartia, P.K., R.D. McPeters, C.L. Mateer, L.E. Flynn, and C. Wellemeyer. 1996. Algorithm for the estimation of vertical ozone profiles from the backscattered ultraviolet technique. *Journal of Geophysical Research Atmospheres* 101(13):18793-18806.

Bierbaum, R., A. Lee, J. Smith, M. Blair, L.M. Carter, F.S. Chapin III, P. Fleming, et al. 2014. Ch. 28: Adaptation. Pp. 670-706 in *Climate Change Impacts in the United States: The Third National Climate Assessment* (eds. J.M. Melillo, T.C. Richmond, and G.W. Yohe). U.S. Global Change Research Program.

Bollasina, M.A., Y. Ming, and V. Ramaswamy. 2011. Anthropogenic aerosols and the weakening of the south asian summer monsoon. *Science* 334(6055):502-505.

Bond, T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, B.J. Deangelo, M.G. Flanner, et al. 2013. Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research Atmospheres* 118(11):5380-5552.

Bony, S., R. Colman, V.M. Kattsov, R.P. Allan, C.S. Bretherton, J.L. Dufresne, A. Hall, et al. 2006. How well do we understand and evaluate climate change feedback processes? *Journal of Climate* 19(15):3445-3482.

Bony, S., B. Stevens, D.M.W. Frierson, C. Jakob, M. Kageyama, R. Pincus, T.G. Shepherd, et al. 2015. Clouds, circulation and climate sensitivity. *Nature Geoscience* 8(4):261-268.

Booth, B.B.B., C.D. Jones, M. Collins, I.J. Totterdell, P.M. Cox, S. Sitch, C. Huntingford, R.A. Betts, G.R. Harris, and J. Lloyd. 2012. High sensitivity of future global warming to land carbon cycle processes. *Environmental Research Letters* 7(2).

Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.M. Kerminen, et al. 2013. Clouds and aerosols. Pp. 571-658 in *Climate Change 2013: The Physical Science Basis* (eds. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley). Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Bourassa, M.A., S.T. Gille, C. Bitz, D. Carlson, I. Cerovecki, C.A. Clayson, M.F. Cronin, et al. 2013. High-latitude ocean and sea ice surface fluxes: Challenges for climate research. *Bulletin of the American Meteorological Society* 94:403-423.

Brienen, R.J.W., O.L. Phillips, T.R. Feldpausch, E. Gloor, T.R. Baker, J. Lloyd, G. Lopez-Gonzalez, et al. 2015. Long-term decline of the Amazon carbon sink. *Nature* 519(7543):344-348.

Brown, R.D., and D.A. Robinson. 2011. Northern Hemisphere spring snow cover variability and change over 1922-2010 including an assessment of uncertainty. *Cryosphere* 5(1):219-229.

Butchart, N. 2014. The Brewer-Dobson circulation. *Reviews of Geophysics* 52(2):157-184.

Carleton, T.A., and S.M. Hsiang. 2016. Social and economic impacts of climate. *Science* 353(6304).

Cazenave, A., N. Champollion, J. Benveniste, and P. Lecomte. 2017. International Space Science Institute (ISSI) Workshop on Integrative Study of the Mean Sea Level and its Components. *Surveys in Geophysics* 38(1).

Cazenave, A., H.B. Dieng, B. Meyssignac, K. von Schuckmann, B. Decharme, and E. Berthier. 2014. The rate of sea-level rise. *Nature Climate Change* 4(5):358-361.

Charron, M., S. Polavarapu, M. Buehner, P.A. Vaillancourt, C. Charette, M. Roch, J. Morneau, et al. 2012. The stratospheric extension of the Canadian global deterministic medium-range weather forecasting system and its impact on tropospheric forecasts. *Monthly Weather Review* 140(6):1924-1944.

Cheng, L., K.E. Trenberth, J. Fasullo, T. Boyer, J. Abraham, and J. Zhu. 2017. Improved estimates of ocean heat content from 1960 to 2015. *Science Advances* 3(3).

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, et al. 2013. Sea level change. Pp. 1137-1216 in *Climate Change 2013: The Physical Science Basis* (eds. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley). Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, et al. 2013. Carbon and other biogeochemical cycles. Pp. 465-570 in *Climate Change 2013: The Physical Science Basis* (eds. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley). Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Clayson, C.A., and A.S. Bogdanoff. 2013. The effect of diurnal sea surface temperature warming on climatological air-sea fluxes. *Journal of Climate* 26(8):2546-2556.

Coffey, M., R. Eckman, K. Jucks, H. Maring, and A. Pszenny. 2014. "Outstanding Questions in Atmospheric Composition, Chemistry, Dynamics and Radiation for the Coming Decade, Proceedings of a Workshop." Paper presented at the NASA SMD Workshop: Atmospheric Composition Outstanding Questions. Moffett Field, CA: NASA Ames Research Center.

Collins, M., R. Knutti, J. Arblaster, J.L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, et al., 2013. Long-term climate change: Projections, commitments and irreversibility. Pp. 1110 *Climate Change 2013: The Physical Science Basis* (eds. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley). Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Comstock, K.K., C.S. Bretherton, and S.E. Yuter. 2005. Mesoscale variability and drizzle in southeast Pacific stratocumulus. *Journal of the Atmospheric Sciences* 62(10):3792-3807.

Cooke, R.M., A. Golub, B.A.Wielicki, M.G. Mlynczak, D.F. Young, and R.R. Baize. 2016. *Real Option Value for New Measurements of Cloud Radiative Forcing*. http://www.rff.org/research/publications/real-option-value-new-measurements-cloud-radiative-forcing. Accessed April 12, 2018.

Cooke, R., A. Golub, B.A.Wielicki, D.F. Young, M.G. Mlynczak, and R.R. Baize. 2017. Using the social cost of carbon to value Earth observing systems. *Climate Policy* 17(3):330-345.

Cooke, R., B.A. Wielicki, D.F. Young, and M.G. Mlynczak. 2014. Value of information for climate observing systems. *Environment Systems and Decisions* 34(1):98-109.

Cooper, O.R., D.D. Parrish, J. Ziemke, N.V. Balashov, M. Cupeiro, I.E. Galbally, S. Gilge, et al. 2014. Global distribution and trends of tropospheric ozone: An observation-based review. *Elementa Science of the Anthropocene* 2(29).

Crisp, D., H. Pollock, R. Rosenberg, L. Chapsky, R. Lee, F. Oyafuso, C. Frankenberg, et al. 2017. The on-orbit performance of the Orbiting Carbon Observatory-2 (OCO-2) instrument and its radiometrically calibrated products. *Atmospheric Measurement Techniques* 10(1):59-81.

DeConto, R.M., and D. Pollard. 2016. Contribution of Antarctica to past and future sea-level rise. *Nature* 531(7596):591-597.

Dee, D.P., M. Balmaseda, G. Balsamo, R. Engelen, A.J. Simmons, and J.N. Thépaut. 2014. Toward a consistent reanalysis of the climate system. *Bulletin of the American Meteorological Society* 95(8):1235-1248.

Derksen, C., and R. Brown. 2012. Spring snow cover extent reductions in the 2008-2012 period exceeding climate model projections. *Geophysical Research Letters* 39(19).

Dessler, A.E. 2010. A determination of the cloud feedback from climate variations over the past decade. *Science* 330(6010):1523-1527.

Dessler, A.E. 2013. Observations of climate feedbacks over 2000-10 and comparisons to climate models. *Journal of Climate* 26(1):333-342.

Dieng, H.B., A. Cazenave, K. Von Schuckmann, M. Ablain, and B. Meyssignac. 2015. Sea level budget over 2005-2013: Missing contributions and data errors. *Ocean Science* 11(5):789-802.

Dlugokencky, E.J., L. Bruhwiler, J.W.C. White, L.K. Emmons, P.C. Novelli, S.A. Montzka, K.A. Masarie, P.M. Lang, A.M. Crotwell, J.B. Miller, and L.V. Gatti. 2009. Observational constraints on recent increases in the atmospheric CH_4 burden. *Geophysical Research Letters* 36:L18803.

Doney, S.C. 2010. The growing human footprint on coastal and open-Ocean biogeochemistry. *Science* 328(5985):1512-1516.

Doney, S.C., W.M. Balch, V.J. Fabry, and R.A. Feely. 2009. Ocean acidification: A critical emerging problem for the ocean sciences. *Oceanography* 22(SPL.ISS. 4):16-25.

Douglas, B.C. 2001. Chapter 3 Sea level change in the era of the recording tide gauge. *International Geophysics* 75:37-64.

Dowell, M., P. Lecomte, R. Husband, J. Schulz, T. Mohr, Y. Tahara, R. Eckman, et al. 2013. *2013: Strategy Towards an Architecture for Climate Monitoring from Space*. http://www.wmo.int/pages/prog/sat/documents/ARCH_strategy-climate-architecture-space.pdf.

Durack, P.J., and S.E. Wijffels. 2010. Fifty-Year trends in global ocean salinities and their relationship to broad-scale warming. *Journal of Climate* 23(16):4342-4362.

Dutton, A., A.E. Carlson, A.J. Long, G.A. Milne, P.U. Clark, R. DeConto, B.P. Horton, S. Rahmstorf, M.E. Raymo. 2015. Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science* 349(6244):10.

Eldering, A., C.W. O'Dell, P.O. Wennberg, D. Crisp, M.R. Gunson, C. Viatte, C. Avis, et al. 2017. The Orbiting Carbon Observatory-2: First 18 months of science data products. *Atmospheric Measurement Techniques* 10(2):549-563.

ESA (European Space Agency). 2015. *Report for Mission Selection: CarbonSat*. ESA-SP-1330/1. June. http://esamultimedia.esa.int/docs/EarthObservation/SP1330-1_CarbonSat.pdf.

Etheridge, D.M., L.P. Steele, R.J. Francey, and R.L. Langenfelds. 1998. Atmospheric methane between 1000 A.D. and present: Evidence of anthropogenic emissions and climatic variability. *Journal of Geophysical Research Atmospheres* 103(D13):15979-15993.

Eyring, V., J.M. Arblaster, I. Cionni, J. Sedláček, J. Perlwitz, P.J. Young, S. Bekki, et al. 2013. Long-term ozone changes and associated climate impacts in CMIP5 simulations. *Journal of Geophysical Research Atmospheres* 118(10):5029-5060.

Fairall, C.W., E.F. Bradley, J.S. Godfrey, G.A. Wick, J.B. Edson, and G.S. Young. 1996. Cool-skin and warm-layer effects on sea surface temperature. *Journal of Geophysical Research C: Oceans* 101(C1):1295-1308.

Fan, J., T. Yuan, J.M. Comstock, S. Ghan, A. Khain, L.R. Leung, Z. Li, V.J. Martins, and M. Ovchinnikov. 2009. Dominant role by vertical wind shear in regulating aerosol effects on deep convective clouds. *Journal of Geophysical Research Atmospheres* 114(D22).

Favier, L., G. Durand, S.L.Cornford, G.H. Gudmundsson, O. Gagliardini, F. Gillet-Chaulet, T. Zwinger, A.J. Payne, and A.M. Le Brocq. 2014. Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nature Climate Change* 4(2):117-121.

Fiore, A.M., D.J. Jacob, B.D. Field, D.G. Streets, S.D. Fernandes, and C. Jang. 2002. Linking ozone pollution and climate change: The case for controlling methane. *Geophysical Research Letters* 29(19):2521-2524.

Fischer, H., M. Birk, C. Blom, B. Carli, M. Carlotti, T. Von Clarmann, L. Delbouille, et al. 2008. MIPAS: An instrument for atmospheric and climate research. *Atmospheric Chemistry and Physics* 8(8):2151-2188.

Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, et al. 2013: Evaluation of climate models. P. 819 in *Climate Change 2013: The Physical Science Basis* (eds. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley). Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Fretwell, P., H.D. Pritchard, D.G. Vaughan, J.L. Bamber, N.E. Barrand, R. Bell, C. Buanchi, et al. 2013. Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica. *Cryosphere* 7(1):375-393.

Friedlingstein, P., M. Meinshausen, V.K. Arora, C.D. Jones, A. Anav, S.K. Liddicoat, and R. Knutti. 2014. Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks. *Journal of Climate* 27(2):511-526.

Fu, L.L. 2016. On the decadal trend of global mean sea level and its implication on ocean heat content change. *Frontiers in Marine Science* 3(MAR).

Gettelman, A., P. Hoor, L.L. Pan, W.J. Randel, M.I. Hegglin, and T. Birner. 2011. The extratropical upper troposphere and lower stratosphere. *Reviews of Geophysics* 49(3).

Ginoux, P., J.M. Prospero, T.E.Gill, N.C. Hsu, and M. Zhao. 2012. Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. *Reviews of Geophysics* 50(3).

Glenn, S.M., T.N. Miles, G.N. Seroka, Y. Xu, R.K. Forney, F. Yu, H. Roarty, O. Schofield, and J. Kohut. 2016. Stratified coastal ocean interactions with tropical cyclones. *Nature Communications* 7.

Gloor, M., J.L. Sarmiento, and N. Gruber. 2010. What can be learned about carbon cycle climate feedbacks from the CO_2 airborne fraction? *Atmospheric Chemistry and Physics* 10(16):7739-7751.

Goldberg, M., G. Ohring, J. Butler, C. Cao, R. Datla, D. Doelling, V. Gärtner, et al. 2011. The global space-based inter-calibration system. *Bulletin of the American Meteorological Society* 92(4):467-475.

Gregory, J.M., C.D. Jones, P. Cadule, and P. Friedlingstein. 2009. Quantifying carbon cycle feedbacks. *Journal of Climate* 22(19):5232-5250.

Gulev, S.K., and K. Belyaev. 2011. Probability distribution characteristics for surface air–sea turbulent heat fluxes over the global ocean. *Journal of Climate* 25(1):184-206.

Hamlington, B.D., S.H. Cheon, P.R. Thompson, M.A. Merrifield, R.S. Nerem, R.R. Leben, and K.Y. Kim. 2016. An ongoing shift in Pacific Ocean sea level. *Journal of Geophysical Research: Oceans* 121(7):5084-5097.

Hansen, J., M. Sato, P. Kharecha, K. von Schuckmann, D.J. Beerling, J. Cao, S. Marcott, et al. 2017. Young people's burden: Requirement of negative CO_2 emissions. *Earth System Dynamics* 8(3):577-616.

Hansen, J., M. Sato, R. Ruedy, L. Nazarenko, A. Lacis, G.A. Schmidt, G. Russell, et al. 2005. Efficacy of climate forcings. *Journal of Geophysical Research D: Atmospheres* 110(18):1-45.

Hartmann, D.L., and K. Larson. 2002. An important constraint on tropical cloud—climate feedback. *Geophysical Research Letters* 29(20):1211-1214.

Hedelius, J.K., H. Parker, D. Wunch, C.M. Roehl, C. Viatte, S. Newman, G.C. Toon, et al. 2017. Intercomparability of X_{CO2} and X_{CH4} from the United States TCCON sites. *Atmospheric Measurement Techniques* 10:1481-1493.

Higgins, W. 2014. "Climate Change and Trends in Weather and Climate Extremes." Presentation at the Glen Gerberg Weather and Climate Summit, Breckenridge, CO.

Hope, C. 2015. The $10 trillion value of better information about the transient climate response. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 373(2054).

Hu, Y., Y. Xia, and Q. Fu. 2011. Tropospheric temperature response to stratospheric ozone recovery in the 21st century. *Atmospheric Chemistry and Physics* 11(15):7687-7699.

Iowa State University. 2015. *Iowa's Bridge and Highway Climate Change and Extreme Weather Vulnerability Assessment Pilot: Tech Transfer Summary*. http://www.intrans.iastate.edu/publications/_documents/t2summaries/IA_climate_change_vulnerability_assessment_t2.pdf.

IPCC (Intergovernmental Panel on Climate Change). 1990. *Climate Change: The IPCC Scientific Assessment.* Cambridge: Cambridge University Press.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis* (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

IPCC. 2013. *Climate Change 2013: The Physical Science Basis* (eds. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley). Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

IPCC. 2014. *Climate Change 2014: Synthesis Report* (eds. Core Writing Team, R.K. Pachauri, and L.A. Meyer). Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Jacob, D.J., B.G. Heikes, S.M. Fan, J.A. Logan, D.L. Mauzerall, J.D. Bradshaw, H.B. Singh, G.L. Gregory, R.W. Talbot, D.R. Blake,and G.W. Sachse. 1996. Origin of ozone and NOx in the tropical troposphere: A photochemical analysis of aircraft observations over the South Atlantic basin. *Journal of Geophysical Research: Atmospheres* 101(D19):24235-24250.

Jacob, T., J. Wahr, W.T. Pfeffer, and S. Swenson. 2012. Recent contributions of glaciers and ice caps to sea level rise. *Nature* 482(7386):514-518.

Jaross, G., P.K. Bhartia, G. Chen, M. Kowitt, M. Haken, Z. Chen, P. Xu, J. Warner, and T. Kelly. 2014. Omps limb profiler instrument performance assessment. *Journal of Geophysical Research* 119(7):4399-4412.

Johnson, G.C., J.M. Lyman, and S.G. Purkey. 2015. Informing deep Argo array design using Argo and full-depth hydrographic section data. *Journal of Atmospheric and Oceanic Technology* 32(11):2187-2198.

Jones, B.M., C.D. Arp, M.T. Jorgenson, K.M. Hinkel, J.A. Schmutz, and P.L. Flint. 2009. Increase in the rate and uniformity of coastline erosion in Arctic Alaska. *Geophysical Research Letters* 36(3).

Jones, B.M., G. Grosse, C.D. Arp, E. Miller, L. Liu, D.J. Hayes, and C.F. Larsen. 2015. Recent Arctic tundra fire initiates widespread thermokarst development. *Scientific Reports* 5.

Joughin, I., B.E. Smith, and B. Medley. 2014. Marine ice sheet collapse potentially under way for the thwaites glacier basin, West Antarctica. *Science* 344(6185):735-738.

Kahn, R.A. 2012. Reducing the uncertainties in direct aerosol radiative forcing. *Surveys in Geophysics* 33(3):701-721.

Kahn, R.A., M.J. Garay, D.L. Nelson, K.K. Yau, M.A. Bull, B.J. Gaitley, J.V. Martonchik, and R.C. Levy. 2007. Satellite-derived aerosol optical depth over dark water from MISR and MODIS: Comparisons with AERONET and implications for climatological studies. *Journal of Geophysical Research Atmospheres* 112(D18).

Karion, A., C. Sweeney, G. Pétron, G. Frost, R.M. Hardesty, J. Kofler, B. Miller, et al. 2013. Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophysical Research Letters* 40(16):4393-4397.

Karion, A., C. Sweeney, P. Tans, and T. Newberger. 2010. AirCore: An innovative atmospheric sampling system. *Journal of Atmospheric and Oceanic Technology* 27(11):1839-1853.

Kaufmann, R.K., H. Kauppi, M.L. Mann, and J.H. Stock. 2011. Reconciling anthropogenic climate change with observed temperature 1998-2008. *Proceedings of the National Academy of Sciences* 108(29):11790-11793.

Keenan, T.F., I.C. Prentice, J.G. Canadell, C.A. Williams, H. Wang, M. Raupach, and G.J. Collatz. 2016. Recent pause in the growth rate of atmospheric CO_2 due to enhanced terrestrial carbon uptake. *Nature Communications* 7.

Kidston, J., A.A. Scaife, S.C. Hardiman, D.M. Mitchell, N. Butchart, M.P. Baldwin, and L.J. Gray. 2015. Stratospheric influence on tropospheric jet streams, storm tracks and surface weather. *Nature Geoscience* 8(6):433-440.

Kinnard, C., C.M. Zdanowicz, D.A. Fisher, E. Isaksson, A. De Vernal, and L.G. Thompson. 2011. Reconstructed changes in Arctic sea ice over the past 1,450 years. *Nature* 479(7374):509-512.

Kirschke, S., P. Bousquet, P. Ciais, M. Saunois, J.G. Canadell, E.J. Dlugokencky, P. Bergamaschi, et al. 2013. Three decades of global methane sources and sinks. *Nature Geoscience* 6(10):813-823.

Kirtman, B.P., D. Min, J.M. Infanti, J.L. Kinter, D.A. Paolino, Q.H. Zhang, H. van den Dool, et al. 2014. The North American Multimodel Ensemble Phase-1 seasonal-to-interannual rediction; Phase-2 toward developing intraseasonal prediction. *Bulletin of the American Meteorological Society* 95(4):585-601.

Knorr, W. 2009. Is the airborne fraction of anthropogenic CO_2 emissions increasing? *Geophysical Research Letters* 36(21).

Kopp, R.E., A. Golub, N.O. Keohane, and C. Onda. 2012. The influence of the specification of climate change damages on the social cost of carbon. *Economics* 6:1-40.

Koren, I., Y.J. Kaufman, D. Rosenfeld, L.A. Remer, and Y. Rudich. 2005. Aerosol invigoration and restructuring of Atlantic convective clouds. *Geophysical Research Letters* 32(14):1-4.

Koren, I., L.A. Remer, O. Altaratz, J.V. Martins, and A. Davidi. 2010. Aerosol-induced changes of convective cloud anvils produce strong climate warming. *Atmospheric Chemistry and Physics* 10(10):5001-5010.

Kulawik, S.S., C. O'Dell, V.H. Payne, L. Kuai, H.M. Worden, S.C. Biraud, C. Sweeney, et al. 2016. Lower-tropospheric CO_2 from near-infrared ACOS-GOSAT observations. *Atmospheric Chemistry and Physics Discussions* 1-55.

Kursinski, E.R., G.A. Hajj, J.T. Schofield, R.P. Linfield, and K.R. Hardy. 1997. Observing Earth's atmosphere with radio occultation measurements using the global positioning system. *Journal of Geophysical Research Atmospheres* 102(19):23429-23465.

Kyrölä, E., J. Tamminen, G.W. Leppelmeier, V. Sofieva, S. Hassinen, J.L. Bertaux, A. Hauchecorne, et al. 2004. GOMOS on Envisat: An overview. *Advances in Space Research* 33(7):1020-1028.

L'Ecuyer, T.S., H.K. Beaudoing, M. Rodell, W. Olson, B. Lin, S. Kato, C.A. Clayson, et al. 2015. The observed state of the energy budget in the early twenty-first century. *Journal of Climate* 28(21):8319-8346.

Le Quéré, C., C. Rödenbeck, E.T. Buitenhuis, T.J. Conway, R. Langenfelds, A. Gomez, C. Labuschagne, et al. 2007. Saturation of the southern ocean CO_2 sink due to recent climate change. *Science* 316(5832):1735-1738.

Le Quéré, C., T. Takahashi, E.T. Buitenhuis, C. Rödenbeck, and S.C. Sutherland. 2010. Impact of climate change and variability on the global oceanic sink of CO_2. *Global Biogeochemical Cycles* 24(4).

Leroy, S.S., J.G. Anderson, and G. Ohring. 2008. Climate signal detection times and constraints on climate benchmark accuracy requirements. *Journal of Climate* 21(4):841-846.

Lettenmaier, D.R., and A.R. Hamlet. 2003. Improving water-resource system performance through long-range climate forecasts: The pacific northwest experience. Pp. 107-122 in *Water and Climate: In the Western United States* (ed. W.M. Lewis, Jr.). Boulder: University Press of Colorado.

Leuliette, E.W., and R.S. Nerem. 2016. Contributions of Greenland and Antarctica to global and regional sea level change. *Oceanography* 29(4):154-159.

Leuliette, E.W., and J.K. Willis. 2011. Balancing the sea level budget. *Oceanography* 24(2):122-129.

Levy II, H., L.W. Horowitz, M.D. Schwarzkopf, Y. Ming, J.C. Golaz, V. Naik, and V. Ramaswamy. 2013. The roles of aerosol direct and indirect effects in past and future climate change. *Journal of Geophysical Research Atmospheres* 118(10):4521-4532.

Li, Z., F. Niu, J. Fan, Y. Liu, D. Rosenfeld, and Y. Ding. 2011. Long-term impacts of aerosols on the vertical development of clouds and precipitation. *Nature Geoscience* 4(12):888-894.

Lin, M., L.W. Horowitz, O.R. Cooper, D. Tarasick, S. Conley, L.T. Iraci, B. Johnson, T. Leblanc, I. Petropavlovskikh, and E.L. Yates. 2015. Revisiting the evidence of increasing springtime ozone mixing ratios in the free troposphere over western North America. *Geophysical Research Letters* 42(20):8719-8728.

Lindqvist, H., C.W. O'Dell, S. Basu, H. Boesch, F. Chevallier, N. Deutscher, L. Feng, et al. 2015. Does GOSAT capture the true seasonal cycle of carbon dioxide? *Atmospheric Chemistry and Physics* 15(22):13023-13040.

Llovel, W., J.K. Willis, F.W. Landerer, and I. Fukumori. 2014. Deep-ocean contribution to sea level and energy budget not detectable over the past decade. *Nature Climate Change* 4(11):1031-1035.

Loeb, N.G., J.M. Lyman, G.C. Johnson, R.P. Allan, D.R. Doelling, T. Wong, B.J. Soden, and G.L. Stephens. 2012. Observed changes in top-of-the-atmosphere radiation and upper-ocean heating consistent within uncertainty. *Nature Geoscience* 5(2):110-113.

Loeb, N.G., B.A. Wielicki, T. Wong, and P.A. Parker. 2009. Impact of data gaps on satellite broadband radiation records. *Journal of Geophysical Research Atmospheres* 114(11).

Lohmann, U., and K. Diehl. 2006. Sensitivity studies of the importance of dust ice nuclei for the indirect aerosol effect on stratiform mixed-phase clouds. *Journal of the Atmospheric Sciences* 63(3):968-982.

Longstreth, J., F.R. de Gruijl, M.L. Kripke, S. Abseck, F. Arnold, H.I. Slaper, G.Velders, Y. Takizawa, and J.C. van der Leun. 1998. Health risks. *Journal of Photochemistry and Photobiology B: Biology* 46(1):20-39.

Los, S.O. 2013. Analysis of trends in fused AVHRR and MODIS NDVI data for 1982-2006: Indication for a CO_2 fertilization effect in global vegetation. *Global Biogeochemical Cycles* 27(2):318-330.

Lucke, R.L., D.R. Korwan, R.M. Bevilacqua, J.S. Hornstein, E.P. Shettle, D.T. Chen, M. Daehler, et al. 1999. The Polar Ozone and Aerosol Measurement (POAM) III instrument and early validation results. *Journal of Geophysical Research Atmospheres* 104(D15):18785-18799.

Ma, Z., C. Peng, Q. Zhu, H. Chen, G. Yu, W. Li, X. Zhou, W. Wang, and W. Zhang. 2012. Regional drought-induced reduction in the biomass carbon sink of Canada's boreal forests. *Proceedings of the National Academy of Sciences* 109(7):2423-2427.

Machida, T., H. Matsueda, Y. Sawa, Y. Nakagawa, K. Hirotani, N. Kondo, K. Goto, T. Nakazawa, K. Ishikawa, and T. Ogawa. 2008. Worldwide measurements of atmospheric CO_2 and other trace gas species using commercial airlines. *Journal of Atmospheric and Oceanic Technology* 25(10):1744-1754.

Mauldin, L.E., N.H. Zaun, M.P. McCormick Jr., J.H. Guy, and W.R. Vaughn. 1985. Stratospheric Aerosol and Gas Experiment II instrument: A functional description. *Optical Engineering* 24(2):307-312.

McKinley, G.A., A.R. Fay, T. Takahashi, and N. Metzl. 2011. Convergence of atmospheric and North Atlantic carbon dioxide trends on multidecadal timescales. *Nature Geoscience* 4(9):606-610.

McPeters, R.D., S.J. Janz, E. Hilsenrath, T.L. Brown, D.E. Flittner, and D.F. Heath. 2000. The retrieval of O_3 profiles from limb scatter measurements: Results from the Shuttle Ozone Limb Sounding Experiment. *Geophysical Research Letters* 27(17):2597-2600.

Meinshausen, M., S.J. Smith, K. Calvin, J.S. Daniel, M.L.T. Kainuma, J.F. Lamarque, K. Matsumoto, et al. 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* 109(1):213-241.

Melillo, J.M., T.T.C. Richmond, and G.W. Yohe. 2014. *Climate Change Impacts in the United States: The Third National Climate Assessment*. http://s3.amazonaws.com/nca2014/high/NCA3_Climate_Change_Impacts_in_the_United%20States_HighRes.pdf.

Merrifield, M.A., P.R. Thompson, and M. Lander. 2012. Multidecadal sea level anomalies and trends in the western tropical Pacific. *Geophysical Research Letters* 39(13).

Messerschmidt, J., M.C. Geibel, T. Blumenstock, H. Chen, N.M. Deutscher, A. Engel, D.G. Feist, et al. 2011. Calibration of TCCON column-averaged CO_2: The first aircraft campaign over European TCCON sites. *Atmospheric Chemistry and Physics* 11(21):10765-10777.

Meza, F.J., J.W. Hansen, and D. Osgood. 2008. Economic value of seasonal climate forecasts for agriculture: Review of ex-ante assessments and recommendations for future research. *Journal of Applied Meteorology and Climatology* 47(5):1269-1286.

Mikaloff Fletcher, S.E., N. Gruber, A.R. Jacobson, S.C. Doney, S. Dutkiewicz, M. Gerber, M. Follows, et al. 2006. Inverse estimates of anthropogenic CO_2 uptake, transport, and storage by the ocean. *Global Biogeochemical Cycles* 20(2).

Miles, E.L., A.K. Snover, L.C. Whitely Binder, E.S. Sarachik, P.W. Mote, and N. Mantua. 2006. An approach to designing a national climate service. *Proceedings of the National Academy of Sciences* 103(52):19616-19623.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Climate change: Stationarity is dead: Whither water management? *Science* 319(5863):573-574.

Morrison, H., and W.W. Grabowski. 2011. Cloud-system resolving model simulations of aerosol indirect effects on tropical deep convection and its thermodynamic environment. *Atmospheric Chemistry and Physics* 11(20):10503-10523.

Mueller, J.A., and F. Veron. 2014. Impact of sea spray on air-sea fluxes. Part I: Results from stochastic simulations of sea spray drops over the ocean. *Journal of Physical Oceanography* 44(11):2817-2834.

Murakami, H., G.A. Vecchi, S. Underwood, T.L. Delworth, A.T. Wittenberg, W.G. Anderson, J.H. Chen, R. Gudgel, L. Harris, S.J. Lin, and F. Zheng. 2015. Simulation and Prediction of Category 4 and 5 Hurricanes in the High-Resolution GFDL HiFLOR Coupled Climate Model. *Journal of Climate* 28(23):9058-9079.

Najafi, M.R., F.W. Zwiers, and N.P. Gillett. 2016. Attribution of the spring snow cover extent decline in the Northern Hemisphere, Eurasia and North America to anthropogenic influence. *Climatic Change* 136(3-4):571-586.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2015. *Continuity of NASA Earth Observations from Space: A Value Framework*. Washington, DC: The National Academies Press.

NASEM. 2016. *Next Generation Earth System Prediction: Strategies for Subseasonal to Seasonal Forecasts*. Washington, DC: The National Academies Press.

NASEM. 2017a. *Antarctic Sea Ice Variability in the Southern Ocean-Climate System: Proceedings of a Workshop*. Washington, DC: The National Academies Press.

NASEM. 2017b. *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*. Washington, DC: The National Academies Press.

Nerem, R.S., D.P. Chambers, C. Choe, and G.T. Mitchum. 2010. Estimating mean sea level change from the TOPEX and Jason Altimeter Missions. *Marine Geodesy* 33:435-446.

Nisbet, E.G., E.J. Dlugokencky, M.R. Manning, D. Lowry, R.E. Fisher, J.L. France, S.E. Michel, et al. 2016. Rising atmospheric methane: 2007-2014 growth and isotopic shift. *Global Biogeochemical Cycles* 30(9):1356-1370.

NOAA/NIDIS (National Oceanic and Atmospheric Administration/National Integrated Drought Information System). 2017. *The National Integrated Drought Information System Implementation Plan: December 2016 Update*. Washington, DC. https://www.drought.gov/drought/sites/drought.gov.drought/files/Implementation-Plan-December-2016-Update.pdf.

Notz, D., and J. Stroeve. 2016. Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission. *Science* 354(6313):747-750.

NRC (National Research Council). 1999. *Making Climate Forecasts Matter*. Washington, DC: National Academy Press.

NRC. 2007. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. Washington, DC: The National Academies Press.

NRC. 2010a. *Assessment of Intraseasonal to Interannual Climate Prediction and Predictability*. Washington, DC: The National Academies Press.

NRC. 2010b. *Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements*. Washington, DC: The National Academies Press.

NRC. 2011a. *America's Climate Choices*. Washington, DC: The National Academies Press.

NRC. 2011b. *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia.* Washington, DC: The National Academies Press.

NRC. 2012. *Climate Change: Evidence, Impacts, and Choices*. Washington, DC: The National Academies Press.

NRC. 2013a. *Abrupt Impacts of Climate Change: Anticipating Surprises*. Washington, DC: The National Academies Press.

NRC. 2013b. *Review of NOAA Working Group Report on Maintaining the Continuation of Long-term Satellite Total Solar Irradiance Observation*. Washington, DC: The National Academies Press.

Pachauri, R.K., and A.E. Reisinger. 2007. *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC.

Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, et al. 2012. *Global Sea Level Rise Scenarios for the United States National Climate Assessment. NOAA Tech Memo OAR CPO-1*. Silver Spring, MD: Climate Program Office.

Pastick, N.J., M.T. Jorgenson, B.K. Wylie, S.J. Nield, K.D. Johnson, and A.O. Finley. 2015. Distribution of near-surface permafrost in Alaska: Estimates of present and future conditions. *Remote Sensing of Environment* 168:301-315.

Pfeffer, W.T., J.T. Harper, and S. O'Neel. 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science* 321(5894):1340-1343.

Pithan, F., and T. Mauritsen. 2014. Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature Geoscience* 7(3):181-184.

Plagge, A., J.B. Edson, and D. Vandemark. 2016. In situ and satellite evaluation of air-sea flux variation near ocean temperature gradients. *Journal of Climate* 29(4):1583-1602.

Pollard, D., R.M. DeConto, and R.B. Alley. 2015. Potential Antarctic ice sheet retreat driven by hydrofracturing and ice cliff failure. *Earth and Planetary Science Letters* 412:112-121.

Polson, D., M. Bollasina, G.C. Hegerl, and L.J. Wilcox. 2014. Decreased monsoon precipitation in the Northern Hemisphere due to anthropogenic aerosols. *Geophysical Research Letters* 41.

Polvani, L.M., D.W. Waugh, G.J.P. Correa, and S.W. Son. 2011. Stratospheric ozone depletion: The main driver of twentieth-century atmospheric circulation changes in the Southern Hemisphere. *Journal of Climate* 24(3):795-812.

Previdi, M., and L.M. Polvani. 2014. Climate system response to stratospheric ozone depletion and recovery. *Quarterly Journal of the Royal Meteorological Society* 140(685):2401-2419.

Prospero, J.M., P. Ginoux, O. Torres, S.E. Nicholson, and T.E. Gill. 2002. Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. *Reviews of Geophysics* 40(1):2-1-2-31.

Purkey, S.G., and G.C. Johnson. 2010. Warming of global abyssal and deep Southern Ocean waters between the 1990s and 2000s: Contributions to global heat and sea level rise budgets. *Journal of Climate* 23(23):6336-6351.

Ravishankara, A.R., J.S. Daniel, and R.W. Portmann. 2009. Nitrous Oxide (N_2O): The Dominant ozone-depleting substance emitted in the 21st century. *Science* 326(5949):123-125.

Reichstein, M., M. Bahn, P. Ciais, D. Frank, M.D. Mahecha, S.I. Seneviratne, J. Zscheischler, et al. 2013. Climate extremes and the carbon cycle. *Nature* 500(7462):287-295.

Remer, L.A., R.G. Kleidman, R.C. Levy, Y.J. Kaufman, D. Tanré, S. Mattoo, J. Vanderlei Martins, C. Ichoku, I. Koren, H. Yu, and B.N. Holben. 2008. Global aerosol climatology from the MODIS satellite sensors. *Journal of Geophysical Research Atmospheres* 113(D14).

Revell, L.E., F. Tummon, R.J. Salawitch, A. Stenke, and T. Peter. 2015. The changing ozone depletion potential of N_2O in a future climate. *Geophysical Research Letters* 42(22):10047-10055.

Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, and P. Rafaj. 2011. RCP 8.5-A scenario of comparatively high greenhouse gas emissions. *Climatic Change* 109(1):33-57.

Richter-Menge, J., J.E. Overland, and J.T. Mathis, eds. 2016. "Arctic Report Card 2016." http://www.arctic.noaa.gov/Report-Card. Accessed April 13, 2018.

Riese, M., F. Ploeger, A. Rap, B. Vogel, P. Konopka, M. Dameris, and P. Forster. 2012. Impact of uncertainties in atmospheric mixing on simulated UTLS composition and related radiative effects. *Journal of Geophysical Research Atmospheres* 117(16).

Rigby, M., S.A. Montzka, R.G. Prinn, J.W.C. White, D. Young, M.F. O'Doherty, M.F. Lunt, et al. 2017. Role of atmospheric oxidation in recent methane growth. *Proceedings of the National Academy of Sciences* 114(21):5373-5377.

Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi, and B. Scheuchl. 2014. Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters* 41(10):3502-3509.

Rignot, E., I. Velicogna, M.R. Van Den Broeke, A. Monaghan, and J. Lenaerts. 2011. Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters* 38(5).

Riser, S.C., H.J. Freeland, D. Roemmich, S. Wijffels, A. Troisi, M. Belbéoch, G. Denis, et al. 2016. Fifteen years of ocean observations with the global Argo array. *Nature Climate Change* 6(2):145-153.

Ritz, C., T.L. Edwards, G. Durand, A.J. Payne, V. Peyaud, and R.C.A. Hindmarsh. 2015. Potential sea-level rise from Antarctic ice-sheet instability constrained by observations. *Nature* 528(7580):115-118.

Rodell, M., H.K. Beaudoing, T.S. L'Ecuyer, W.S. Olson, J.S. Famiglietti, P.R. Houser, and M. Adler. 2015. The observed state of the water cycle in the early twenty-first century. *Journal of Climate* 28(21):8289-8318.

Roe, G.H., and M.B. Baker. 2007. Why is climate sensitivity so unpredictable? *Science* 318(5850):629-632.

Roemmich, D., J. Church, J. Gilson, D. Monselesan, P. Sutton, and S. Wijffels. 2015. Unabated planetary warming and its ocean structure since 2006. *Nature Climate Change* 5(3):240-245.

Russell III, J.M. 1993. The halogen occultation experiment. *Journal of Geophysical Research* 98(D6):10777-10,797.

Sabine, C.L., R.A. Feely, N. Gruber, R.M. Key, K. Lee, J.L. Bullister, R. Wanninkhof, et al. 2004. The oceanic sink for anthropogenic CO_2. *Science* 305(5682):367-371.

Salawitch, R.J., T.P. Canty, A.P. Hope, W.R. Tribett, and B.F. Bennett. 2017. *Paris Climate Agreement: Beacon of Hope, 1st edition*. Springer International Publishing.

Saleeby, S.M., S.R. Herbener, S.C. van den Heever, and T. L'Ecuyer. 2015. Impacts of cloud droplet-nucleating aerosols on shallow tropical convection. *Journal of the Atmospheric Sciences* 72(4):1369-1385.

Sarmiento, J.L., M. Gloor, N. Gruber, C. Beaulieu, A.R. Jacobson, S.E.M. Fletcher, S. Pacala, and K. Rodgers. 2010. Trends and regional distributions of land and ocean carbon sinks. *Biogeosciences* 7(8):2351-2367.

Scaife, A.A., A. Arribas, E. Blockley, A. Brookshaw, R.T. Clark, N. Dunstone, amd A. Williams. 2014. Skillful long-range prediction of European and North American winters. *Geophysical Research Letters* 41(7):2514-2519.

SCC (Interagency Working Group on Social Cost of Carbon). 2010. *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*. https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf.

Schaefer, H., S.E.M. Fletcher, C. Veidt, K.R. Lassey, G.W. Brailsford, T.M. Bromley, E.J. Dlugokencky, et al. 2016. A 21st-century shift from fossil-fuel to biogenic methane emissions indicated by 13CH4. *Science* 352(6281):80-84.

Schimel, D., B.B. Stephens, and J.B. Fisher. 2015. Effect of increasing CO_2 on the terrestrial carbon cycle. *Proceedings of the National Academy of Sciences* 112(2):436-441.

Schuster, U., and A.J. Watson. 2007. A variable and decreasing sink for atmospheric CO_2 in the North Atlantic. *Journal of Geophysical Research: Oceans* 112(11).

Schuur, E.A.G., A.D. McGuire, C. Schädel, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius, et al. 2015. Climate change and the permafrost carbon feedback. *Nature* 520(7546):171-179.

Schwietzke, S., O.A. Sherwood, L.M.P. Bruhwiler, J.B. Miller, G. Etiope, E.J. Dlugokencky, S.E. Michel, V.A. Arling, B.H. Vaughn, J.W. White, and P.P. Tans. 2016. Upward revision of global fossil fuel methane emissions based on isotope database. *Nature* 538(7623):88-91.

Seinfeld, J.H., C. Bretherton, K.S. Carslaw, H. Coe, P.J. DeMott, E.J. Dunlea, G. Feingold, et al. 2016. Improving our fundamental understanding of the role of aerosol-cloud interactions in the climate system. *Proceedings of the National Academy of Sciences* 113(21):5781-5790.

Serreze, M.C., A.P. Barrett, J.C. Stroeve, D.N. Kindig, and M.M. Holland. 2009. The emergence of surface-based Arctic amplification. *Cryosphere* 3(1):11-19.

Shea, Y.L., B.A. Wielicki, S. Sun-Mack, and P. Minnis. 2017. Quantifying the dependence of satellite cloud retrievals on instrument uncertainty. *Journal of Climate* 30(17).

Shepherd, A., E.R. Ivins, A. Geruo, V.R. Barletta, M.J. Bentley, S. Bettadpur, K.H. Briggs, et al. 2012. A reconciled estimate of ice-sheet mass balance. *Science* 338(6111):1183-1189.

Shindell, D.T., G. Faluvegi, A. Lacis, J. Hansen, R. Ruedy, and E. Aguilar. 2006. Role of tropospheric ozone increases in 20th-century climate change. *Journal of Geophysical Research: Atmospheres* 111(8).

Sigmond, M., J.F. Scinocca, V.V. Kharin, and T.G. Shepherd. 2013. Enhanced seasonal forecast skill following stratospheric sudden warmings. *Nature Geoscience* 6(2):98-102.

Simmons, A., J.L. Fellous, V. Ramaswamy, K. Trenberth, G. Asrar, M. Balmaseda, J.P. Burrows, et al. 2016. Observation and integrated Earth-system science: A roadmap for 2016-2025. *Advances in Space Research* 57(10):2037-2103.

Skofronick-Jackson, G.M., B.T. Johnson, and S.J. Munchak. 2013. Detection thresholds of falling snow from satellite-borne active and passive sensors. *IEEE Transactions on Geoscience and Remote Sensing* 51(7):4177-4189.

Slaper, H., G.J.M. Velders, J.S. Daniel, F.R. de Gruijl, and J.C. van der Leun. 1996. Estimates of ozone depletion and skin cancer incidence to examine the Vienna Convention achievements. *Nature* 384(6606):256-258.

Smith, S.J., and T.C. Bond. 2014. Two hundred fifty years of aerosols and climate: The end of the age of aerosols. *Atmospheric Chemistry and Physics* 14(2):537-549.

Soden, B.J., I.M. Held, R.C. Colman, K.M. Shell, J.T. Kiehl, and C.A. Shields. 2008. Quantifying climate feedbacks using radiative kernels. *Journal of Climate* 21(14):3504-3520.

Solomon, S., D.J. Ivy, D. Kinnison, M.J. Mills, R.R. Neely, and A. Schmidt. 2016. Emergence of healing in the Antarctic ozone layer. *Science* 353(6296):269-274.

Solomon, S., K.H. Rosenlof, R.W. Portmann, J.S. Daniel, S.M. Davis, T.J. Sanford, and G.K. Plattner. 2010. Contributions of stratospheric water vapor to decadal changes in the rate of global warming. *Science* 327(5970):1219-1223.

Song, X., and G.J. Zhang. 2011. Microphysics parameterization for convective clouds in a global climate model: Description and single-column model tests. *Journal of Geophysical Research: Atmospheres* 116(2).

SPARC (Stratosphere-troposphere Processes and Their Role in Climate). 2010. *SPARC CCMVal Report on the Evaluation of Chemistry-Climate Models*. http://www.sparc-climate.org/publications/sparc-reports/. Accessed April 13, 2018.

Spence, P., S.M. Griffies, M.H. England, A.M. Hogg, O.A. Saenko, and N.C. Jourdain. 2014. Rapid subsurface warming and circulation changes of Antarctic coastal waters by poleward shifting winds. *Geophysical Research Letters* 41(13):4601-4610.

Sriver, R.L., N.M. Urban, R. Olson, and K. Keller. 2012. Toward a physically plausible upper bound of sea-level rise projections. *Climatic Change* 115(3-4):893-902.

Stephens, G.L., J. Li, M. Wild, C.A. Clayson, N. Loeb, S. Kato, T. L'Ecuyer, P.W. Stackhouse Jr., M. Lebsock, and T. Andrews. 2012. An update on Earth's energy balance in light of the latest global observations. *Nature Geoscience* 5(10):691-696.

Stephens, G.L., and D.G. Vane. 2008. "Advances in the Remote Sensing of Clouds and Precipitation from Cloudsat and the A-train." Paper presented at the Proceedings of SPIE—The International Society for Optical Engineering. Noumea, New Caledonia.

Stevenson, D.S., P.J. Young, V. Naik, J.F. Lamarque, D.T. Shindell, A. Voulgarakis, R.B. Skeie, et al. 2013. Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). *Atmospheric Chemistry and Physics* 13(6):3063-3085.

Storelvmo, T., C. Hoose, and P. Eriksson. 2011. Global modeling of mixed-phase clouds: The albedo and lifetime effects of aerosols. *Journal of Geophysical Research Atmospheres* 116(5).

Streets, D.G., T. Canty, G.R. Carmichael, B. De Foy, R.R. Dickerson, B.N. Duncan, D.P. Edwards, et al. 2013. Emissions estimation from satellite retrievals: A review of current capability. *Atmospheric Environment* 77:1011-1042.

Stroeve, J., M.M. Holland, W. Meier, T. Scambos, and M. Serreze. 2007. Arctic sea ice decline: Faster than forecast. *Geophysical Research Letters* 34(9).

Stroeve, J.C., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W.N. Meier. 2012. Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters* 39(16).

Suzuki, K., G.L. Stephens, and M.D. Lebsock. 2013. Aerosol effect on the warm rain formation process: Satellite observations and modeling. *Journal of Geophysical Research Atmospheres* 118(1):170-184.

Suzuki, K., G.L. Stephens, S.C. Van Den Heever, and T.Y. Nakajima. 2011. Diagnosis of the warm rain process in cloud-resolving models using joint cloudsat and MODIS observations. *Journal of the Atmospheric Sciences* 68(11):2655-2670

Swart, N.C., and J.C. Fyfe. 2012. Observed and simulated changes in the Southern Hemisphere surface westerly wind-stress. *Geophysical Research Letters* 39(16).

Sweet, W.V., and J.J. Marra. 2015. *2014 State of Nuisance Tidal Flooding*. https://www.ncdc.noaa.gov/monitoring-content/sotc/national/2015/aug/sweet-marra-nuisance-flooding-2015.pdf.

Sweet, W.V., and J. Park. 2014. From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future* 2(12):579-600.

Thompson, D.W.J., S. Solomon, P.J. Kushner, M.H. England, K.M. Grise, and D.J. Karoly. 2011. Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nature Geoscience* 4(11):741-749.

Trenberth, K.E., R.A. Anthes, A. Belward, O.B. Brown, T. Habermann, T.R. Karl, S. Running, B. Ryan, M. Tanner, and B. Wielicki. 2013. Challenges of a sustained climate observing system. Pp. 13-50 in *Climate Science for Serving Society: Research, Modeling and Prediction Priorities* (eds. G.R. Asrar and J.W. Hurrell). Dordrecht: Springer Netherlands.

Trenberth, K.E., and J.T. Fasullo. 2010. Tracking Earth's energy. *Science* 328(5976):316-317.

Turner, A.J., C. Frankenberg, P.O. Wennberg, and D.J. Jacob. 2017. Ambiguity in the causes for decadal trends in atmospheric methane and hydroxyl. *Proceedings of the National Academy of Sciences* 114(21):5367-5372.

USGCRP (U.S. Global Change Research Program). 2017. *Climate Science Special Report: Fourth National Climate Assessment, Volume I.* Washington, DC: U.S. Global Change Research Program.

Valdivieso, M., K. Haines, M. Balmaseda, Y.S. Chang, M. Drevillon, N. Ferry, Y. Fujii, et al. 2017. An assessment of air-sea heat fluxes from ocean and coupled reanalyses. *Climate Dynamics* 49(3):983-1008.

van Vuuren, D.P., E. Stehfest, M.G.J. den Elzen, T. Kram, J. van Vliet, S. Deetman, M. Isaac, et al. 2011. RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change* 109(1):95-116.

VanZanten, M.C., B. Stevens, L. Nuijens, A.P. Siebesma, A.S. Ackerman, F. Burnet, A. Cheng, et al. 2011. Controls on precipitation and cloudiness in simulations of trade-wind cumulus as observed during RICO. *Journal of Advances in Modeling Earth Systems* 3(2).

Verdy, A., and M.R. Mazloff. 2017. A data assimilating model for estimating Southern Ocean biogeochemistry. *Journal of Geophysical Research: Oceans* 122(9):6968-6988.

Vitart, F., M.R. Huddleston, M. Déqué, D. Peake, T.N. Palmer, T.N. Stockdale, M.K. Davey, S. Ineson, A. Weisheimer. 2007. Dynamically-based seasonal forecasts of Atlantic tropical storm activity issued in June by EUROSIP. *Geophysical Research Letters* 34(16).

Von Schuckmann, K., M.D. Palmer, K.E. Trenberth, A. Cazenave, D. Chambers, N. Champollion, J. Hansen, et al. 2016. An imperative to monitor Earth's energy imbalance. *Nature Climate Change* 6(2):138-144.

Walter Anthony, K., R. Daanen, P. Anthony, T. Schneider Von Deimling, C.L. Ping, J.P. Chanton, and G. Grosse. 2016. Methane emissions proportional to permafrost carbon thawed in Arctic lakes since the 1950s. *Nature Geoscience* 9(9):679-682.

Wang, H., and G. Feingold. 2009a. Modeling mesoscale cellular structures and drizzle in marine stratocumulus. Part I: Impact of drizzle on the formation and evolution of open cells. *Journal of the Atmospheric Sciences* 66(11):3237-3256.

Wang, H., and G. Feingold. 2009b. Modeling mesoscale cellular structures and drizzle in marine stratocumulus. Part II: The microphysics and dynamics of the boundary region between open and closed cells. *Journal of the Atmospheric Sciences* 66(11):3257-3275.

Ward, B., R. Wanninkhof, P.J. Minnett, and M.J. Head. 2004. SkinDeEP: A profiling instrument for upper-decameter sea surface measurements. *Journal of Atmospheric and Oceanic Technology* 21(2):207-222.

Waters, J.W., L. Froidevaux, R.S. Harwood, R.F. Jarnot, H.M. Pickett, W.G. Read, P.H. Siegel, et al. 2006. The Earth Observing System Microwave Limb Sounder (EOS MLS) on the aura satellite. *IEEE Transactions on Geoscience and Remote Sensing* 44(5):1075-1092.

Weatherhead, E.C., G.C. Reinsel, G.C. Tiao, X.L. Meng, D. Choi, W.K. Cheang, T. Keller, et al. 1998. Factors affecting the detection of trends: Statistical considerations and applications to environmental data. *Journal of Geophysical Research Atmospheres* 103(D14):17149-17161.

Weatherhead, E.C., B.A. Wielicki, V. Ramaswamy, M. Abbott, T. Ackerman, R. Atlas, G. Brasseur, et al. 2017. Designing the climate observing system of the future. *Earth's Future* 6(1).

Wentz, F.J., L. Ricciardulli, E. Rodriguez, B.W. Stiles, M.A. Bourassa, D.G. Long, R.N. Hoffman, et al. 2017. Evaluating and extending the Ocean Wind Climate Data Record. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 10(5).

Westermann, S., M. Peter, M. Langer, G. Schwamborn, L. Schirrmeister, B. Etzelmüller, and J. Boike. 2017. Transient modeling of the ground thermal conditions using satellite data in the Lena River delta, Siberia. *Cryosphere* 11(3):1441-1463.

Wielicki, B.A., D.F. Young, M.G. Mlynczak, K.J. Thome, S. Leroy, J. Corliss, J.G. Anderson, et al. 2013. Achieving climate change absolute accuracy in orbit. *Bulletin of the American Meteorological Society* 94(10):1519-1539.

Winker, D.M., M.A. Vaughan, A. Omar, Y. Hu, K.A. Powell, Z. Liu, W.H. Hunt, and S.A.Young. 2009. Overview of the CALIPSO mission and CALIOP data processing algorithms. *Journal of Atmospheric and Oceanic Technology* 26(11):2310-2323.

WMO (World Meteorological Organization). 2014. *Scientific Assessment of Ozone Depletion: 2014—Complete 2014 Scientific Assessment of Ozone Depletion.* Geneva: World Meteorological Organization.

WMO. 2016. *The Global Observing System for Climate: Implementation Needs.* https://library.wmo.int/opac/doc_num.php?explnum_id=3417. Accessed April 13, 2018.

Wofsy, S.C., and R.C. Hariss. 2002. *The North American Carbon Program Plan (NACP).* Report of the NACP Committee of the U.S. Carbon Cycle Science Program. Washington, DC.

Wolf, J., G.R. Asrar, and T.O. West. 2017. Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock. *Carbon Balance and Management* 12(1).

Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, B. DeAngelo, S. Doherty, K. Hayhoe, R. Horton, J.P. Kossin, P.C. Taylor, A.M. Maple, and C.P. Weaver. 2017. Executive summary. Pp. 12-34 in *Climate Science Special Report: Fourth National Climate Assessment, Volume I* (eds. D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock). Washington, DC: U.S. Global Change Research Program.

Wunch, D., G.C. Toon, V. Sherlock, N.M. Deutscher, C. Liu, D.G. Feist, and P.O. Wennberg. 2015. The Total Carbon Column Observing Network's GGG2014 Data Version. ftp://tccon.ornl.gov/2014Public/documentation/tccon_ggg2014.pdf.

Wunch, D., G.C. Toon, P.O. Wennberg, S.C. Wofsy, B.B. Stephens, M.L. Fischer, O. Uchino, et al. 2010. Calibration of the total carbon column observing network using aircraft profile data. *Atmospheric Measurement Techniques* 3(5):1351-1362.

Wunch, D., P.O. Wennberg, G. Osterman, B. Fisher, B. Naylor, C.M. Roehl, C. O'Dell, et al. 2016. Comparisons of the Orbiting Carbon Observatory-2 (OCO-2) XCO2 measurements with TCCON. *Atmospheric Measurement Techniques Discussion* 1-45.

Wunch, D., P.O. Wennberg, G.C. Toon, B.J. Connor, B. Fisher, G.B. Osterman, C. Frankenberg, et al. 2011. A method for evaluating bias in global measurements of CO_2 total columns from space. *Atmospheric Chemistry and Physics* 11(23):12317-12337.

Wunsch, C., and P. Heimbach. 2014. Bidecadal thermal changes in the Abyssal Ocean. *Journal of Physical Oceanography* 44(8):2013-2030.

Xu, K.M., T. Wong, S. Dong, F. Chen, S. Kato, and P.C. Taylor. 2017. Cloud object analysis of CERES Aqua observations of tropical and subtropical cloud regimes: Evolution of cloud object size distributions during the Madden-Julian Oscillation. *Journal of Quantitative Spectroscopy and Radiative Transfer* 188:148-158.

Yang, X.S., A. Rosati, S.Q. Zhang, T.L. Delworth, R.G. Gudgel, R. Zhang, G. Vecchi, et al. 2013. A predictable AMO-like pattern in the GFDL Fully Coupled Ensemble Initialization and Decadal Forecasting System. *Journal of Climate* 26(2):650-661.

Yohe, G., K. Knee, and P. Kirshen. 2011. On the economics of coastal adaptation solutions in an uncertain world. *Climatic Change* 106(1):71-92.

Zelinka, M.D., S.A. Klein, and D.L. Hartmann. 2012. Computing and partitioning cloud feedbacks using cloud property histograms. Part II: Attribution to changes in cloud amount, altitude, and optical depth. *Journal of Climate* 25(11):3736-3754.

Zelinka, M.D., D.A. Randall, M.J. Webb, and S.A. Klein. 2017. Clearing clouds of uncertainty. *Nature Climate Change* 7(10):674-678.

Zhang, S., M.J. Harrison, A.T. Wittenberg, A. Rosati, J.L. Anderson, and V. Balaji. 2005. Initialization of an ENSO forecast system using a parallelized ensemble filter. *Monthly Weather Review* 133(11):3176-3201.

Zhou, L., Y. Tian, R.B. Myneni, P. Ciais, S. Saatchi, Y.Y. Liu, S. Piao, H. Chen, E.F. Vermote, C. Song, and T. Hwang. 2014. Widespread decline of Congo rainforest greenness in the past decade. *Nature* 508(7498):86-90.

Zhu, Z., S. Piao, R.B. Myneni, M. Huang, Z. Zeng, J.G. Canadell, P. Ciais, et al. 2016. Greening of the Earth and its drivers. *Nature Climate Change* 6(8):791-795.

10

Earth Surface and Interior: Dynamics and Hazards

INPUT SUMMARY

Earth's terrestrial surface is the nexus where diverse systems vital to the habitability of the planet converge. Tectonic processes and flow in Earth's interior drive deformation of Earth's surface that can lead to destructive earthquakes, tsunamis, and volcanic eruptions. Climatic processes affect the dynamics of Earth's ice sheets and glaciers, and along with local tectonic processes, modulate changes in average sea level. Long-term climatic trends (e.g., toward increased drought, storminess, or climate extremes) create a key context within which the intensity, location, and persistence of weather events determine local impacts (e.g., topsoil loss, channel formation, and coastal erosion). Both ecological and hydrological processes respond to changes in water abundance, soil quality, and nutrient availability; to climatic and meteorological trends; and to societal activities. This ensemble of Earth system processes drives continual change of Earth's terrestrial surface. Given that this surface is also the home to humans and to many resources that sustain society, our greatest task is to understand how Earth's surface evolves; what controls its response, resilience, and vulnerability to natural and anthropogenic events; and how to use science and space-based observations to guide decision making to ensure a sustainable future.

Space-based measurements of Earth's surface and interior provide fundamental information about the current state and ongoing dynamics of the planet—critical ingredients for defining and mitigating hazards. Many major processes affecting hazards and habitability can be observed and compared over Earth's surface only from space. Over the coming decade next-generation satellites could finally have sufficient accuracy, spatial resolution, coverage, and temporal sampling to enhance modeling, forecasting, mitigation, and response to impulsive events (e.g., earthquakes, volcanoes, or landslides), to long-term trends (e.g., sea-level rise, ice-sheet decay, or groundwater depletion), and to chronic and event-driven processes (e.g., erosion and deposition on hillsides, in channels, and along coasts) that impact society and shape our planet.

NOTE: This chapter was written by members of the Panel on Earth Surface and Interior: Dynamics and Hazards and is provided for reference only. Any study finding or consensus recommendation will appear in Chapters 1-5, the report from the survey steering committee.

Based on input from the science community, as well as recent planning documents, the Panel on Earth Surface and Interior: Dynamics and Hazards considered the important science and applications areas that could be significantly advanced over the next decade using mainly space-based measurements. The panel's science and applications priorities, as addressed in its questions and measurement objectives (Table 10.1), provide a vision for critical advances in understanding Earth processes and hazards.

TABLE 10.1 Summary of Science and Applications Questions and Their Priorities

Science and Applications Questions		**Highest Priority Measurement Objectives (MI=Most Important, VI=Very Important)**
S-1	How can large-scale geological hazards be accurately forecast in a socially relevant time frame?	**(MI) S-1a.** Measure the pre-, syn-, and posteruption surface deformation and products of Earth's entire active land volcano inventory with a time scale of days to weeks.
		(MI) S-1b. Measure and forecast interseismic, preseismic, coseismic, and postseismic activity over tectonically active areas on time scales ranging from hours to decades.
		(VI) S-1c. Forecast and monitor landslides, especially those near population centers.
		One objective ranked Important (S-1d).
S-2	How do geological disasters directly impact the Earth system and society following an event?	**(MI) S-2a.** Rapidly capture the transient processes following disasters for improved predictive modeling, as well as response and mitigation through optimal retasking and analysis of space data.
		(VI) S-2b. Assess surface deformation (<10 mm), extent of surface change (<100 m spatial resolution) and atmospheric contamination, and the composition and temperature of volcanic products following a volcanic eruption (hourly to daily temporal sampling).
		(VI) S-2c. Assess co- and postseismic ground deformation (spatial resolution of 100 m and an accuracy of 10 mm) and damage to infrastructure following an earthquake.
S-3	How will local sea level change along coastlines around the world in the next decade to century?	**(MI) S-3a**. Quantify the rates of sea-level change and its driving processes at global, regional, and local scales, with uncertainty <0.1 mm/yr for global mean sea-level equivalent and <0.5 mm/yr sea-level equivalent at resolution of 10 km.
		(MI) S-3b. Determine vertical motion of land along coastlines at uncertainty <1 mm/yr.
S-4	What processes and interactions determine the rates of landscape change?	**(MI) S-4a.** Quantify global, decadal landscape change produced by abrupt events and by continuous reshaping of Earth's surface from surface processes, tectonics, and societal activity.
		Two objectives ranked Important (S-4b and S-4c).
S-5	How does energy flow from the core to Earth's surface?	**(VI) S-5a.** Determine the effects of convection within Earth's interior, specifically the dynamics of Earth's core and its changing magnetic field, and the interaction between mantle convection and plate motions.
		Two objectives ranked Important (S-5b and S-5c).
S-6	How much water is traveling deep underground and how does it affect geological processes and water supplies?	**(VI) S-6a.** Determine the fluid pressures, storage, and flow in confined aquifers at spatial resolution of 100 m and pressure of 1 kPa (0.1 m head).
		Three objectives ranked Important (S-6b, S-6c, and S-6d).
S-7	How do we improve discovery and management of energy, mineral, and soil resources?	One objective ranked Important (S-7a).

Two of the high-priority science and application areas relate to understanding, forecasting, and responding to geologic natural disasters including volcanic eruptions, earthquakes, and landslides (Questions S-1 and S-2).[1] Over the past decade tremendous progress has been made in monitoring and modeling volcanoes and earthquake faults from space using high spatial resolution deformation measurements along with frequent imaging and measurements of gravity change. The objectives over the next decade are (1) to forecast earthquakes, volcanic eruptions, and landslides on a time scale relevant to society; and (2) to assess and mitigate the hazards posed by these sudden events by monitoring disaster-prone areas. Complete imaging and modeling of these geologic systems requires measurements that span time scales from seconds to thousands of years and spatial scales from meters to thousands of kilometers. When high spatial resolution maps of deformation generated using Interferometric Synthetic Aperture Radar (InSAR) are combined with the high accuracy and high temporal resolution of Global Positioning System (GPS) data, they can fill a large part of this space-time spectrum. Improved, high-resolution global topography provides a critical component and context for hazard assessment and mitigation. Frequently acquired, high spatial resolution optical and multispectral imager data are especially important for understanding volcanic activity, as well as for supporting disaster response and mitigation. Additional measurements (discussed later) could fuel further advances.

A second high-priority science and application area is to monitor and forecast sea-level change, especially along highly populated coastlines where millions of people will be affected (Question S-3). This effort involves two different but important tasks. The first is to monitor the redistribution of water over Earth between the ice sheets, oceans, and land. Quantifying this redistribution can be done only using very accurate satellite-based measurements of (1) the volume changes of the ice sheets; (2) the mass changes of the oceans, ice, and land; (3) thermal changes of the ocean; and (4) spatial and temporal variations in sea level. These critical measurements are also priorities of other panels, but over the past three decades, geodesists have been at the leading edge of developing the precise measurement tools, such as satellite altimetry, gravity (i.e., mass) change, InSAR, and the terrestrial reference frame. The second sea-level task, not considered by other panels, is to monitor and forecast vertical land motion along coastlines caused by postglacial rebound, sediment loading and compaction, tectonics, recent glacier or ice-sheet melting, and anthropogenic processes. Rates of land subsidence commonly exceed rates of sea-level rise, especially in areas with high sediment compaction (e.g., deltas) or extraction of groundwater or hydrocarbons. The tools needed to monitor vertical land motion are InSAR, GPS, swath altimetry, and gravity change.

A third high-priority area is to monitor, understand, and predict the complex interactions of the "critical zone," which extends from the top of the vegetation canopy to the base of the weathered bedrock (Question S-4). This zone is the dynamic surface where freshwater flows, soils are created and destroyed, and terrestrial life flourishes—key features on which modern civilization depends. Over time the critical zone has achieved a rough equilibrium where water, nutrient, and energy fluxes are in an approximate balance. However, after centuries of human activity, some of these landscapes may be near tipping points or thresholds at which relatively modest changes in the governing fluxes can cause abrupt, large-scale, and irreversible changes. Major challenges include (1) quantifying the fluxes and the resultant "balance" as reflected in the shape, dynamics, chemistry, and biota of undisturbed landscapes; and (2) predicting and measuring how perturbations owing to tectonics, weather, ecological changes, or human activities (agriculture, construction, fire) have affected (or soon will) the established balance. Progress in understanding and predicting changes in the critical zone relies on a suite of terrestrial and space-based measurements. High-resolution, multispectral, and hyperspectral imagery are used to help detect patterns and rates of

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[1] In this report, a "forecast" is a probabilistic assessment of the likelihood and timing of an event. In contrast, a "prediction" is a deterministic statement about where and when the event will occur, and it will be either correct or incorrect. Short-term predictions of some natural hazards may never be possible.

vegetative, mineralogic (topsoil, nutrients), and surface change. A critical missing ingredient is the measurement of bare-earth topography—a goal attainable now with directed airborne surveys and ultimately with global coverage from space-based swath lidar.

The fourth high-priority area is to improve understanding of the dynamics of Earth's mantle and core (Question S-5). Convection of Earth's fluid inner core generates the protective magnetic field. Changes in the field on yearly time scales are best monitored from multiple small magnetometer satellites. Mantle and core dynamics are mainly studied using terrestrial measurements such as seismology, combined with advanced modeling of thermal convection. The surface manifestation of mantle convection is plate tectonics, and plate motions are measured using a suite of geodetic tools, such as Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), GPS, and InSAR. These same tools are used to maintain the terrestrial reference frame to the 0.1 mm/yr accuracy needed to monitor global sea level. Major shifts in the reference frame, such as those caused by recent megathrust earthquakes, need to be accurately modeled and removed from the sea-level time series.

The fifth high-priority area is to monitor water traveling underground and how it affects geological processes and water supplies (Question S-6). Growing reliance on subsurface water requires measuring, monitoring, and managing aquifer systems in a sustainable way to prevent risks to human health in many parts of the world. Overproduction of groundwater aquifers not only reduces the amount of immediately available water but also can lead to loss of storage capacity, such that the aquifer may no longer be able to be recharged, even if rainfall is abundant. In addition wastewater disposal in oil and gas wells induces earthquakes in regions where such activity has historically been minimal. Ground deformation is a sensitive but underutilized indicator of the health of deep groundwater reserves.

Over the coming decade, next-generation satellites with higher spatial resolution, expanded Earth coverage, and higher temporal sampling promise to enhance observation, quantification, forecasts, mitigation, and response to Earth surface and interior processes that affect society and shape the planet. New spaceborne measurements needed to support the highest priority science and applications objectives are summarized in Table 10.2. Other important spaceborne measurements and complementary terrestrial measurements (notably, GPS), and airborne measurements (notably, lidar) are described in the section "Enabling Measurements."

TABLE 10.2 Priority Targeted Observables Mapped to the Science and Applications Objectives That Were Ranked as Most Important (MI) or Very Important (VI)

Priority Targeted Observables	Science and Applications Objectives
Surface Deformation and Change	Earthquake, volcano, and landslide dynamics, forecasts, and impacts (S-1a, S-1b, S-1c, S-2a, S-2b, S-2c); dynamics of the deep interior (S-5a); sea-level change (S-3a, S-3b); landscape change (S-4a); and subsurface water flow (S-6a)
Surface Topography and Vegetation	Earthquake, volcano, and landslide dynamics, forecasts, and impacts (S-1a, S-1b, S-1c, S-2c); sea-level change (S-3a, S-3b); and landscape change (S-4a)
Mass Change	Megathrust earthquakes (S-1b, S-2c); ice mass loss and postglacial rebound (S-3a); and landscape changes (S-4a)
Surface Biology and Geology	Volcanic activity and impacts (S-1a, S-2b); and landslide monitoring (S-1c)
Surface Water Height	Sea-level change (S-3a); deep Earth dynamics (S-5a); and subsurface water flow (S-6a)
Magnetic Field	Dynamics of the deep Earth and its magnetic field (S-5a)
Terrestrial Reference Frame	Underpins accurate positioning and navigation of all satellite and aircraft missions; the most stringent requirements come from monitoring sea-level change (S-3a)

Surface deformation and topography measurements each support a wide variety of science and applications objectives. Deformation measurements, such as InSAR, are an important tool for understanding the dynamics of earthquakes, volcanoes, landslides, glaciers, groundwater, and the deep interior; for quantifying the rates and driving processes of sea-level change and landscape change; and for supporting hazard forecasts and disaster impact assessments. High-resolution topography measurements provide the physical template for the processes that carve the planet and control the critical zone where most terrestrial life occurs. Reliable, repeated high-resolution (~1 m spatial resolution and 0.1 m vertical resolution) topography supports the objectives of quantifying dynamic change and processes in landscapes, as well as making accurate forecasts of how impulsive events (e.g., earthquakes or storms) and long-term trends (e.g., sea-level rise or deforestation) affect landscapes and society. Developing such a capability from space is a high priority. In the meantime, it will be necessary to expand acquisition of airborne lidar.

High-resolution image data are needed to support objectives related to geological hazards and disasters as well as landscape change. In particular, hyperspectral data from ultraviolet to thermal wavelengths are a priority for tracking pre-, syn-, and posteruption volcanic gases, ash, and other eruptive products (like lava); for quantifying the extent and impact of natural and man-made disasters owing to earthquakes, volcanic eruptions, storms, floods, coastal inundation, and wildfire; for exploring resources; and for documenting ecological and mineralogical changes that modulate landscape evolution.

Temporal variations in gravity capture shrinkage and growth of key water resources—glaciers, ice sheets, and subsurface water. Tracking mass changes in both the surface and subsurface using gravity with an increasingly higher spatial resolution, as with Gravity Recovery and Climate Experiment-Follow On (GRACE-FO) and successor missions, will permit quantification of spatial changes in glaciers and ice sheets, seasonal snowpack, and large surface and groundwater reservoirs. Radar altimetry is essential for measuring an accurate mean sea surface, from which high-resolution (<10 km) ocean gravity can be derived, and for measuring sea-surface height—a critical aspect of sea-level change studies.

At a deeper Earth scale, a constellation of vector magnetic satellites would provide fundamental new insights into the dynamics of the deep Earth and its magnetic field.

Underpinning all spaceborne observations is an accurate terrestrial reference frame, which is critical for accurate positioning and navigation of all satellite and aircraft missions, especially now that it is necessary to reliably integrate data from constellations of satellites. Notably, ground networks (VLBI, SLR, and GPS) remain an essential component for reliable, sustained quantification of this terrestrial reference frame. Consequently, a major Earth observing priority for the next decade is to maintain and improve the terrestrial reference frame.

Implementing the vision outlined earlier will enable advances in the following scientific and applications areas:

- Forecasting natural disasters, including the timing and size of earthquakes, the timing and duration of volcanic eruptions, and the timing and location of landslides.
- Responding rapidly to natural disasters and mitigating their consequences.
- Quantifying global, decadal landscape change owing to surface processes, tectonics, and societal activities.
- Understanding and forecasting regional variations in sea-level rise.
- Measuring and forecasting vertical land motion along coastlines to assess and mitigate hazards from relative sea-level rise.
- Monitoring, understanding, and forecasting spatial and temporal variations of Earth's magnetic field.
- Quantifying mantle convection to understand how it drives plate motions and generates earthquakes and volcanic eruptions.

- Understanding temporal variations of water discharge and subsurface water storage and transport.
- Understanding Earth surface and interior processes caused or influenced by anthropogenic activity.

INTRODUCTION AND VISION

Since the satellite era began, measurements of Earth from space have captured our imagination with gripping images of downwind ash plumes from newly awakened volcanoes or the swaths of destruction wreaked by tsunamis, fires, and typhoons. Imagery of the aftermath shows the incremental response, recovery, or degradation of landscapes, ecological systems, and society (e.g., Figure 10.1). These images and other remotely sensed data from Earth observing satellites play a key role in helping us understand Earth's surface and interior. Fluid motions in the core generate the magnetic field, protecting us from space radiation. Mantle convection drives plate tectonics and deforms Earth's surface, creating volcanic eruptions, earthquakes, tsunamis, and landslides, and sometimes causing great destruction. Erosion and sedimentation reshape Earth's surface and affect water and agricultural systems, as well as infrastructure. Vertical land motions driven by the redistribution of water and ice on the planet change sea levels and shorelines. Last, human activity has a profound impact on water resources, landscape stability, ecological diversity and health, and long-term sustainability. These processes operate on diverse time scales, from continuous (e.g., river erosion) to episodic (e.g., volcanic eruptions) and from minutes (e.g., earthquakes) to millions of years (e.g., subduction zone tectonics).

Earth's surface is *the* critical interface at which many other vital systems (atmosphere, hydrosphere, biosphere, tectosphere, and human) interact: interactions that determine the planet's habitability. Nutrient-rich soils sustain global agriculture and healthy ecosystems. Groundwater aquifers are tapped and increasingly depleted to meet agricultural, industrial, and social needs. Within Earth lie key minerals and energy resources needed to maintain technologies and quality of life. Both the discovery of essential resources and the adverse impacts of their extraction, use, and disposal pose persistent challenges for society. The ability to leverage a growing understanding of these processes and interactions and to answer still-open questions will strengthen society's ability to forecast, prepare for, and mitigate the impact of disruptive change on multiple time scales.

Enhanced understanding of the dynamics of Earth's surface and interior and their societal relevance requires both global observations from space as well as diverse and detailed ground and aircraft measurements. Sequential observations over decades enable the definition of long-term trends and the examination of the impact of events, such as volcanic eruptions or surging glaciers, that engender a chain of subsequent responses. Such observations also allow the identification of key thresholds that, when crossed, typically cause disruptive change. For example, what threshold conditions of strain accumulation nucleate destructive earthquakes? Last, a sustained, high-resolution, remote sensing record provides the critical basis for reliable analysis of cause and effect. For example, what combination of seismic shaking, hillslope steepening, rainfall, and vegetation change causes catastrophic collapse of mountainsides?

Key goals of sustained, high-resolution, space-based observation of the Earth surface and interior are (1) to quantify the nature and pace of change, such as melting ice sheets and shifting coastlines; (2) to characterize the precursors, impacts, and key thresholds of disruptive events, such as earthquakes, volcanic eruptions, or wildfires; (3) to delineate incremental change in Earth's life-sustaining surface (its critical zone; Brantley et al., 2007) in response both to events and to sustained trends (e.g., increased drought, permafrost loss, or ecological shifts); and (4) to assess the impact of human activity on resources, environmental quality, sustainability, and habitability.

This section first summarizes some significant improvements in understanding, monitoring, and forecasting Earth surface and interior processes using remotely sensed observations over the past two decades.

FIGURE 10.1 Coastal inundation in the Sendai Bay, Japan, region captured by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite before and after the 2011 Tohoku earthquake and tsunami—the costliest natural disaster in history. SOURCE: Modified from NASA Earth Observatory, "Tohoku Earthquake and Tsunami: Looking Back from Space—Closeup of Tsunami Damage, Rikuzentakata," March 14, 2011, https://earthobservatory.nasa.gov/Features/Gallery/tsunami.php.

Next, seven science and application challenges are identified and prioritized where spaceborne data could lead to major advances for both science and society. Last, a set of new measurements are proposed that would lead to substantial progress on these science and applications priorities over the next 10 years.

Benefits of Prior Investments in Earth Observing Satellites

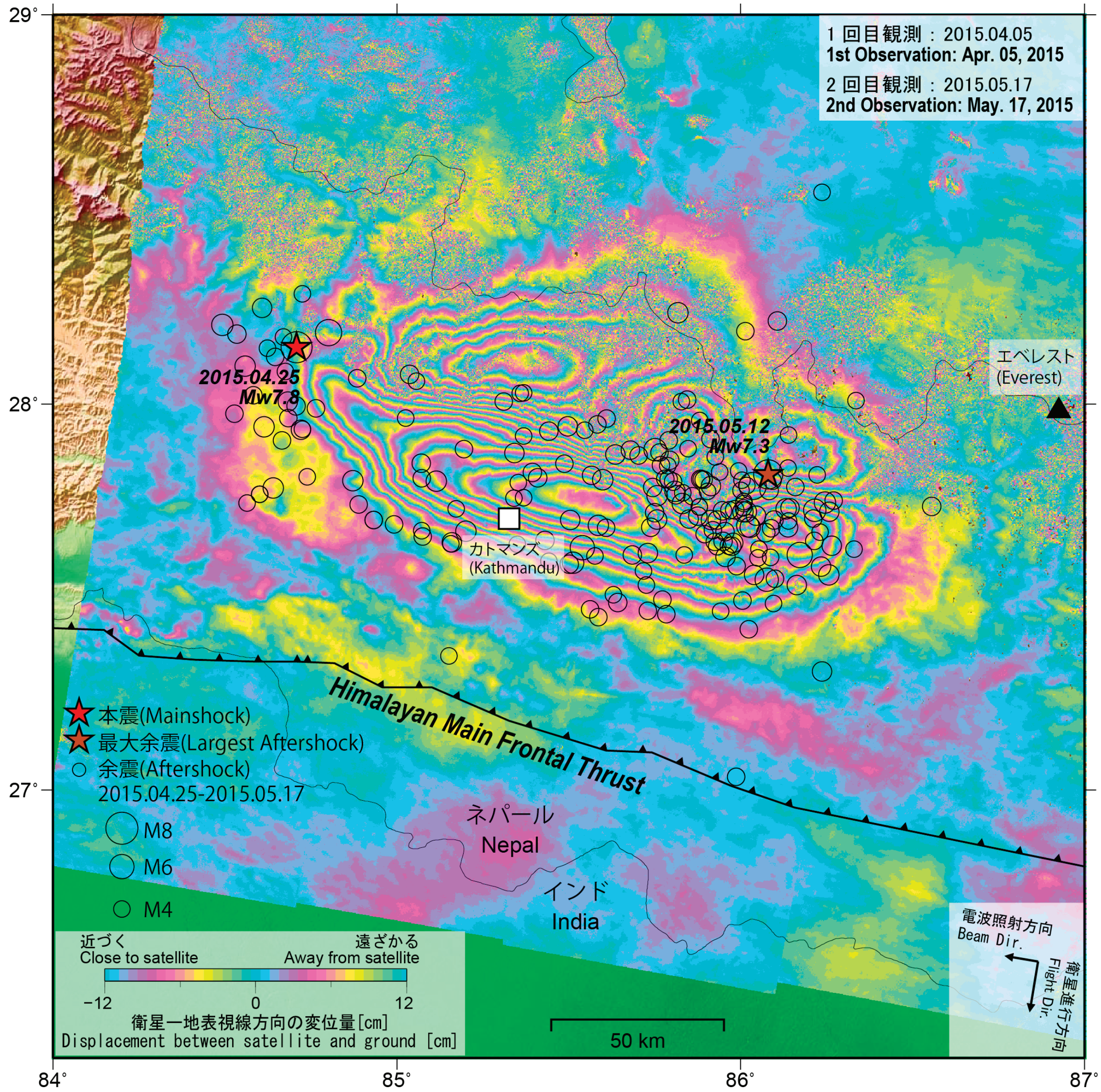
Over the past two decades, advances in observational capabilities—including Synthetic Aperture Radar (SAR) interferometry, time-variable gravity, global and bare-earth topography, laser and radar altimetry, magnetometry, and hyperspectral imaging—have underpinned new scientific insights. Some of these insights were based on data from a single satellite, some from a synthesis of data from multiple satellites, and some from the integration of multiple satellite data with airborne observations. Importantly, the invaluable terrestrial reference frame that permits reliable integration of nearly all Earth observations from space was also significantly enhanced during the past decade. Several such advances are summarized here (Davis et al., 2016).

Land-Surface Deformation

Earth's surface is constantly changing, and its deformation reveals details of earthquake cycles, plate motion, volcanic processes, sediment deposition and compaction, and groundwater extraction. Land-surface deformation is now commonly quantified using a combination of GPS and InSAR. In vegetated areas where correlation degrades, the use of longer wavelength radar and persistent scatterers (i.e., outcrops or buildings) has permitted coherent deformation patterns to be observed (Bürgmann et al., 2006). L-band, which provides superior phase coherence even in the most challenging snow-covered terrain on Earth, will be used in the NASA-ISRO Synthetic Aperture Radar (NISAR) interferometer. These new capabilities are bringing novel insights. The first L-band, wide-swath interferogram of a large thrust-fault earthquake (Nepal; Figure 10.2) showed that the earthquake and subsequent aftershock left an unruptured gap on the fault surface. This discontinuity suggests that a high seismic hazard exists for the densely populated area abutting the main rupture. Along the Himalayan front, a spatially nuanced and temporally resolved perspective on surface uplift and subsidence is emerging from repeat satellite surveys, revealing some fundamentally new processes and interactions. For example, geodetic and seismic time series, combined with GRACE gravity data, have revealed surprising connections between annual cycles of water loading by monsoonal rains and seismicity in the Himalaya (Figure 10.3).

Detection and Compositional Analysis of Volcanic Plumes

Greatly improved temporal and spatial resolution in multi- to hyperspectral data has driven remarkable new insights on volcanic systems and the plumes they produce. Data from imagers, spectrometers, and sounders in wavelengths spanning from ultraviolet (UV) to thermal infrared (TIR) enable detection of silicate ash composition and particle size, sulfur dioxide, and numerous other gases and aerosols. For example, exploiting multispectral TIR data from ASTER acquired at sub-100 m resolution, Henney et al. (2012) were able to quantify passive SO_2 degassing at Lascar Volcano (Chile)—the first time that small (less than 1 km), low-level, passive plumes were detected from space. This advance allows detection any time of day and is many times more sensitive than UV-based retrievals owing to the small spatial scales and detection capability at the vent of the volcano. Such an approach, especially coupled with higher temporal resolution, could lead to critical improvements in our ability both to monitor and forecast eruptions and to explore how weakly emitted plumes (both man-made and natural) affect the chemistry of the atmosphere. For example,



Analysis by GSI from ALOS-2 raw data of JAXA

FIGURE 10.2 InSAR image of deformation for the Nepal M7.8 earthquake and M7.3 aftershock from Advanced Land Observing Satellite (ALOS)-2 interferometry. Repeated SAR acquisitions provide maps of ground displacement used to understand locations of possible large aftershocks and postseismic activity. This interferogram shows the benefits of using the longer wavelength SAR technology to be deployed in the NISAR mission for mapping line-of-sight ground displacement in a region of extreme topography. SOURCE: Geospatial Information Authority of Japan, "The 2015 Nepal Earthquake: Crustal Deformation Detected by ALOS-2 Data," last updated August 4, 2015, http://www.gsi.go.jp/cais/topic150429-index-e.html.

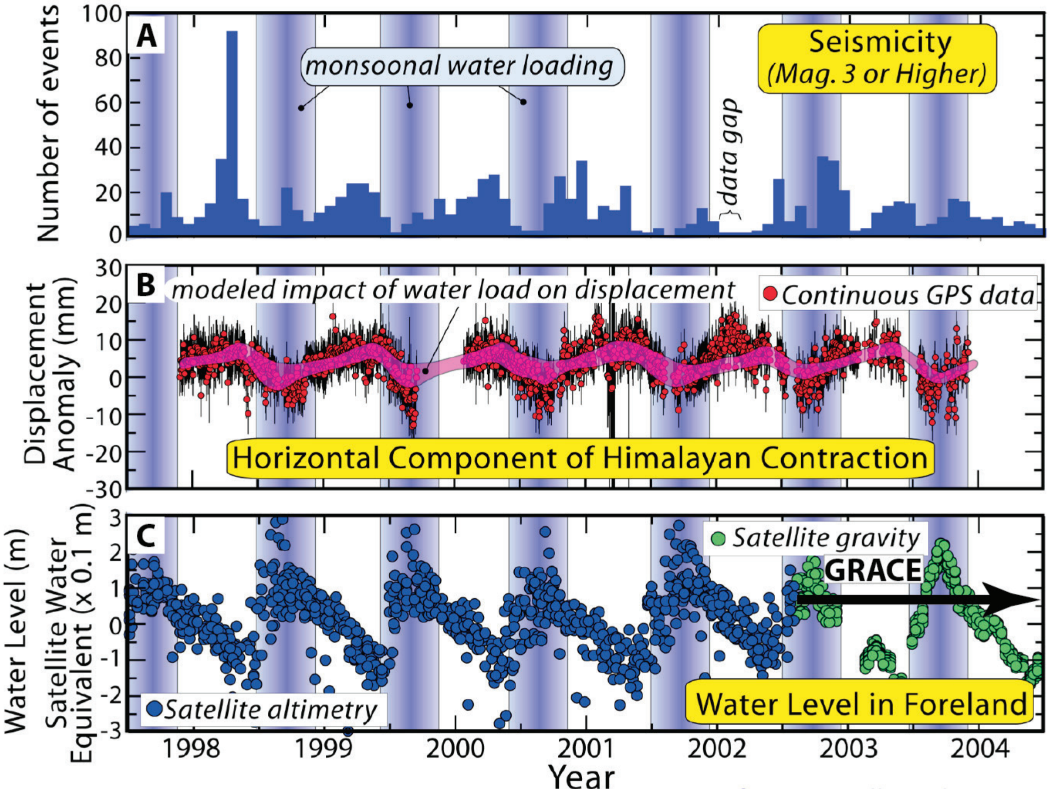


FIGURE 10.3 In the Himalaya, annual cycles of lower seismicity (A) are correlated with reductions in the rate of north-south contraction (B) and with water loading in the foreland basin (C), as defined by continuous GPS and gravity data (note the much greater precision that begins with GRACE gravity measurements in 2003). Water loading in the Himalayan foreland owing to the annual summer monsoon is interpreted to flex the crust downward, causing extensional stresses that oppose the tectonically driven north-south contraction. These reduced rates of contraction are interpreted to cause decreasing rates of earthquakes and can be observed only using satellite-based measurements. SOURCE: Modified from Bettinelli et al. (2008).

the improving temporal frequency of sensors over the last decade has allowed near-real-time exploration of the dynamics of plumes. Geostationary sensors deliver these data, but at the expense of spatial resolution, and so they can detect only the largest activity (e.g., Prata and Kerkmann, 2007). Smaller plume activity can be explored using polar-orbiting sensors. For example, Gouhier and Coppola (2011) calculated gas fluxes and lava-discharge rates using the combined data from the Moderate-Resolution Imaging Spectroradiometer (MODIS) and Ozone Monitoring Instrument (OMI) sensor for the 2007 eruption of Piton de la Fournaise (Reunion). Their analysis pinpointed the plume's location, allowed the gas concentration to be inferred (Figure 10.4), and quantified a significant difference between the volume of SO_2 that was erupted and the volume that was degassed. This discrepancy revealed a large active hydrothermal system below the summit, a critical indicator of future eruptive activity.

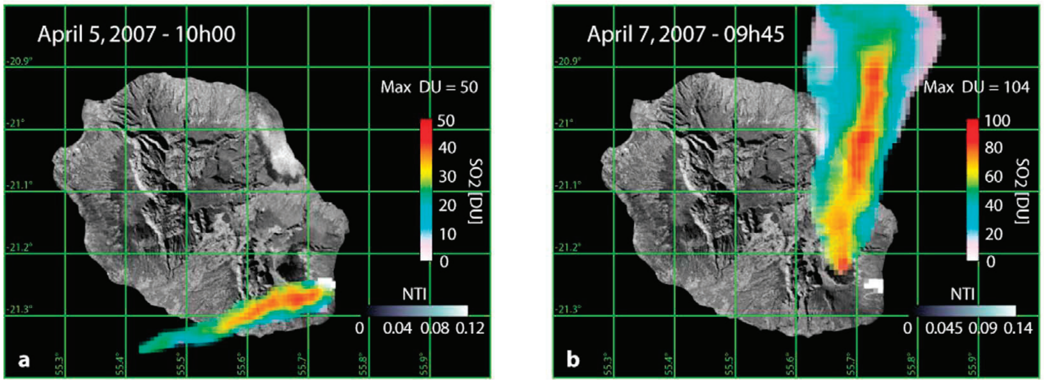


FIGURE 10.4 MODIS-derived image of SO_2 emitted during the 2007 eruption of Piton de la Fournaise Volcano. A: SO_2 plume from the active lava flow. B: Much larger degassed SO_2 plume from the vent, following the collapse of the crater, indicating an extensive, previously unrecognized active hydrothermal system. SOURCE: Gouhier and Coppola (2011).

Sea Level and Global Redistribution of Water and Mass

One of the most important discoveries over the past two decades is that sea-level rise is highly variable around Earth, with some regions (e.g., the Western Pacific) rising rapidly and some regions (e.g., parts of the Eastern and South Pacific) actually falling (Figure 10.5). Moreover, sea-level rise along the coast also depends on vertical land motion owing to tectonics, sediment compaction, extraction of groundwater and hydrocarbons, and the rebound of the solid Earth in response to ice unloading, as well as to reduced gravitational pull owing to ice-sheet melting (Milne and Mitrovica, 2008). Unraveling the complex interactions of the solid earth, the cryosphere, and the oceans has been enabled through a combination of space- and ground-based measurements, including (1) satellite radar altimetry to measure ocean volume change; (2) laser altimetry to measure ice-volume change; (3) temporal variations in gravity (e.g., GRACE) to measure the redistribution of the mass of water (solid and liquid) over the surface of the planet; and (4) GPS to measure the viscoelastic rebound of the solid earth (Lange et al., 2014).

Bare-Earth Topography

The shape of Earth's surface (i.e., its topography: gradient, relief, curvature, convergence) is a catalyst for numerous surface processes, including water and sediment routing, landslide initiation, coastal inundation, and ice-sheet dynamics. Topographic data, like those revealing fault displacements or changes caused by volcanic eruptions, illuminate active tectonic processes and serve as a base upon which many other geophysical measures depend (e.g., InSAR; Pritchard et al., 2004). Over the past two decades increasingly higher resolution digital topography has transformed understanding of controls on the topographic structure of the planet (e.g., Kirby and Whipple, 2012), the way in which watersheds change shape over time (e.g., Willett et al., 2014), and the effect of anthropogenic forcing on coastal subsidence (e.g., Syvitski et al., 2007). Accurate elevation measurements in polar regions have demonstrated that elevation drops as ice-sheet flow accelerates (Pritchard et al., 2009), and have led to the discovery of complex subglacial water-drainage systems (Chu et al., 2016; Smith et al., 2009). Such discoveries depend on both reliable, high-resolution topographic data and repeated acquisitions of such data to document the pace and context of change through time.

At present, 30 m gridded topographic data are available for the globe (Shuttle Radar Topography Mission [SRTM], ASTER). TerraSAR-X Add-on for Digital Elevation Measurement (TanDEM-X) is providing 12 m topographic resolution (global coverage, but limited access), and DigitalGlobe is currently releasing 2-5 m resolution topography. Many of the digital elevation models (DEMs) built from these data have a common shortcoming in vegetated regions: the "topography" commonly more closely mimics the average canopy height than the actual bare-earth surface. Hence, the gravitational stresses at the ground surface owing to the actual surface slopes remain unknown. Airborne lidar can penetrate to the actual ground surface and also measure vegetative (carbon) mass above the ground. It also offers higher resolution than space-based systems—typically, 1 m or smaller. Data collected from airborne lidar have led to the discovery of major fault systems and previously unknown large landslides (Haugerud et al., 2003; Figures 4.9 and 10.6). These data have also illuminated details of surface processes at submeter scales, documented controls on landscape thresholds (e.g., the triggers for gully formation or landslide initiation), and significantly improved quantification and modeling of numerous surface processes that sculpt Earth's surface (Hurst et al., 2013).

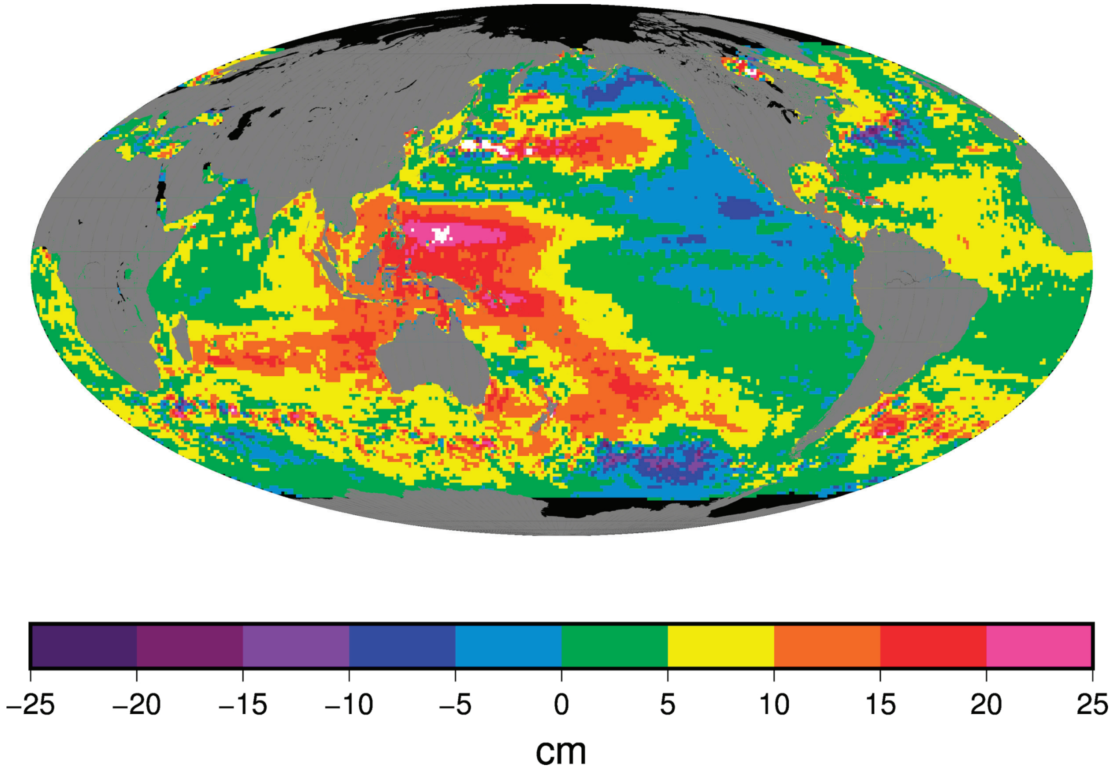


FIGURE 10.5 Sea-level change from January 1993 to December 2014 as measured by the consecutive satellite missions Ocean Topography Experiment (TOPEX)/Poseidon (1993-2002), Jason-1 (2002-2008), and Jason-2 (2008-2014). The global mean change over this period was 7 cm. The larger regional patterns are the result of decadal changes in the winds, ocean circulation, and heat and mass redistribution.

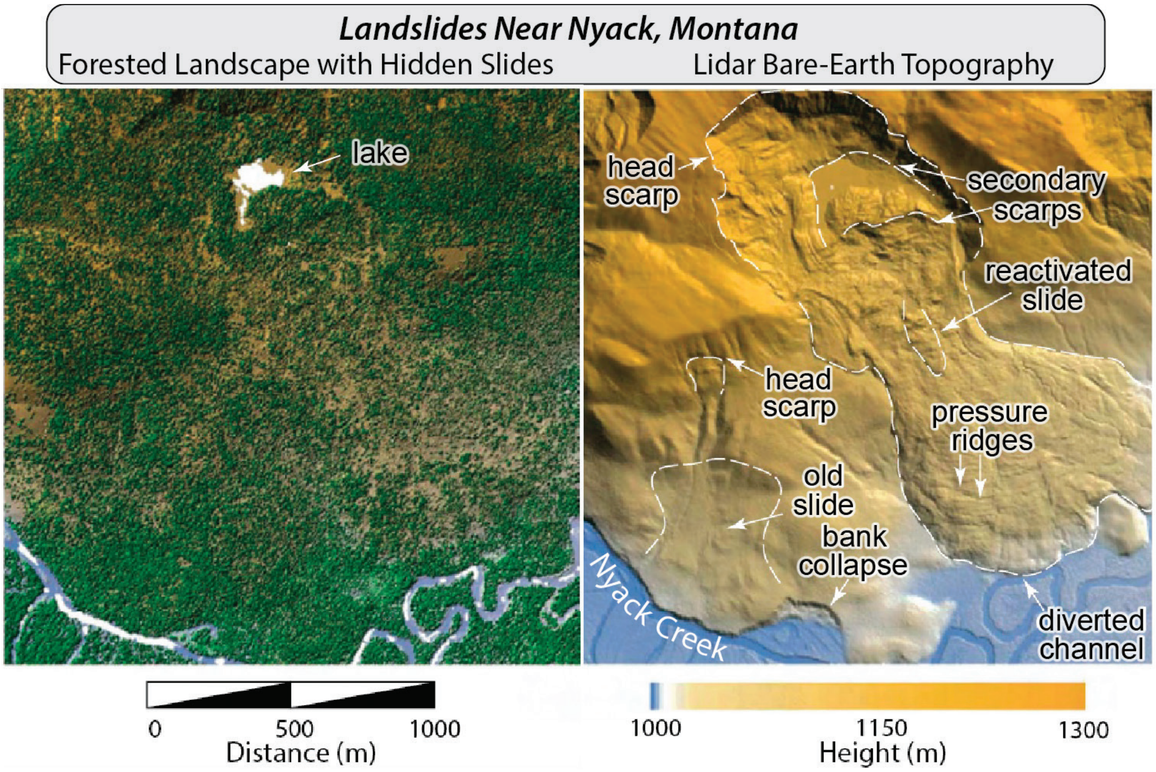


FIGURE 10.6 Discovering landslides, Nyack, Montana: the role of lidar bare-earth topography. *Left panel:* Landsat/GoogleEarth image of the flank of Loneman Mountain. The isolated lake provides a clue to a topography disrupted by landslides. SOURCE: GoogleEarth. *Right panel:* Lidar bare-earth, shaded relief topography exposes multiple generations of landslides with diverse modes of failure and movement, including mass flows, block rotations, and gravitational collapse. Back rotation in the headward area of the large slide ponded drainages and created the upland lake. Removal of vegetation and topographic resolution at ≤1 m reveals nested slides, modes of mass movement, contrasts in surface roughness related to the relative sequence of landsliding, undercutting by and deflection of rivers, reactivation of older slides, and changes of channel geometry owing to base-level changes by landslides. SOURCE: Data provided by Ramesh Shrestha and the National Center for Airborne Laser Mapping.

Vertical Surface Deformation and Mass Change

A new, global perspective on vertical land motion has emerged from the GRACE mission. For example, GRACE data have been used to estimate great earthquake (M>8) source parameters that integrate all of the short-term processes that lead to mass change spanning the coseismic and early postseismic period of days to a month (Han et al., 2013). A unique contribution of GRACE has been the measurement of postseismic gravity change, which has improved characterization of the rheological structure of Earth over a wide range of tectonic settings (e.g., Han et al., 2014). Last, GRACE measurements have provided a regional to global context to interpret the mass changes associated with groundwater depletion in deep aquifers, long-term deformation owing to the loss of ice sheets at the end of the Pleistocene, the shrinkage of many alpine glaciers and lake systems over the past 200 years, and modern ice-sheet melting on temporal scales of days to a decade (Figure 10.7).

Challenges and Opportunities

Priorities for advancing understanding of Earth's surface and interior have been documented in recent studies (Lay et al., 2009; NRC, 2010a, 2010b; NRC, 2012a; Davis et al., 2012, 2016; NASEM, 2017). Those areas for which space-based measurements can make a significant contribution include geologic hazards and forecasts, complex interactions of the critical zone, sea-level change along coastlines, dynamics of Earth's mantle and core, effect of water traveling underground on geologic processes, and energy and mineral resources. These topics are discussed in the following section. Here, we identify challenges and opportunities that influenced the selection and focus of these topics.

Given that more than half of Earth's population lives within reach of major earthquakes, volcanic eruptions, or landslides, advance warning of these events could save lives and change the way society progresses. Advance warning can be within reach if sufficient repeat time of key remote sensing data is used to supplement land-based observations. Constellations offer a promising strategy in the sensor-web

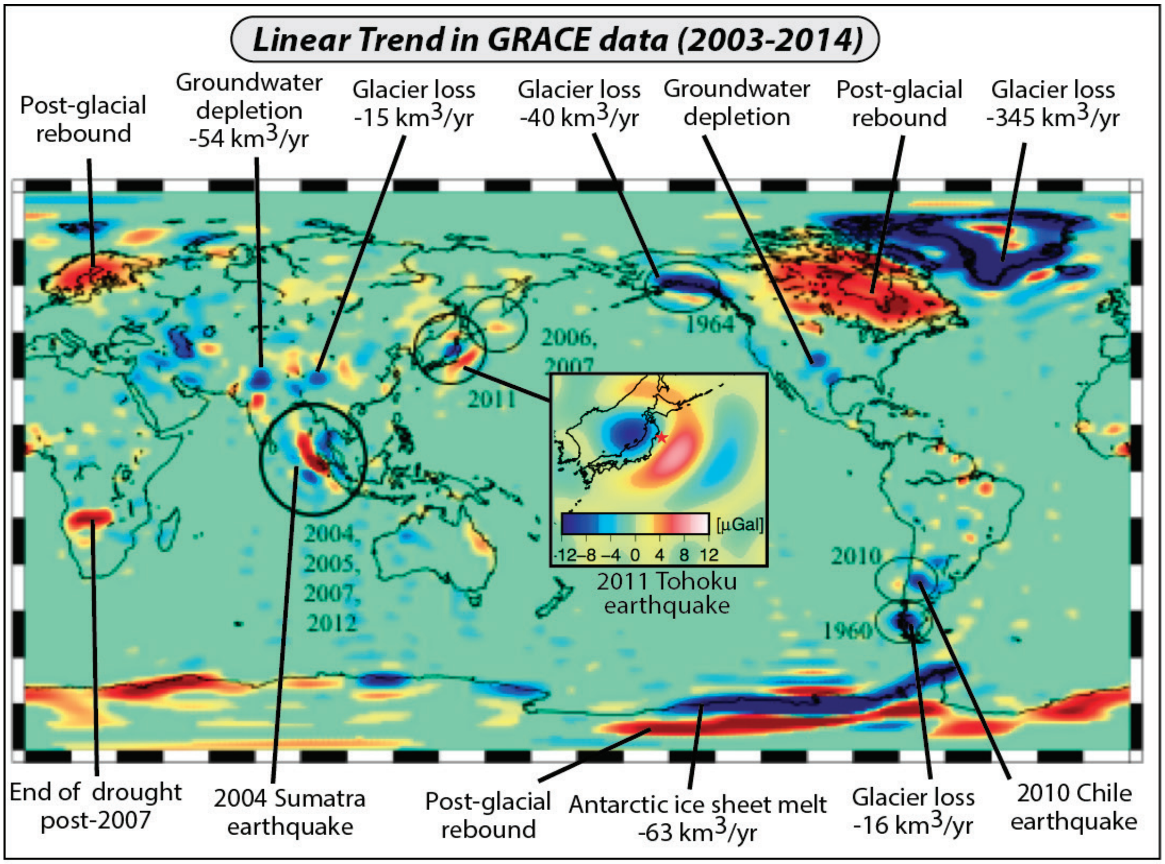


FIGURE 10.7 A decade of gravimetric data from GRACE illustrates decadal trends in mass changes as a response to seismic deformation (years of large earthquakes are shown), as well as to mass loss owing to loss of groundwater, surface water, or ice, and mass gains owing to postglacial crustal rebound, the end of a drought, and increased snow accumulation on parts of existing ice sheets. Inset shows the decadal gravimetric changes owing to the 2011 Tohoku earthquake. SOURCE: Han et al. (2015).

approach. Such systems would integrate (1) surface deformation observations from InSAR, seismic, strain, seafloor geodetic, and GPS/Global Navigation Satellite System (GNSS) observations for earthquakes and volcanic eruptions; (2) high-resolution optical and thermal imaging for volcanic eruptions and wildfire; and (3) topography, vegetation dynamics, weather, and societal infrastructure for forecasting coastal inundation, landslides, floods, debris flows, and major erosion/deposition events. Challenges include increasing data spatial and temporal resolution, improving geolocation accuracy, upgrading download capability, and rapidly processing high-volume, rapid data flow to create high-level data products (e.g., maps). Placing these data products in the hands of decision makers as quickly as possible is important both for anticipating and for responding to devastating events.

Merging “big data” and high-performance computing with community analysis and modeling software has the potential to improve forecasts of natural disasters. For example, advances in experimental and computational models for volcanic processes, combined with enhanced monitoring (e.g., global InSAR data with a repeat time of a few days, spatially and temporally enhanced remote sensing of gas emissions, and ground-monitoring data), would enable model-based forecasting—a paradigm shift for volcano science (NASEM, 2017).

The availability of higher resolution remote sensing data will help drive advances in a wide range of applications. For example, as a result of unconventional hydrocarbon production, Oklahoma has had a higher rate of small to moderate earthquakes than California over the past few years. To understand the mechanics of inducing earthquakes, direct measurement of the ground deformation accompanying both oil and gas production, as well as wastewater injection, is needed. Because industrial activity covers vast tracts and is continually changing, high-resolution satellite measurements (e.g., InSAR and imagery) provide a key tool to monitor activity, identify the triggering process, and manage the induced earthquakes.

Novel insights can be gained from innovative analyses of existing data. For example, vertical positioning data from GPS/GNSS can be used to monitor water changes caused by snowpack, soil moisture, and groundwater variations, whereas reflected signals from GPS/GNSS can be used to estimate soil moisture, snow depth, snow-water equivalent, vegetation, firn density, permafrost changes, and sea level (Box 10.1). Such surface reflections could be particularly valuable for providing inexpensive in situ data on the cryosphere, as well as validation data for spaceborne sensors such as Ice, Cloud, and Land Elevation Satellite-2 (ICESat2), NISAR, and Surface Water and Ocean Topography (SWOT). At present, however, few of these capabilities are exploited using existing GPS networks.

New sensors are needed to achieve the key goals of higher resolution, shorter temporal spacing, and improved accuracy. In particular, applications that require topography would benefit from multibeam, space-based lidar to obtain global coverage of bare-earth topography and of the biomass/canopy at <<5 m spatial and 0.1 m vertical resolutions. Such a capability could substantially reduce the need for directed aircraft surveys. A low-cost InSAR capability with multidecadal duration and the ability to revisit anywhere on Earth within a few days would be invaluable for responding to and monitoring natural hazards and for resolving rapid motion, such as surging glaciers, creep events on faults, temporally persistent landslides, reservoir filling and overtopping, or ice-shelf disintegration. Low-cost hyperspectral imaging sensors with spatial resolution at the sub-50 m scale and revisit times approaching 3-5 days would both continue the multidecadal Landsat record and, more importantly, improve Landsat’s detection and mapping capability. Such a system would allow the capture of higher frequency geological/ecological processes and improve the response to natural disasters. A critical element for all of these is the infrastructure for downloading and processing ever-increasing data streams.

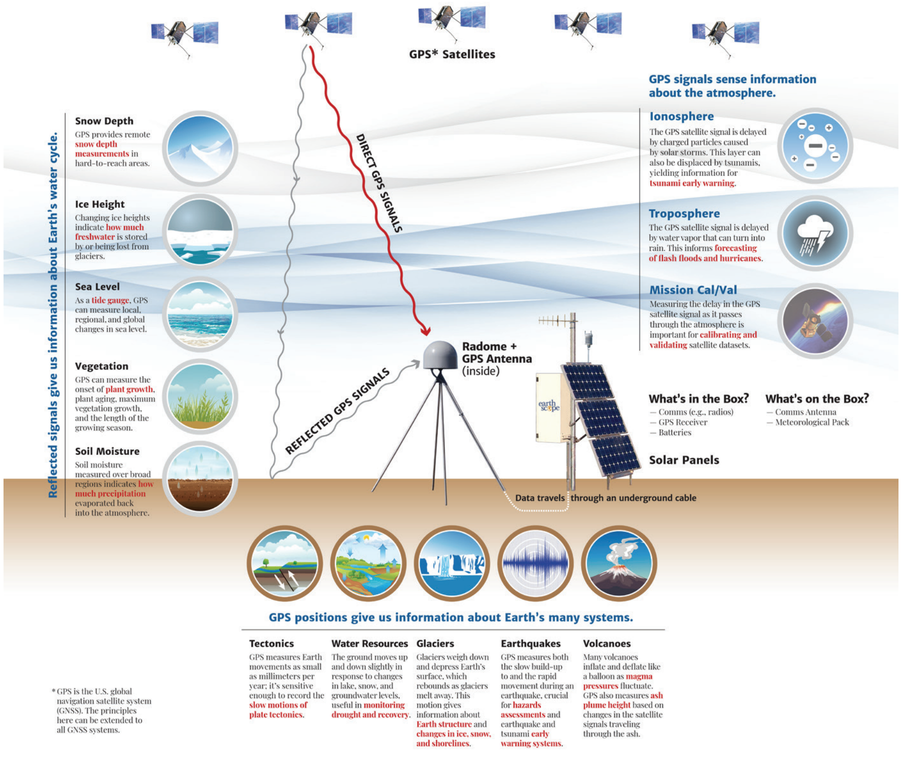
Some useful high-resolution data, especially topography and imagery, collected by private companies or other countries are commonly not available or affordable. For example, scientists have only limited access to 12 m topographic data collected by TanDEM-X, a German mission. If the National Aeronautics and

BOX 10.1 WHAT GPS CAN TELL US ABOUT EARTH

The GPS constellation of satellites, better known for its real-time navigation capabilities, is used both to pinpoint locations on Earth's surface (with precision better than <1 mm) and to calculate the orbits of other satellites or aircraft used to analyze Earth's surface. GPS accurately measures deformation at multiple temporal scales, from plate-boundary deformation and tectonic motions (1-100 mm/yr) to earthquakes (~cm/sec), volcanic inflation/deflation (~cm/hr), and ice-sheet speeds (~m/day). When real-time telemetry is available, GPS data are used in earthquake and tsunami warning systems. GPS is also a key component of the terrestrial reference frame, and on-orbit GPS occultation measurements provide valuable information about atmospheric temperature and humidity.

Additionally, GPS positions can be used to infer changes in water loads (from ice sheets, glaciers, snow, lakes, and soil moisture), as illustrated in Figure 10.1.1. Delays in the GPS signal are used to estimate water vapor in the atmosphere and total electron content. The high temporal sampling of GPS water vapor products is particularly useful for monitoring extreme weather events. Total electron content changes are used both to study the ionosphere and for tsunami forecasting.

In the past decade it has been demonstrated that reflected GPS data can be used to measure key water cycle data, including surface soil moisture, snow depth, vegetation-water content, firn density, sea-ice formation, permafrost changes, and coastal sea level. Such data are based on signals that reflect from the land surface lying below the GPS antenna and sense a larger area (1000 m^2) than most in situ sensors. Notably, because of the ubiquitous availability of GPS/GNSS data (>14,000 sites with public data streams), many of these new environmental products can be calculated for very low cost. At present, however, few of these sites are utilized to yield such high-value water cycle data.



Snow Depth GPS provides remote snow depth measurements in hard-to-reach areas.

Ice Height Changing ice heights indicate how much freshwater is stored by or being lost from glaciers.

Sea Level As a tide gauge, GPS can measure local, regional, and global changes in sea level.

Vegetation GPS can measure the onset of plant growth, plant aging, maximum vegetation growth, and the length of the growing season.

Soil Moisture Soil moisture measured over broad regions indicates how much precipitation evaporated back into the atmosphere.

Ionosphere The GPS satellite signal is delayed by charged particles caused by solar storms. This layer can also be displaced by tsunamis, yielding information for tsunami early warning.

Troposphere The GPS satellite signal is delayed by water vapor that can turn into rain. This informs forecasting of flash floods and hurricanes.

Mission Cal/Val Measuring the delay in the GPS satellite signal as it passes through the atmosphere is important for calibrating and validating satellite datasets.

What's in the Box?
— Comms (e.g., radios)
— GPS Receiver
— Batteries

What's on the Box?
— Comms Antenna
— Meteorological Pack

Tectonics GPS measures Earth movements as small as millimeters per year; it's sensitive enough to record the slow motions of plate tectonics.

Water Resources The ground moves up and down slightly in response to changes in lake, snow, and groundwater levels, useful in monitoring drought and recovery.

Glaciers Glaciers weigh down and depress Earth's surface, which rebounds as glaciers melt away. This motion gives information about Earth structure and changes in ice, snow, and shorelines.

Earthquakes GPS measures both the slow build-up to and the rapid movement during an earthquake, crucial for hazards assessments and earthquake and tsunami early warning systems.

Volcanoes Many volcanoes inflate and deflate like a balloon as magma pressures fluctuate. GPS also measures ash plume height based on changes in the satellite signals traveling through the ash.

*GPS is the U.S. global navigation satellite system (GNSS). The principles here can be extended to all GNSS systems.

FIGURE 10.1.1 Ground-based GPS receivers play an important role in Earth science. GPS receivers precisely measure the latitude, longitude, and height of the receiver—information that is used for tectonic, volcano, and earthquake applications. Atmospheric researchers use the delays on the GPS signals to infer tropospheric water vapor and total electron content in the ionosphere. Reflected GPS signals can be used to measure soil moisture, snow depth, vegetation water content, and sea level. SOURCE: Courtesy of UNAVCO.

Space Administration (NASA) cannot gain access to these data for the research community, a TanDEM-like follow-on mission could be important to achieve the needed accuracy and resolution. Likewise, most high-resolution (<2 m) optical imagery is being provided by the commercial sector. Rather than developing this capability, NASA and the U.S. Geological Survey (USGS) could negotiate data agreements with the National Geospatial-Intelligence Agency (NGA) to satisfy research objectives. Such agreements will need to include specific requirements for subpixel geolocation accuracy.

Given cost considerations, miniaturization using CubeSats, SmallSats, and satellite constellations could be an efficient pathway to technological development. Particularly promising are (1) a miniaturized time-variable gravity mission with higher spatial resolution (100-150 km or less) that can reduce the aliasing of the measurements that results from high-frequency (<10 days) atmospheric, oceanic, or hydrospheric mass variations; and (2) miniaturized vector magnetometry systems with sufficient accuracy and cadence to separate time variations in the internal field from those in the external field.

Last, a key challenge is maintaining an accurate global terrestrial reference frame—one that provides the essential framework for positioning scientific satellites and aircraft, and also underpins our modern technology and commerce infrastructure. Maintaining the reference frame to a positional accuracy of 1 mm and a rate accuracy of 0.1 mm/yr requires NASA's continued participation and support of VLBI and SLR for defining the terrestrial reference frame and its changes with time, and for monitoring Earth rotation (Davis et al., 2016). It also requires support for the GPS/GNSS global tracking network and maintenance of the software. The challenge is fivefold: (1) maintaining global participation and funding support with other agencies/countries; (2) increasing capacity; (3) lowering cost; (4) upgrading older sites (some VLBI/SLR instruments are more than 30 years old): and (5) improving real-time capabilities for GPS/GNSS.

PRIORITIZED SCIENCE OBJECTIVES AND ENABLING MEASUREMENTS

This section describes the panel's science questions, objectives, and measurements, which are summarized in the Science and Applications Traceability Matrix in Appendix B.

Science Questions and Objectives

Question S-1: How can large-scale geological hazards be accurately forecast in a societally relevant time frame?

Over the past century and, in particular, over the past decade, geological disasters—earthquakes, tsunamis, volcanic eruptions, and landslides—have taken a deadly and costly toll on society. For example, the 2004 M9.2 megathrust earthquake in Sumatra produced a tsunami that killed more than 230,000 people in coastal areas surrounding the Indian Ocean. The 2010 Eyjafjallajökull volcanic eruption in Iceland shut down air traffic in Northern Europe, causing an estimated $5 billion loss to the global economy. The 2011 M9.0 Tohoku earthquake and tsunami in Japan (see Figure 10.1) was the costliest natural disaster in world history ($309 billion) and also transformed our understanding of the safety of coastal nuclear power generation. Threats of this scale in the United States occur in the Pacific Northwest (last major earthquake in 1700 and last major volcanic eruption in 1980), Alaska-Aleutian subduction zones (last great [M9.2] earthquake in 1964), and San Andreas Fault system (last major earthquakes in 1857 and 1906).

Accurate forecasts of the types of events and their timing can reduce adverse impacts on life and property. However, such forecasts remain a major scientific challenge. Some volcanoes erupt with little to no warning, whereas others produce months of interpretable precursors (e.g., NASEM, 2017). For example, the 1980 Mount St. Helens eruption (Figure 10.8) was preceded by 2 months of earthquakes, volcanic steam releases, and large-scale surface deformation, which enabled warnings and limited evacuations (Lipman and Mullineaux, 1981), although the timing, directionality, and scale of the eruption was not anticipated. Some catastrophic landslides are triggered by seismic shaking or huge storms, whereas as others lack clear triggers. The M9.0 Tohoku earthquake and a number of other recent large events were preceded by a sequence of seismic and aseismic precursors, but short-term forecasts of earthquakes are not yet in reach. Progress will be made by continuously observing areas prone to earthquakes, volcanic eruptions, or landslides. A broad array of processes need to be observed to successfully capture events. Advances from the last decade of space-based measurements suggest that scientists are on the verge of a breakthrough in natural hazards research if a strategic set of observations are taken now.

Objective S-1a: Measure the pre-, syn- and posteruption surface deformation and products of Earth's entire active land volcano inventory with a time scale of days to weeks.

- *Priority—Most Important:* Volcanic eruptions are likely to pose an increasing threat as more people move to coasts along subduction zones, where most volcanoes occur. A combination of ground-based and space-based observations are needed to monitor volcanoes and forecast eruptions. Space-based observations provide a means to collect data on all volcanoes, and may be the only practical avenue for collecting data in remote or dangerous areas. Systematic monitoring has led to accurate forecasts of the timing and duration of some eruptions.
- *Relevant quantities:* Three quantities need to be measured and monitored. The first is the changing shape of the volcano measured using InSAR. Expansion or contraction of the summit region provides an estimate of the changing magma supply volume and depth beneath the volcano, and larger

FIGURE 10.8 Eruption of Mount St. Helens on May 18, 1980. The eruption was the most disastrous in U.S. history, killing 57 people—most outside the evacuation area—and causing $1.1 billion in damages. SOURCE: U.S. Geological Survey.

scale deformation is linked to deeper magma supply. The second quantity is the composition and quantity of the gas emitted prior to and during an eruption as well as the composition of any ash, which provide insight into the drivers and intensity of eruptions. Hyperspectral UV, near infrared, and TIR data are used to measure SO_2, H_2S, CO_2, and ash emissions; and spaceborne lidar and radar are used to estimate plume altitude. The third is the temperature of the ground/lake surfaces to observe shallower changes as the magma reaches the uppermost plumbing system prior to an eruption. Thermal measurements are made using multi- to hyperspectral data spanning the visible to shortwave infrared (VSWIR) and TIR region, depending on the temperature of the surface, but high-quality TIR data are critical for detecting the small-scale temperature changes of the surface leading up to an eruption (Figure 10.9).

- *Length and time scales over which responses should be quantified:* Changes in SO_2, CO_2, and other gas emission rates (e.g., Carn et al., 2016) and in ground temperature (Figure 10.9) have been detected from space weeks to months prior to an eruption. Variations in these parameters occur at a much higher frequency as the eruption proceeds, and require much improved temporal observations (e.g., minutes) at spatial scales small enough to enable modeling. Detectable changes in volcano shape, gas emissions, and thermal output prior to a new eruption event occur over time scales ranging from months to minutes. The relevant length scales are 10 m to 200 km for surface and plume measurements, with most shape changes occurring over length scales greater than 1 km. The necessary vertical precision (1-10 mm) and the temporal frequency need to be adjusted to match the activity of a particular volcano. High-repeat/temporal frequency (e.g., hours to days) image-derived/compositional analysis is critical to capture transient behavior in an ongoing eruption and to model the vent-scale processes.

Objective S-1b: Measure and forecast interseismic, preseismic, coseismic, and postseismic activity over tectonically active areas on time scales ranging from hours to decades.

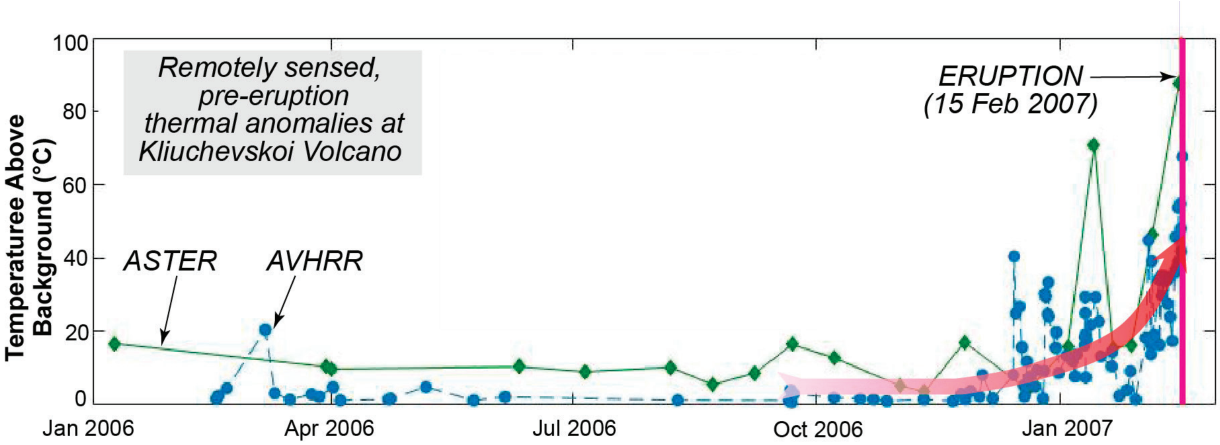
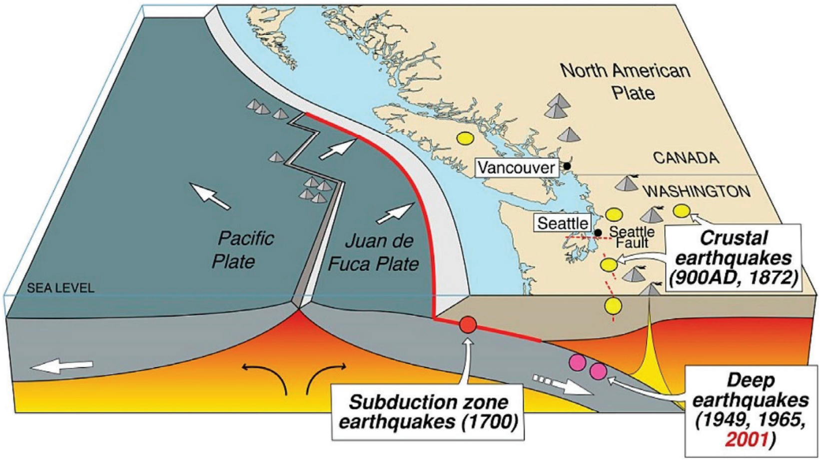


FIGURE 10.9 Temperature variations at Kliuchevskoi volcano from January 2006 to February 2007, when the eruption occurred (red line). ASTER detected persistently elevated temperatures as early as 11 months prior to the eruption owing to its thermal sensitivity and its higher spatial resolution (90 m/pixel) in comparison to Advanced Very High Resolution Radiometer (AVHRR; 1 km/pixel), which did not detect elevated temperatures until 2 months before the eruption. SOURCE: Modified from Reath et al. (2016).

- *Priority—Most Important:* GPS measurements of surface deformation reveal that earthquake cycles contain much richer behavior than previously thought. For example, the Cascadia subduction zone fault is accumulating elastic energy that will eventually be released in a catastrophic earthquake offshore Washington and Oregon (Figure 10.10). Over the past decade space-based measurements have revealed that this steady strain accumulation is punctuated by creep events that occur at the down-dip limit of the locked fault. Similar transient slip behavior has been observed at most megathrust earthquake zones globally, as well as around the locked zones of the San Andreas fault system. Measuring the details of these transients over time scales of days and years may provide insight into the physics of the earthquake cycle and ultimately support forecasts of the timing of a major rupture on socially relevant time scales.
- *Relevant quantities:* Four main types of measurements are needed. The first is related to the interseismic crustal deformation surrounding a locked fault. InSAR and GPS measurements will reveal the rate of stress accumulation that will be released by future earthquakes. The length of time since the last rupture multiplied by the rate of interseismic crustal deformation can be used to assess the magnitude and probability of the occurrence of earthquakes. Terrestrial measurements from seismometers and GPS will provide the high temporal sampling needed to observe co- and postseismic deformation and ground shaking. Space-based InSAR and high-resolution optical imagery will provide the high spatial resolution needed to observe the near-fault co- and postseismic deformation. For very large earthquakes, temporal variations in gravity can reveal large-scale offshore deformation not observable by other methods. Last, high-resolution bare-earth topography along areas of surface rupture can be used with surface dating methods to decipher the rupture history of a fault over many earthquake cycles.
- *Length and time scales over which responses should be quantified:* Surface deformation associated with the earthquake cycle occurs over spatial scales ranging from meters to thousands of kilometers and time scales ranging from seconds to thousands of years. The relevant deformation scales observable from spaceborne radar interferometry range from 10 m to 1000 km. Interseismic motion needs to be measured to a precision of 1 mm/yr over lengths scales of 10 m to 100 km. Particularly critical are measurements of slow slip events (e.g., Figure 10.10) at resolution of 1 mm/week over scale of tens of kilometers. Co- and postseismic processes require frequent acquisitions (12 days or shorter) over seismically active areas. High-resolution bare-earth topography needs to be measured only once before an event at 5 m spatial resolution and 1 m vertical accuracy for topographic correction of interferograms as well as for paleoseismic studies. Investigation of near-fault coseismic processes requires optical or SAR measurements of surface fractures at a spatial resolution of ~1-10 m from satellites or aircraft.

Objective S-1c: Forecast and monitor landslides, especially those near population centers.

- *Priority—Very Important:* Landslides typically affect fewer people than large-scale volcanic eruptions and earthquakes, yet they regularly cost lives and disrupt economies. Sudden landslides can be triggered by heavy precipitation, earthquakes, or volcanic eruptions. Steep slopes are the most important factor in making an area susceptible to landslides, but other key factors include recent rainfall or wildfire, seismicity and the presence of nearby faults, the strength of bedrock and soils, deforestation, and the presence of roads. Landslide susceptibility has been mapped using space-based data (Figure 10.11), and an online tool, Landslide Hazard Assessment Model for Situational Awareness, has been developed that identifies areas with high or moderate landslide probability every 30 minutes based on the preceding 7 days of precipitation using the Global Precipitation



	Source	Affected area	Max. Size	Recurrence
●	Subduction Zone	W.WA, OR, CA	M 9	500-600 yr
●	Deep Juan de Fuca plate	W.WA, OR	M 7+	30-50 yr
●	Crustal faults	WA, OR, CA	M 7+	Hundreds of yr?

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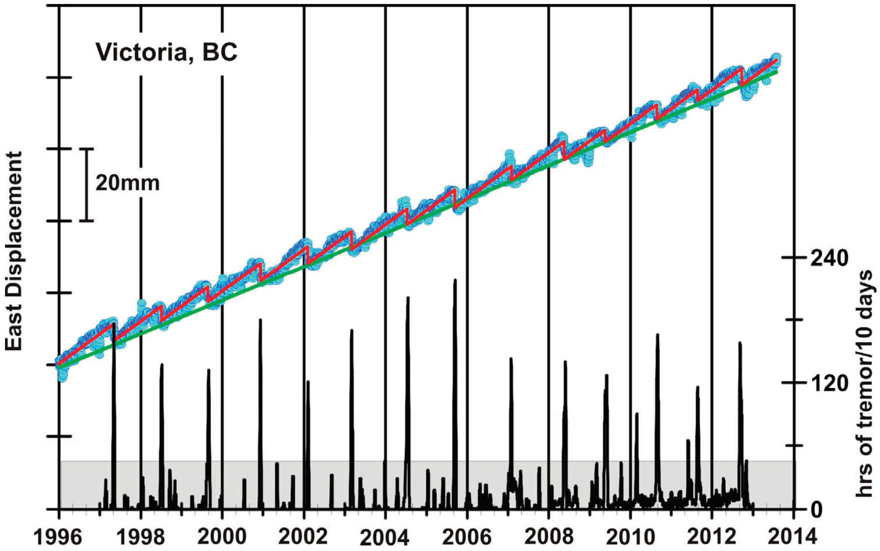

FIGURE 10.10 *Upper panel:* Cascadia subduction zone is accumulating seismic energy between the surface and about 40 km deep. The last rupture in 1700 caused 2 m of subsidence along the Washington shoreline and generated a large tsunami that impacted the entire Pacific Basin. SOURCE: USGS. *Lower panel:* GPS and seismicity measurements at station ALBH over the past 18 years shows the gradual accumulation of stress on the fault that is punctuated with slow slip events at 14-month intervals. This episodic tremor and slip occurs at the expected nucleation site of a major earthquake, and so understanding the phenomena will aid in earthquake forecasting. SOURCE: Personal communication, H. Dragert, Geological Survey of Canada, March 2017.

Measurement estimates. An important objective is to detect and monitor slow-moving landslides and to shorten forecasts of sudden collapse events (e.g., rapidly moving slides) in order to warn and evacuate local populations.

- *Relevant quantities:* The important quantities to be measured are high-resolution, bare-earth topography; land-surface deformation; precipitation; and permafrost melt, combined with hyperspectral imaging of vegetation and rock/soil composition to improve and augment existing high spatial resolution land-cover data.
- *Length and time scales over which responses should be quantified:* The relevant length scales range from meters to tens of km, and time scales range from seconds to years. High-resolution, bare-earth topography at 1-5 m spatial resolution and 0.1 m vertical precision is needed over all potential landslide areas to establish a baseline. Subsequently, more frequently acquired data are required prior to a suspected slide event and then following its occurrence. Land-surface deformation is needed at better than 50 m spatial resolution, and 1 mm/yr precision at a better than seasonal cadence for slow-moving landslides. Hyperspectral imaging in the VSWIR and TIR regions at ~30 m spatial scale and ~weekly time scale is required to map land-cover composition and changes. High spatial resolution images from commercial sources are ideal for linking topography to land cover and eventually for mapping composition from space.

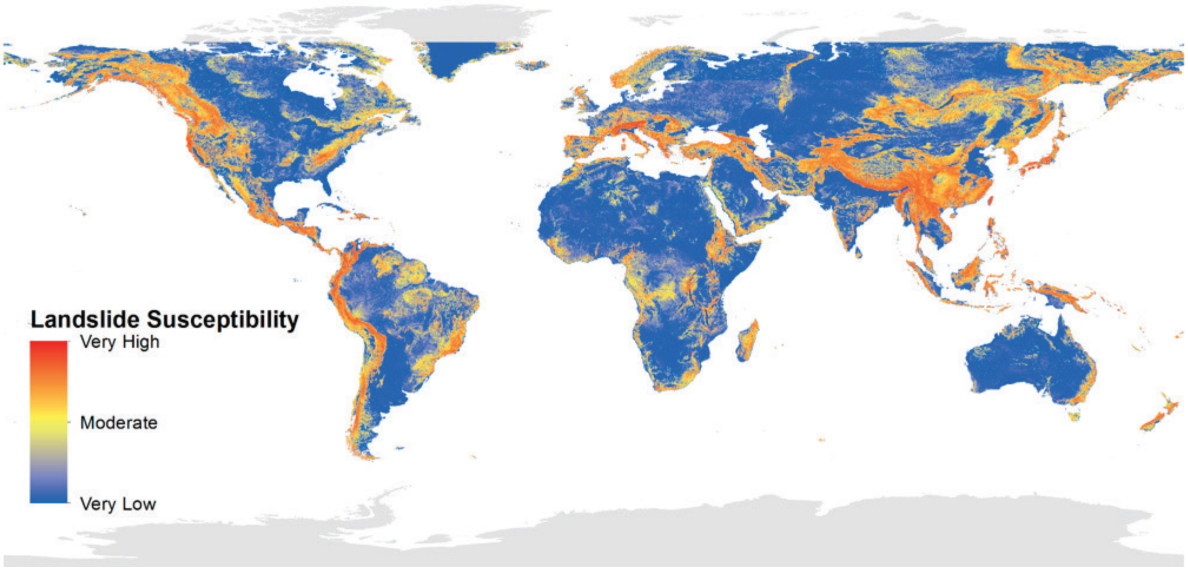

FIGURE 10.11 Global landslide susceptibility map developed using topography data from the Shuttle Radar Topography Mission (SRTM), forest loss information from Landsat, and other geophysical variables. SOURCE: Stanley and Kirschbaum (2017).

Objective S-1d: Forecast, model, and measure tsunami generation, propagation, and run-up for major seafloor events.

- *Priority—Important:* Tsunamis are one of the most destructive hazards on Earth, yet satellites are only peripheral in monitoring their generation and propagation. Mapping ionospheric waves has recently provided some limited information on tsunami propagation. Improved models of the shape of the seafloor as well as high-resolution coastal topography are critically needed to improve modeling of tsunami run-up and its impact on coastal populations. The topography of the deep ocean floor (>1,000 m) affects the overall velocity, focusing, and amplitude of the wave as it propagates across an ocean basin. The detailed topography of the shallow ocean floor (<1,000 m) and coastal areas affects the velocity, amplitude, and inundation of the wave as it flows over the land.
- *Relevant quantities:* Key measurements are in situ seismicity, ground deformation via GPS, and seafloor pressure changes. The most important contribution from a space or aircraft mission is high-resolution (1 m spatial and 0.1 m vertical), bare-earth topography and bathymetry of coastal areas, which requires aircraft-based lidar and improved seafloor mapping. The large-scale bathymetry of the deep oceans is provided by sparse ship soundings (17 percent of the seafloor is mapped at <1 km resolution) and dense satellite altimeter measurements of the gravity field associated with seafloor bathymetry (83 percent of the seafloor is mapped at 6 km spatial resolution). New swath altimetry technology, such as the planned SWOT mission, could dramatically increase the accuracy and resolution of the global bathymetry.

  Satellite altimetry profiles can also provide open-ocean measurements of the tsunami wave that are important for modeling source and propagation effects. Similarly, high spatial resolution measurements of the total electron content of the ionosphere provide a means to indirectly map tsunamis. To provide useful results, the altimeter or GPS array has to be in the right place at the right time.
- *Length and time scales over which responses should be quantified:* The bathymetry and topography only need to be measured once, followed by repeat measurements after a significant change.

Linkages of S-1 Objectives to Other Panels and Integrating Themes

Extreme events like volcanic eruptions, earthquakes, tsunamis, and large landslides can have spatially extensive consequences on hydrology, ecology, weather, climate, and human habitability. Such events commonly damage or destroy infrastructure, disrupt ecological patterns, rearrange drainage networks, and abruptly alter the biogeochemistry, nutrient fluxes, water budget, and energy balance in affected areas. Hence, they bridge numerous integrating themes and panel objectives. Volcanic eruptions spread ash and nutrients that impact local ecology (Ecology Objective E-2c) and alter both water (Hydrology Objective H-3b) and air quality. Directed volcanic blasts and effusive eruptions can cause localized but catastrophic ecological change (Ecology Objective E-5b) and widespread infrastructure damage. At scales of weeks to months, large, persistent volcanic eruptions affect local weather and precipitation patterns (Climate Objectives C-5a, C-5d, and C-7b; Weather Objectives W-5a and W-6a). At scales of minutes, earthquakes, tsunamis, and landslides abruptly and, typically, nonreversibly alter landscapes, ecological communities, hydrologic systems, and both energy and nutrient fluxes. All of these “extreme events” commonly have large impacts on nearby communities and infrastructure, and potentially affect distant sites (e.g., as volcanic plumes intercept airline routes). The panel’s forecasting emphasis for these extreme events relies in part on identifying thresholds or triggers related to other panels’ objectives: exceedance thresholds for rainfall that trigger landslides; particulate fluxes from volcanos that effectively alter weather or climate patterns and nutrient availability; scales of landslides or volcanic eruptions that significantly disrupt local ecology or hydrology; and coastal and shallow-marine topography that, when combined with seafloor earthquake ruptures, determines tsunami impacts on coastal ecology, hydrology, and infrastructure.

Question S-2: How do geological disasters directly impact the Earth system and society following an event?

Large geological disasters, such as those discussed earlier, can have major impacts on the Earth system and society. Satellites can see affected areas and collect data at spatial scales needed to assess the impacts during and following a disaster, but only if relevant assets are deployed in a timely manner. Examples of satellite-based emergency mapping of hydrometeorological, geophysical, and biologic disasters are shown in Figure 10.12.

Objective S-2a: Rapidly capture the transient processes following disasters for improved predictive modeling, as well as response and mitigation through optimal retasking and analysis of space data.

- *Priority—Most Important:* Rapid capture and delivery of synoptic data by spaceborne assets following a disaster can directly mitigate the loss of life and infrastructure. These data can be obtained by rapidly retasking existing satellites, deploying new satellites dedicated to a specific measurement objective, or by deploying a constellation of future satellites that provide the temporal fidelity required. The International Charter "Space and Natural Disasters" was developed by space-faring nations to reschedule their satellites to observe regions struck by a disaster and to deliver those data to the decision makers in that region. An example of the international response to the 2015 earthquakes and landslides in Nepal is shown in Figure 10.13.
- *Relevant quantities:* The relevant quantities are largely defined by the disaster and available space assets. High-resolution optical (<5 m) and SAR (<30 m) image data can provide information on the magnitude and extent of damage in the affected areas. Repeated InSAR and high-resolution optical data can provide information on both the magnitude of the ground motion and the decorrelated regions where a majority of the infrastructure may be damaged. Hyperspectral UV through TIR data are especially valuable for monitoring ongoing changes in the temperature, composition, and extent of erupted volcanic materials, including gases, as well as constraining forecasts of the duration of the activity. High-resolution topography enables quantified assessments of landscape change owing to erosion, deposition, and vegetation disturbance. An important objective for all of these data is the rapid dissemination of higher level products to local emergency responders and the global scientific community.
- *Length and time scales over which responses should be quantified:* The scales are dictated by the extent and duration of the disaster. Inundation from flooding (or tsunamis) and the associated erosion/deposition can persist for days to weeks. In the case of the 2015 Nepal earthquakes (see Figure 10.2), satellite remote sensing information was most valuable when delivered to the remote mountainous areas in hours to days (Figure 10.13). However, the threats from additional large aftershocks may persist for months to years following an event. Volcanic eruptions and their secondary hazards (e.g., lahars, remobilization of ash) can last hours to decades.

Objective S-2b: Assess surface deformation (<10 mm), extent of surface change (<100 m spatial resolution) and atmospheric contamination, and the composition and temperature of volcanic products following a volcanic eruption (hourly to daily temporal sampling).

- *Priority—Very Important:* Active volcanoes can erupt intermittently or continuously for decades or more. Consequently, ongoing data collection is required to determine whether the eruption is waning, increasing, or transitioning to a new phase. These synoptic data of the estimated 1,500

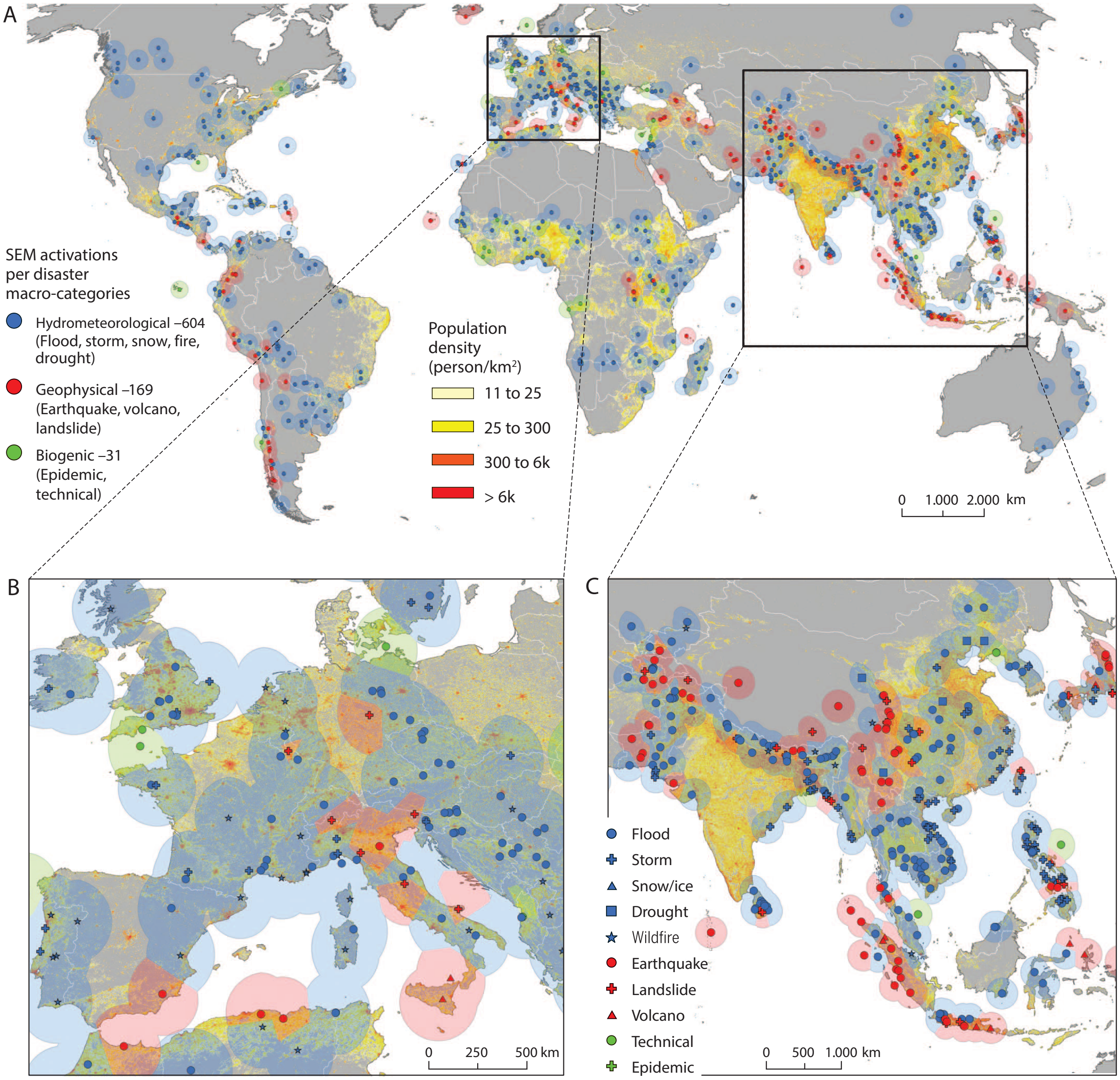

FIGURE 10.12 Recent satellite-based emergency mapping (SEM) activations at the global level (A) and regional level (B and C). Disaster categories are (1) hydrometeorological, including flood, storm, snow, wildfire, and drought events (blue symbols); (2) geophysical, including earthquake, volcano, and landslide events (red symbols); and (3) biogenic, including epidemic outbreaks and technical accidents (green symbols). Polygons highlight clustering of activations for the various disaster categories. All three panels show population density in the background. SOURCE: Voigt et al. (2016).

FIGURE 10.13 Repeated acquisitions of high-resolution optical imagery provided details on destroyed buildings and other infrastructure following the 2015 M7.8 Nepal earthquake. The earthquake destroyed centuries-old buildings, killed nearly 9,000 people, and left hundreds of thousands homeless. The shaking also triggered numerous landslides, which contributed to widespread destruction of many small villages. The International Charter "Space and Natural Disasters" was invoked to enable space agencies to target space acquisitions in the damaged areas. SOURCE: Pleiades image, European Commission-Copernicus Emergency Management Service.

active volcanoes around the world can be provided only by spaceborne assets, most critically for those that lie in remote locations and in poorer countries. For example, the 2012-2013 eruption at Tolbachik Volcano in Kamchatka (Russia) triggered a response in the Earth Observing Mission-1 (EO-1) and ASTER sensor webs and led to the acquisition of high spatial resolution image data for the next 6 months of the eruption. Heat flow measured in the SWIR and TIR during the development of one of the largest lava flow fields in the last 50 years, combined with digital elevation models, constrained models of future lava flows.

- *Relevant quantities:* The primary quantities are land-surface deformation; volume, composition and temperature of the eruptive products, including gases (especially SO_2 and CO_2); and mass and energy fluxes across the solid earth/atmospheric boundary. Changes in the color of volcanic lakes and the health of nearby ecosystems over time can signal changes in the flux or species of degassing, which are critical to detect both prior to and following an eruption.
- *Length and time scales over which responses should be quantified:* The data scales (spatial, spectral, temporal) and wavelength region required are directly related to the measured volcanic property. Volcanoes with persistent plumes and those in persistently cloudy regions are best imaged by SAR backscatter data at spatial scales ~30 m or better, which can provide ongoing observations of changes in the active vent and erupted lava. UV, VSWIR, and TIR multi- to hyperspectral data observations (both day and night) at ~30 m or better are effective in regions with less cloud cover, and measure the heat flow and abundance of gas in the column, the composition and particle size of ash in persistent and passive plumes, as well as the land cover and ecosystem changes near the volcano. Consis-

tent measurements at time scales no longer than 1-3 days throughout the posteruption period are required. Data acquired at even higher frequencies are essential for hazard mitigation (e.g., aircraft interactions with drifting ash clouds, lava/ash flow inundation) and also enable modeling of higher frequency processes, such as changes in lava and gas production, which are directly linked to the underlying magmatic system driving the eruptive activity. Repeat pass InSAR data at spatial scales ~30 m or better and time scales of 1-2 weeks are critical for measuring the inflation or deflation in the volcanic edifice following the eruption, which can signal new or renewed activity. Such data have been used to measure changes in the eruptive products over time (e.g., the cooling deflation of a lava flow), with the decorrelated areas indicating the location of newly emplaced products. To maximize their utility to society, all of these space-based observations need to be rapidly downlinked following acquisition.

Objective S-2c: Assess co- and postseismic ground deformation (spatial resolution of 100 m and an accuracy of 10 mm) and damage to infrastructure following an earthquake.

- *Priority—Very Important:* Monitoring the ground motion following a large earthquake would improve understanding of how the crust accommodates the stresses imposed through a combination of continued slip on faults, viscoelastic relaxation, and flow of crustal fluids. Identifying the correct mechanism for relaxation is critical for understanding how a fault heals and prepares for the next event. Coseismic models based on GPS, InSAR, seismic waves, and high-resolution optical imagery are used to estimate the immediate change in crustal stress surrounding the rupture zone. Frequent and accurate measurements of postseismic deformation will reveal the rheological properties of the crust and upper mantle. More importantly, measuring the evolution of the deformation after an earthquake provides a window into stress increases on surrounding faults. High spatial resolution optical difference maps as well as InSAR decorrelation maps can be used to identify areas of destroyed infrastructure associated with coseismic events.
- *Relevant quantities:* The relevant quantities to be measured are similar to the quantities need for Objective S-1b. These are crustal deformation surrounding the fault from InSAR, seismometers, and GPS; temporal variations in gravity, which can reveal large-scale offshore deformation not observable by other methods; and high-resolution, bare-earth topography, which can reveal the repeated deformations over many earthquake cycles.
- *Length and time scales over which responses should be quantified:* Postseismic processes are strongest immediately following an earthquake and typically decay logarithmically with time. In the first days to weeks following a rupture, the near-field (ideally <100 km from the fault plane) crustal deformation measurements will need to be acquired continuously with ground GPS and at least weekly with InSAR from at least two look directions. Over the time period of 6 months to 10 years following a major rupture, far-field (100-500 km from the fault) and synoptic gravity measurements become more important for monitoring viscoelastic processes.

Linkages of S-2 Objectives to Other Panels and Integrating Themes

Responses to disruptive, extreme geological events like earthquakes or volcanic eruptions require both rapid quantification of event characteristics and timely dissemination of those data. Efficient and accurate observation and prompt communication are critical ingredients underpinning effective societal responses. Weather forecasters, climate modelers, and air-traffic controllers improve their predictions by incorporating fluxes of volcanic gases and aerosols into their models (Weather Objectives W-5a and W-6a). The same space-based sensors for aerosols and gasses are proposed by the Climate Panel and this panel. Accurate forecasts of intense storms (Weather Objectives W-2a and W-4a) improve preparedness and response for landslides, flooding, and hillslope, river, and coastal erosion. Holistic assessment of the effects of earthquakes, volcanic eruptions, or tsunamis (e.g., spatial extent and character of infrastructure damage; fragility of residual infrastructure; landslide size, spatial frequency, and characteristics of affected slopes, ecology, and hydrology; and inundation or dam failures) enables effective emergency responses to these extreme events. Topographic characteristics, coupled with better understanding of long-term, ongoing ecological and hydrological change (Ecology Objectives E-1b and E-1d; Hydrology Question H-4), enables improved prediction of the impact of extreme events, including estimates of hillslope stability, vulnerability to erosion, and both estimation and development of mitigation strategies for fluxes of sediment, water, and contaminants.

Question S-3: How will local sea level change along coastlines around the world in the next decade to century?

Over Earth's history, sea level has fallen during glacial periods, when seawater is transferred to the continents and stored as ice, and risen during intervals of warm global temperatures (interglacial periods). During the last Glacial Maximum (26,000 years ago), sea level was approximately 125 m lower than it is today (Peltier and Fairbanks, 2006). During one of the warmest periods in Earth's history (100 million years ago), the North American continent was split by a vast seaway created by a combination of sea-level rise and tectonically induced subsidence. Global sea level has risen an average of 1.7 mm/yr over the past century, and 3.2 mm/yr from 1993 to 2010 (Church et al., 2013). Sea-level rise over the next several decades is a major concern for society at large. Whereas the coastal zone represents just 2 percent of Earth's total land area, it generates more than 10 percent of the world's gross domestic product, and ~600 million people are coastal dwellers. Even moderate sea-level rise over the next century will lead to significant increases in coastal flooding and storm surge, as well as saltwater intrusion into aquifers.

Although a number of missions measuring aspects of sea-level rise are flying or are in development (e.g., Jason-3, SWOT, GRACE-FO, ICESat-2), several important geophysical observables are not being adequately measured. These include observations of (1) vertical land motion, (2) ice-sheet and glacier-surface melt (the first-order product of the warming atmosphere), and (3) the location and properties of the base of the ice sheet (i.e., bedrock topography and seawater intrusion). Lack of knowledge of these important parameters continues to hamper our ability to project future sea-level rise.

Objective S-3a: Quantify the rates of sea-level change and its driving processes at global, regional, and local scales, with uncertainty <0.1 mm/yr for global mean sea-level equivalent[2] and <0.5 mm/yr sea-level equivalent at resolution of 10 km.

- *Priority—Most Important:* Sea-level change arises from a combination of ocean volume changes (thermal expansion or contraction of seawater), mass input from the cryosphere, ocean and atmosphere dynamics, gravitational changes, and vertical land motion. The global ice sheets contain the greatest potential for rapid sea-level rise in the coming decades. Over the decade from January 2005 to December 2014, ice sheets and other glaciers contributed approximately 70 percent to

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[2] Current altimetry missions, such as Jason-3, have a mission goal of 1 mm/yr, in order to accommodate the inherent measurement uncertainty and the effects of seasonal and interannual variations. The current uncertainty in the global mean sea-level rise rate over the last 25 years has been 0.3-0.5 mm/yr (e.g., Leuliette and Nerem, 2016; Ablain et al., 2017), with acceleration rates estimated to be 0.084±0.025 mm/yr^2 (Nerem et al., 2018). As a result, the goal for future systems is to achieve an accuracy as high as 0.1-0.3 mm/yr, with differing opinions among experts about where it should fall in that range in order to adequately capture not only the current rates of sea-level rise but also changes in these rates.

observed global mean sea level by increasing the mass of the ocean, and thermal expansion of seawater contributed about 30 percent (Figure 10.14). The most rapid accelerations in sea level over the last decade derive from ice sheets, particularly Greenland. Change in Antarctica has the greatest potential to cause sea-level rise in North America in the coming century. To project future sea-level rise, it is necessary to first quantify the current rate of global mean sea-level rise as well as the relative contributions of the driving processes. Achieving this objective requires both observations of the global sea-surface height and the changing ice sheets. The sea-surface height varies regionally at significantly higher rates than the global mean for periods of several years to several decades owing to changes in the winds and ocean circulation (e.g., Savage and Thatcher, 1992).

- *Relevant quantities:* Sea-surface height has been measured using satellite radar altimeters (e.g., TOPEX/Poseidon, Jason-1, and Jason-2) since 1993. Precise sea-surface height measurements also require geodetic-quality GPS receivers for orbits, microwave radiometers to correct for water-vapor path delays, dual frequencies for ionospheric corrections, and a stable and well-defined terrestrial reference frame (GPS, SLR, VLBI). Maintaining the global tide gage network is required to detect biases and drift.

Observations needed to understand ice-sheet contributions to sea level include ice thickness (the difference between the ice-sheet topography and the bedrock topography) for ice-sheet models, seasonal and interannual ice velocities, time-variable gravity, ice topography and its change,

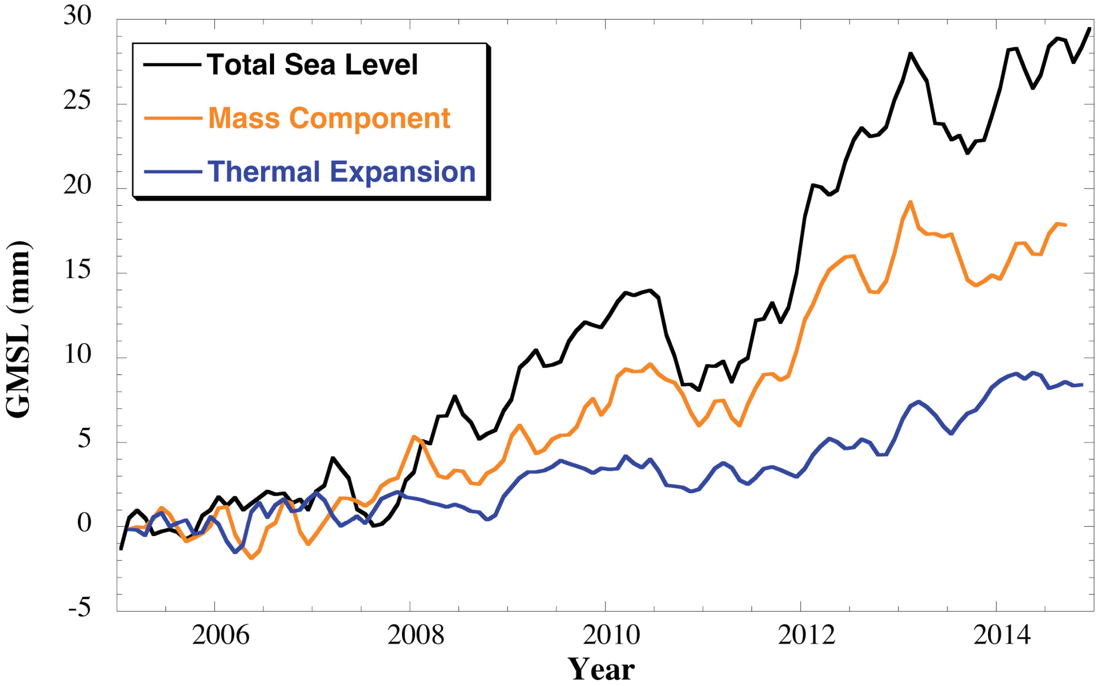

FIGURE 10.14 Total global mean sea-level change from January 2005 to December 2014 as measured by the consecutive Jason-1 and Jason-2 missions (black line), as well as the mass component (orange line) measured by the GRACE mission, and thermal expansion (blue line) measured by Argo and in situ temperature recorders. SOURCE: Data for plot from Chambers et al. (2017).

three-dimensional (3D) surface deformation, snow density, coastal sea-level data, and surface melt. Observations of ice-sheet change needed for projections of sea-level rise include ice-surface topography measurements from satellite laser altimetry or lidar, ice velocity using both InSAR and GPS, mass estimates using both GRACE and GRACE-FO, and the basic geometry of the base of the ice sheet through airborne radar campaigns. An unresolved issue is that sea-level and ice-mass changes relative to a terrestrial reference frame are sensitive to geocenter motion, but satellite gravity measurements are not. Thus, independent measurements of geocenter, such as those obtained from SLR, are required.

- *Length and time scales over which responses should be quantified:* Sea surface height is measured with good precision (2 cm root mean square [RMS] accuracy at 100 km resolution). The current temporal and spatial resolution for altimetry in the deep ocean is sufficient, but improving the resolution to 10 km in coastal waters would better enable the study of dynamical sea-surface height changes, which are different in shallow, coastal waters than in the deep ocean owing to interactions with bathymetry. Measurements over ice sheets (ice thickness, ice velocity, ice topography change, surface melt) need to be made continuously over decades to detect and understand potentially rapid changes. The time sampling can be monthly (or less), and the spatial resolution will depend on the measurement objectives. The spatial resolution of ice thickness near the grounding line needs to be less than 250 m, the spatial resolution of ice-topography change needs to be better than 100 m, and the spatial resolution of ice velocity needs to be better than 250 m.

Objective S-3b: Determine vertical motion of land along coastlines at uncertainty <1 mm/yr.

- *Priority—Most Important:* The influence of vertical land motion on local sea-level rise is profound but poorly constrained. Vertical land motion is driven by natural and anthropogenic processes ranging from changes in the mass load, isostatic (and nonisostatic) adjustment of the solid Earth in response to changes in loading (ice, water, sediment), sediment compaction, extraction of fluids (oil, gas, and water) from underground reservoirs, and tectonics. Currently, vertical land motion is not regularly measured in most areas. Where it has been measured, we now know that land subsidence can be more than an order of magnitude greater than sea-surface elevation changes owing to ocean mass changes and thermal expansion or contraction (Figure 10.15). Thus, in many areas of the world, land subsidence is the leading contributor to coastal sea-level rise. Conversely, coastal areas being uplifted owing to tectonics (e.g., Pacific Northwest) are experiencing a lower rate of sea-level rise than the global average (NRC, 2012b).
- *Relevant quantities:* The most critical measurement needed to quantify vertical land motion is land-surface deformation, typically measured with GPS, but increasingly with InSAR. Global measurements made once to produce a high-resolution (1 m horizontal, 10 cm vertical), bare-earth topography model are needed, especially for predicting inundation effects. Such global topography measurements would aid in modeling the pathway of water in future sea-level rise scenarios and storm-surge modeling.
- *Length and time scales over which responses should be quantified:* The processes that drive vertical land motion in many areas (water extraction, sediment compaction) are nonlinear, which means that long-term (>10 years) measurements at monthly or shorter time sampling is required. Because significant changes in vertical land motion (>15 mm/yr) occur at small scales (Figure 10.15), a spatial resolution of 10 km or better is required.

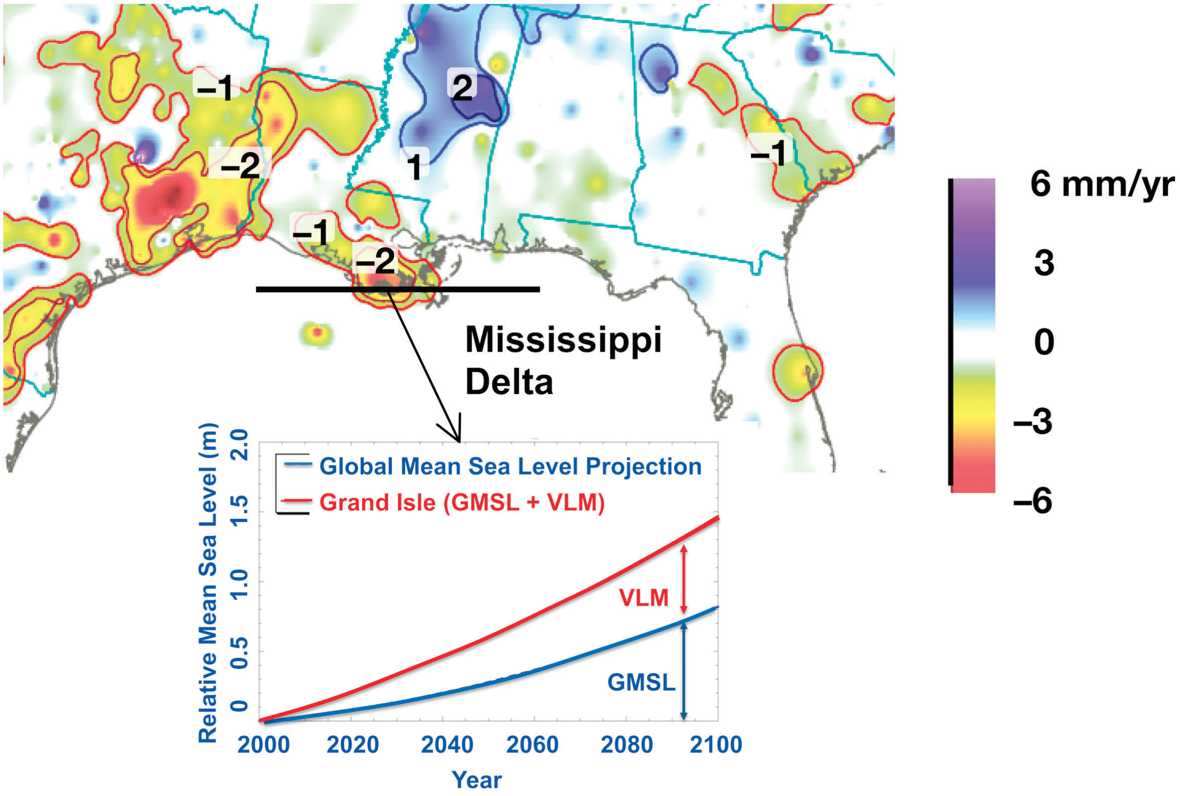

FIGURE 10.15 *Upper panel:* Vertical land motion (VLM) determined from GPS stations for the Gulf of Mexico coast. Positive values indicate uplift; negative values indicate subsidence. The inset shows the expected relative sea-level rise for the Mississippi Delta using a projection of global mean sea level (bottom curve) and a projection that also includes the observed vertical land motion over the past decade (top curve). SOURCE: Map from Donald Argus, Jet Propulsion Laboratory, California Institute of Technology (Argus and Shirzaei, in preparation, 2018). The sea-level projection is adapted from Figure 13.11 (RCP 8.5 scenario) in Church et al. (2013).

Linkages of S-3 Objectives to Other Panels and Integrating Themes

Improved quantification of the rate and cause of local and global sea-level rise or fall is closely aligned with objectives of all other panels. Ongoing, incremental coastal inundation affects both terrestrial and nearshore ecology and hydrology (Ecology Objectives E-1b, E-1d, E-2b, E-3a, E-4a, E4b, and E-5b; Hydrology Questions H-2 and H-4). The extent and thermal state of the ocean's surface boundary layer can, for example, influence the intensity and tracks of hurricanes and typhoons (Weather Objectives W-1a, W-2a, and W-3a), as well as modulate long-term climate change (Climate Question C-1; Climate Objectives C-4a, C-4d, C-7c, and C-7d). Potential destabilization of ice sheets owing to global warming and sea-level rise would have catastrophic impacts for coastal nations, even if such an extreme event were to occur over decades. Along with local tectonics, mass loss from ice sheets and glaciers is driving localized coastal uplift and sea-level fall (or conversely, in other locations, sufficient subsidence to accelerate sea-level rise), with related impacts on both ecology and hydrology, as well as infrastructure. Ice loss is closely related to integrating themes of water and energy budgets, and when considered at longer time scales, of extreme events. Notably maintaining and upgrading the terrestrial reference frame to achieve stringent geodetic objectives is an implicit, shared linkage among all panels.

Question S-4: What processes and interactions determine the rates of landscape change?

Earth's landscapes serve as the interface between Earth's interior, atmosphere, hydrosphere, cryosphere, and biosphere, and they define the habitable Earth. Landscapes facilitate mass and energy transfers among these components of the Earth system, and they are shaped by processes facilitating these transfers over a broad range of spatial and temporal scales. Over time scales ranging from decades to millions of years, processes acting to shape Earth's landscapes play a central role in controlling atmospheric chemistry and climate (Kump et al., 2000), modulating crustal deformation in active mountain belts (Molnar and England, 1990; Willett, 1999), and shaping and filling the sedimentary basins that host water and hydrocarbon resources (DeCelles and Giles, 1996). Climate changes operating over millennia alter the distribution of ice and the transport of sediment, which together produce long-wavelength deformation of Earth's surface and modulate sea level (Kopp et al., 2009). Weather events commonly amplify coastal and river erosion and can trigger abrupt processes such as landsliding, which disaggregate and transport rock within landscapes and produce measurable changes in Earth's surface (Hilley et al., 2004). Seasonal melt in or adjacent to snow- or glacier-clad mountain belts can both cause flooding and sustain agriculture during dry seasons.

Our species and the processes that shape Earth's surface are inextricably bound to and co-evolve with one another. Modern civilization depends on the water and soil resources hosted in landscapes and is impacted by the ways in which they change, including posing risk to humans in the form of landslides, coastal erosion, and flooding (Zoback et al., 2013). The widespread and efficient expansion of human enterprises now affects many of Earth's surface processes and resources that provide critical support for civilization. Consequently, it is in our vital interest to understand the ways in which Earth surface processes have shaped the development of the planet, operated prior to industrialization, and changed in the face of a rapidly growing population.

A promising path forward is in the progressive quantification of surface processes through the merger of theory with diverse observations of cause and effect of surface processes within landscapes. Success in this effort will help define how and why landscapes evolve, what conditions and interactions set the pace of landscape change, and what roles are played by natural and anthropogenic forcing.

Airborne and space-based observations have played a central role in advancing this understanding (Figure 10.16). For example, long-term satellite observations quantify natural changes in coastal and river erosion, hillslope stability, wildfire pathways, and ecological domains, as well as ways in which humans utilize and alter landscapes and their resources (Harris et al., 2012). Airborne imaging of the nutrient content of vegetation canopies reveals ways in which landscapes facilitate elemental transfers between rocks and the biosphere (Porder et al., 2005).

Objective S-4a: Quantify global, decadal landscape change produced by abrupt events and by continuous reshaping of Earth's surface from surface processes, tectonics, and societal activity.

- *Priority—Most Important:* Enhanced understanding of the processes that change landscapes and how they relate to other elements of the Earth system requires a robust image of the landscape change itself. Hence, the magnitude of change, the processes and interactions driving change, the rates of change, and the limitations on those process rates all need to be quantified.

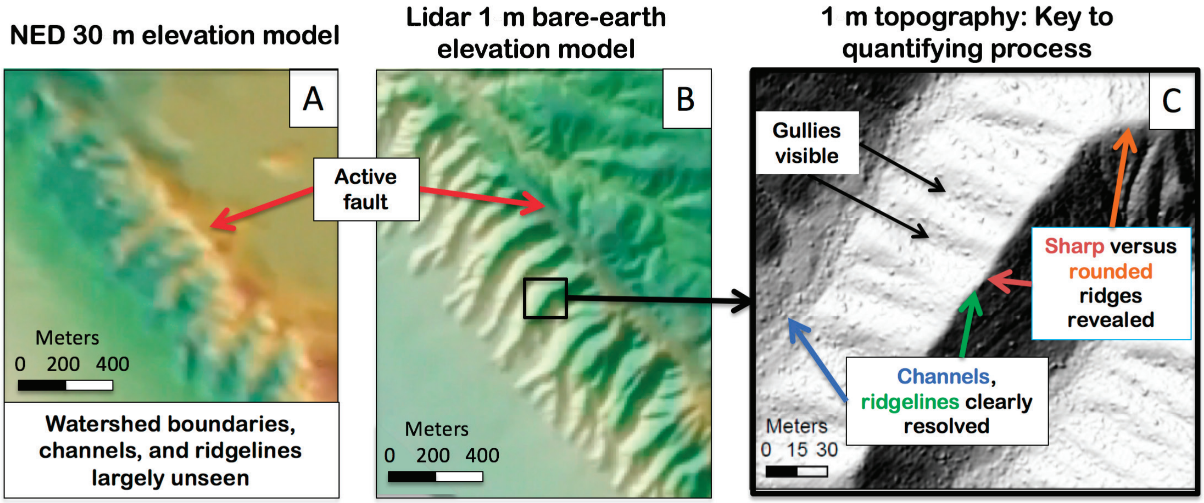

FIGURE 10.16 A: A shaded-relief image of a portion of the Dragon's Back Pressure Ridge derived from the 30 m resolution National Elevation Dataset (NED) fails to resolve basic landscape attributes, such as watershed boundaries, ridgelines, and channels. SOURCE: Data set from the USGS. B: High-resolution (1 m), bare-earth topography of the same area clearly shows the location of the active San Andreas Fault and discriminates fundamental landscape elements. SOURCE: Data from www.opentopography.org. C: A close-up clearly reveals the transition between gullies, hillslopes, and channels, as well as changes in the geometry of these landforms that result from variations in the rates of surface processes and fault-related uplift. SOURCE: Modified from Hurst et al. (2013).

Disruption of Earth's surface materials, as happens during landslides (Figure 10.16), may transform surface properties while changing elevations, as material is transported and deposited elsewhere or formerly buried materials are exposed at the surface. Similarly, large volcanic eruptions can mantle the terrain with fresh debris that can feed destructive lahars for decades after the eruption has ceased. In contrast, ground elevations can sometimes change without disrupting the attributes of the surface itself. In these cases, deformational processes, such as viscous creep owing to gravity acting on soils on hillslopes or poroelastic deformation that attends groundwater pressure changes, result in surface warping but not in change of its physical and chemical characteristics. Capturing quantitatively impulsive and persistent temporal processes and both modes of topographic change—in which elevation changes may or may not be accompanied by changes in slope or composition of surface materials—is necessary to ultimately understand the processes that drive landscape change.

- *Relevant quantities:* Earth's landscape comprises the rock, soil, water, ice, snow, and biomass extending from the base of the vadose zone to the top of the vegetative canopy (the critical zone). A fundamental quantity for understanding global landscape change is change in the bare-earth topography, as derived from swath lidar. From such topography, attributes such as local slope, curvature, and topographic convergence or divergence can be derived and interpreted in terms of their controls on both continuous and impulsive fluxes of water and sediment through the landscape (e.g., soil creep, landslides, debris flows, and channel incision). Another important quantity is the baseline and changing composition of Earth materials, including the water and soil carbon content of the surface zone, the mineralogical composition and spatial configuration of rock and soil, the fraction of water that is ice, and the standing water present on Earth's surface, all of which are relevant for quantifying the nature, rates, and processes driving changes in the character of the surface.

- *Length and time scales of surface change:* The scales over which landscapes change vary over orders of magnitude, depending on the process at work. Changes in ice-sheet volume and resultant crustal loads produce long-wavelength (hundreds of km) bending of the surface, and flow of deep-earth materials (e.g., subduction) alters this bending over similar length scales for tens of thousands of years following loading or unloading. In contrast, earthquakes disrupt the surface over tens of seconds at scales of centimeters to meters, but can produce permanent warping of landscapes over tens of kilometers around the fault rupture and can affect areas for hundreds of kilometers. The landslides generated by earthquakes commonly initiate during a few minutes of the shaking and cover areas of less than a few square kilometers (Figure 10.17). Accelerated channel incision at the base of a slope can take centuries to induce responses along slopes subjected to soil creep, or seconds on steep slopes subject to landslides. Floods can modify river channels and surrounding floodplains from event to event (months to years), whereas a large rainfall event can reroute the channel over days. Abrupt vegetation disturbance by fire or deforestation or gradual vegetative migration in the face of climate change commonly modify landscape stability and susceptibility to erosion during storms, seismic shaking, or other impulsive events. Overall, understanding landscape change requires a high-resolution, baseline depiction of Earth's topographic, ecological, and compositional landscapes, as well as the ability to capture changes that occur over short time scales (days to months), particularly in areas where changes have occurred or are likely to imminently occur and in areas where humans and their infrastructure are threatened.

Objective S-4b: Quantify weather events, surface hydrology, and changes in ice/water content of near-surface materials that produce landscape change.

- *Priority—Important:* The primary observables for this objective would be used to understand the driving factors responsible for landscape changes. Given that quantifying landscape change itself (Objective S-4a) was deemed the highest order objective, quantification of the processes driving these changes was regarded as a vital but slightly lower priority set of observables.
- *Relevant quantities:* The observables needed to quantify drivers of landscape change include the spatial and temporal distribution of rainfall and snowfall, the total (and changing) amounts of rain and snow present near the landscape surface over time (drivers of root-zone and soil-moisture content), seasonal temperatures that may modulate the fraction of ice and water in the surface and subsurface, freeze-thaw cycles, and human activities (e.g., construction, excavation, or land use change) that alter hillslope character and, thus, sensitivity to precipitation and, ultimately, susceptibility to erosion.
- *Length and time scales over which driving factors should be quantified:* The appropriate scales of observation depend on the particular process that is interrogated. Minutes-long cloudbursts can drive hillslope failure, but so can passing a saturation threshold after a week of persistent rainfall. Both primary surface changes owing to anthropogenic land-cover change (direct human intervention) and secondary changes (natural response to human intervention) can occur over time scales of months to decades, but many of these drivers act over length scales of meters to kilometers. For example, a river channel may be reconfigured during a flood over hours or days, but the flood is produced by regional storms that affect the hydrology of large areas. For large rivers imaging of these types of processes likely requires high temporal sampling, but could permit coarser spatial resolution. At the most challenging extreme, landslides are generally small features, ranging in dimension from several

FIGURE 10.17 Before and after images of Langtang village, Nepal, which was buried by a landslide during the 2015 Gorkha earthquake. The M7.8 earthquake triggered more than 4,000 landslides. SOURCE: D. Breashears, Glacier Works, “Panorama Images of Langtang Village Taken Before (October 2012) and After (May 2015) the Nepal Earthquake,” October 2012, http://www.icimod.org/before-after/langtang/.

meters to several kilometers. Hydrologic triggers are locally mediated (e.g., by proximal slopes, vegetation cover, and previous history), and so observations of factors that control this hydrology need to be at the scale of individual landslides. Furthermore, rates of landslide motion vary over seven orders of magnitude, from seconds-long rapid failure or mobilization of rock and soil in a debris flow to continuous landslide creep that can persist for decades.

Objective S-4c: Quantify ecosystem response to and causes of landscape change.

- *Priority—Important:* Understanding the coevolution of landscapes and ecosystems is a central and vibrant locus of inquiry in landscape development. Achieving this objective strongly relies on the quantification of the landscape change (Objective S-4a) associated with variations in ecosystem characteristics.
- *Relevant quantities:* Ecosystem response and causes refer to the extent, biogeochemical composition, and health of the aboveground biomass; its species composition; interaction among species; its mechanical characteristics (such as root strength and surface roughness); and its soil-generation and transport characteristics, and how these factors vary with landscape position, changing landscape properties, and time. Relevant quantities for characterizing this response include nutrient composition/status of the ecosystem, distribution of the carbon stock (as a function of aboveground elevation) in the biomass, biomass water-cycling characteristics, species composition of the aboveground biomass, surface shear strength imparted by vegetation communities, biogeochemical fluxes from the biomass to the soil, and the history of wildfires (Lamb et al., 2011; see also Figure 10.18).
- *Length and time scales over which responses should be quantified:* Length scales should be matched to those required to image different landscape elements (i.e., from meters to entire landscapes: hundreds of km^2). Baseline observations need to be collected throughout the year to adjust for seasonal variations in biomass properties. Imaging change over time needs to be flexible, depending on the processes leading to landscape changes under investigation. High-impact events such as wildfires impose abrupt changes, whereas persistent groundwater drawdown creates incremental impacts. Thus, a means of acquiring global baseline measurements at high spatial resolution that could be revisited for specific areas at different return frequencies is necessary.

Linkages of S-4 Objectives to Other Panels and Integrating Themes

Landscapes are situated at the interface between the geosphere, atmosphere, hydrosphere, cryosphere, and biosphere. The physical shape and composition of the land surface, its soils, and its ecology are critical controls on the ways in which water, carbon, nutrients, and energy cycle through the critical zone, making this interface a nexus for many integrating themes. Along with soil characteristics, surface water, snowmelt, and groundwater (Hydrology Objectives H-1c, H-3b, H-4a, H-4b, and H-4c; Ecology Objective E-1d; Climate Objective C-2e; and Weather Objectives W-1a, W-3a, and W-4a) are fundamental controls on erosion and deposition at the surface and on the structure of the ecosystem. They also modulate soil and rock resistance to failure (in part through vegetation properties). Climate change, temporal variability in land use (Hydrology Objectives H-2a and H-4d), and societal activity affect the shape, structure, vulnerability, and resilience of landscapes and associated ecological and hydrological systems (Ecology Objectives E-1b, E-1e, E-3a, and E-5b), including water and air quality, groundwater recharge, and food production. High-resolution, lidar-based topography and its changes through time provide a critical and spatially nuanced template for predicting and assessing fluxes of sediment, energy, water, nutrients, and carbon through landscapes (Weather Objectives W-3a. W-4a; Hydrology Objectives H-1a, H-2a, H-4a, and H-4b; and Ecology Objectives E-4a, E-5a, E-5b, and E-5c). Lidar enables more reliable quantification

FIGURE 10.18 DigitalGlobe false-color composite image of a California wildfire (September 2014) made from three short-wave infrared bands that are able to see through the fire's smoke. Vegetative and soil quality change owing to fire strongly affect postfire erosion rates. SOURCE: Courtesy of DigitalGlobe.

of the likely impacts of changes in climate, weather, forestry, agriculture, or other societal uses, and also illuminates the 3D structure of both aboveground ecosystems and carbon inventories. The variables, such as surface slope and shape, rainfall rates, vegetation cover and type, and soil character, that control the rates and character of surface processes will also determine how the landscape, including its hydrologic and ecologic character, responds to and recovers from both incremental and extreme events, either natural or anthropogenic.

Question S-5: How does energy flow from the core to Earth's surface?

Earth has a liquid core, which slowly cools by energy transfer through the mantle to the surface. A solid inner core has crystallized out of the core fluid. In the remaining fluid of the outer core, thermal and chemical convection with speeds of tens of kilometers per year generate Earth's magnetic field (Figure 10.19), which prevents Earth's atmosphere from being depleted by the solar wind and shields society from harmful radiation. Core motions and waves are responsible for prominent changes in Earth's magnetic field, as seen in features such as the movement of the geomagnetic poles and the South Atlantic magnetic anomaly. Angular momentum exchange with the overlying mantle further leads to subtle variations in Earth rotation, which are manifested in changes of the length of the day, precession, and nutation of the rotation axis.

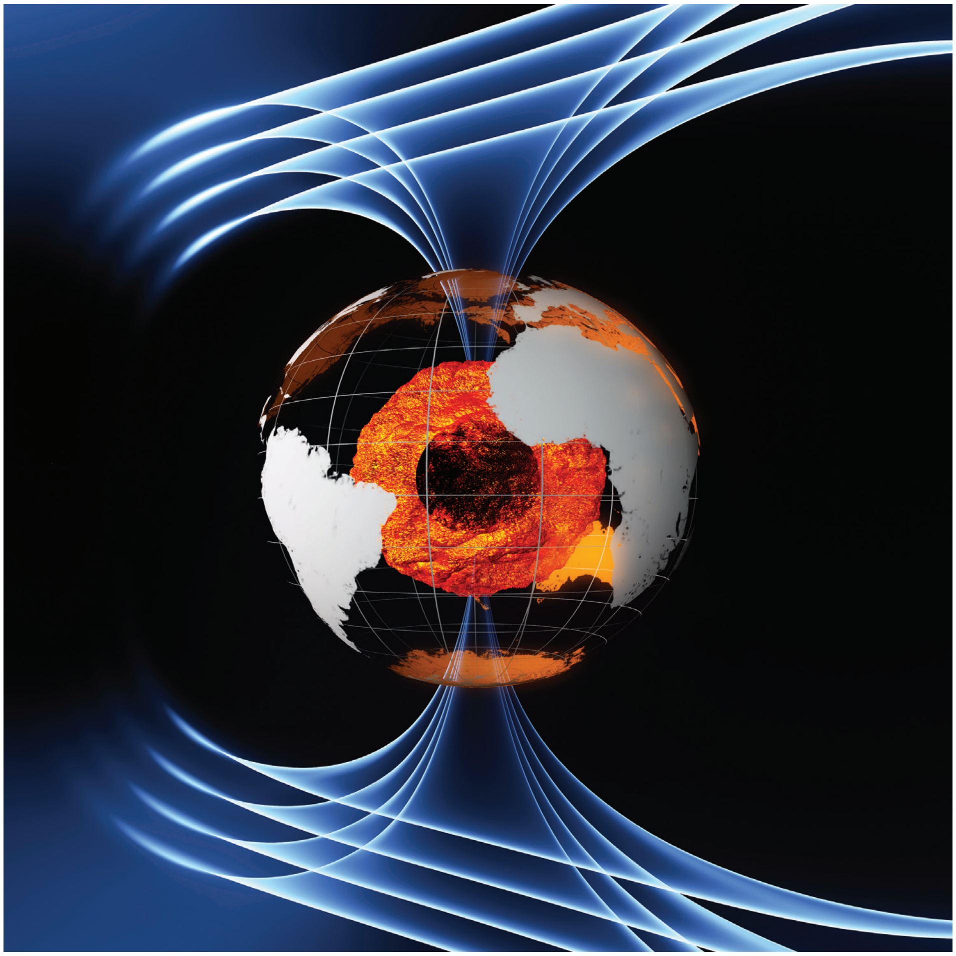

FIGURE 10.19 Schematic of the generation of Earth's magnetic field by vigorous convection in the fluid outer core. The core field changes orientation and amplitude over time scales ranging from years to millions of years. SOURCE: Courtesy of the European Space Agency.

Heat transfer from the core to the surface also drives convection and flow of Earth's viscous mantle. Cooling at the surface generates rigid lithospheric plates that slide across the viscoelastic asthenosphere. These geodynamic processes are evident in plate motions, variations in geoid height, and dynamic topography. New tectonic plates are created at volcanic midocean ridges and are recycled back into the mantle at subduction zones, generating both earthquake and volcanic activity. These plate tectonic processes cycle CO_2, water, and other fluids through Earth's interior and atmosphere, helping to create and maintain a habitable planet.

Although plate tectonics explains the occurrence of earthquakes, volcanoes, mountain belts, and geologic features, fundamental questions remain. Specifically, what is the nature of plate boundary deformation; what fraction of the strain rate is elastic, to be released in future earthquakes; and what fraction is inelastic, forming diffuse deformation far from the plate boundary (Figure 10.20)? We do not know how much water is trapped in the deep interior. How much does this water affect mantle viscosity and the initiation of plate tectonics? We know that density and temperature variations lead to circulation of Earth's mantle, but does this circulation extend through the entire mantle or is it partitioned with depth? How does this circulation influence surface topography, plate motions, and the evolution of plate boundaries?

Objective S-5a: Determine the effects of convection within Earth's interior, specifically the dynamics of Earth's core and its changing magnetic field, and the interaction between mantle convection and plate motions.

- *Priority—Very Important:* Better characterization of deep Earth dynamics and its drivers is key to understanding deep Earth phenomena such as geomagnetic field variations, mantle convection, and plate motions. Because Earth's deep interior cannot be probed directly, our understanding is largely based on indirect measurements and observations. The primary challenge in reaching a better understanding of deep Earth dynamics is overcoming the present sparsity of observations and the nonuniqueness in their interpretation. Opportunities for improving the observational basis include

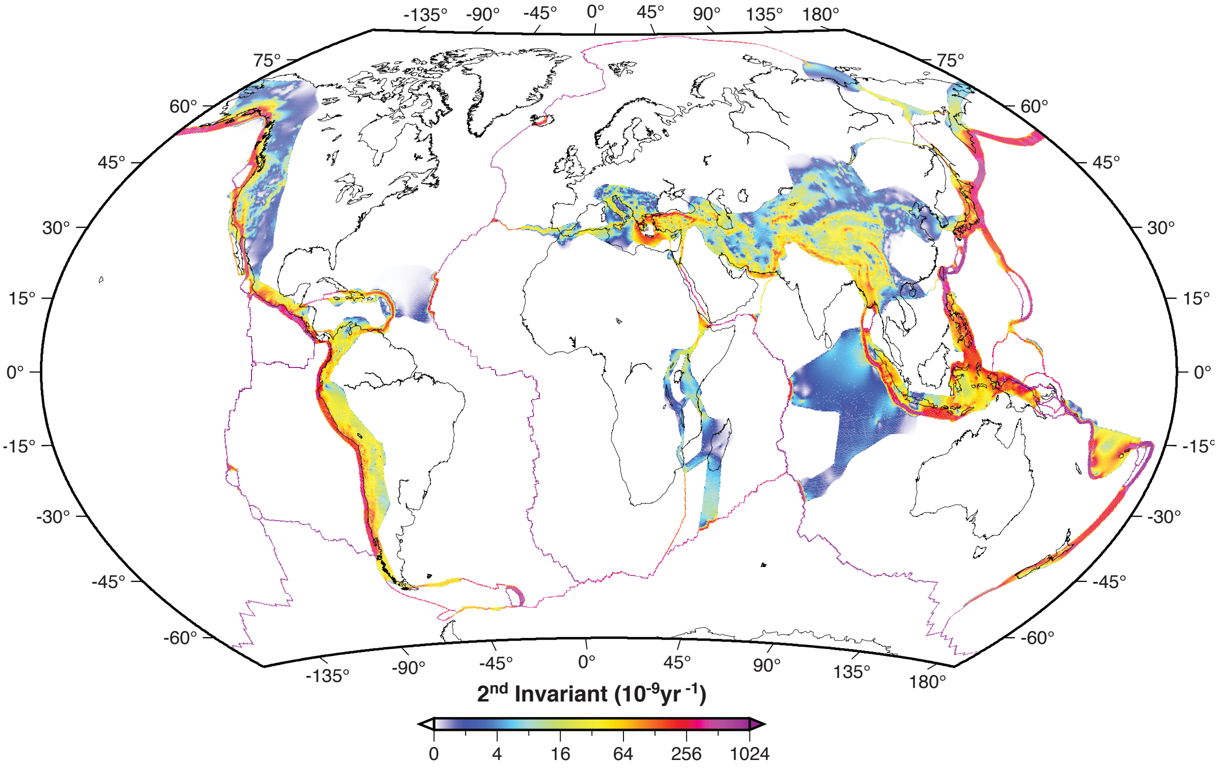

FIGURE 10.20 Color contours of the strain rate along the boundaries of the major tectonic plates derived from 22,500 GPS velocities. Most major earthquakes occur in these high strain rate areas, and so refined mapping is needed to improve the accuracy of the global earthquake hazard maps as well as to better understand the physics of plate boundaries and the extent and physics of intraplate deformation. SOURCE: Kreemer et al. (2014).

(1) multisatellite simultaneous measurements of the magnetic field to separate internal contributions and relate them to motions in the core, and (2) establishing more accurate terrestrial reference frames for monitoring Earth rotation parameters, deformation, and mass transport.

- *Relevant quantities:* Accurate global monitoring of the magnetic field provides valuable insights because the magnetic field of the core passes almost unobstructed through the mantle. Other helpful measurements include changes in the gravity field and earth-rotation parameters. Core and mantle structure can be inferred from imaging by seismic waves. Models of mantle convection require knowledge of the physical parameters of Earth's interior—specifically, density and viscosity. The thickness of the elastic lithosphere and viscosity structure of the asthenosphere can be constrained using long time series of GPS measurements combined with time-dependent gravity measurements. The distribution of density within the mantle, determined from seismic models, can be constrained using gravity and topography data. Improved understanding of the nature of deforming plate boundaries—specifically, the level of coupling between the rigid crust and mantle and the convecting asthenosphere and how that coupling relates to surface faulting—requires both temporal and spatial measurements of strain accumulation. Continuous time series measured by GPS and repeat InSAR images provide the temporal resolution needed to assess levels of transient behavior, earthquake processes, aseismic deformation, long-term tectonic motions, and accommodation of relative plate motions across continental boundaries.
- *Length and time scales over which responses should be quantified:* Earth's core magnetic field changes on subannual to decadal time scales and thus needs to be monitored continuously from space. Exchange of angular momentum between core and mantle from changes in earth-rotation parameters also requires continuous monitoring.

Objective S-5b: Determine the water content in the upper mantle by resolving electrical conductivity to within a factor of 2 over horizontal scales of 1,000 km.

- *Priority—Important:* Significant quantities of water, perhaps several times the volume of the surface oceans, may be stored in Earth's deep interior, distributed as point defects in the nominally anhydrous minerals that make up the bulk of the mantle. The actual volume and distribution remain highly uncertain, but water (or more precisely, hydrogen) modifies both rheological properties and melting relationships, with potentially significant impacts on the dynamics and geochemical evolution of Earth. Quantitative understanding of Earth's deep water cycle and the distribution of volatiles in the interior would clarify key aspects of the dynamic Earth, ranging from the initiation and maintenance of plate tectonics to the nature of the asthenosphere and the stability of ancient cratons.
- *Relevant quantities:* Conductivity imaging with electromagnetic induction methods is likely the best probe for constraining the distribution of water in the mantle on a global scale. For plausible variations in water content, conductivity can vary by orders of magnitude. Satellite magnetometers have a unique potential to provide new 3D global views of upper mantle and transition zone water content—in particular, shedding light on large-scale variations between continental and oceanic domains.
- *Length and time scales over which responses should be quantified:* Mantle conductivity changes over geological time scales and is best determined over spatial scales of hundreds of kilometers globally. This scale requires a constellation of polar-orbiting satellites taking simultaneous magnetic vector measurements over multiple years.

Objective S-5c: Quantify the heat flow through the mantle and lithosphere within 10 mW/m^2.

- *Priority—Important:* The heat flow from Earth's interior is of primary importance for understanding the dynamics of deep Earth processes, and it also has a role in basal heating under the large ice sheets. However, accurate measurements of heat flow are challenging because (1) the interior heat flow is much smaller than the solar energy, and (2) observable geophysical parameters, such as acoustic velocity and electrical conductivity, are related only weakly to temperature.
- *Relevant quantities:* Methods for determining heat flow include direct downhole measurements, hyperspectral surface imaging, and mapping Curie isotherm depth from magnetic anomaly surveys.
- *Length and time scales over which responses should be quantified:* Lithospheric heat flow changes over geological time frames and, therefore, has to be measured only once. Relevant length scales are of the order of tens of kilometers.

Linkages of S-5 Objectives to Other Panels and Integrating Themes

Earth's magnetic field plays a critical role in shielding the biosphere and society from harmful radiation and enabling global communication, and so an improved understanding of its character and temporal variability could prove invaluable. A significant increase (or decrease) in radiation would have a notable impact on weather and climate (Weather Objectives W-1a, W-3a, and W-10a; Climate Objectives C-2a, C-2g, C-2h, C-6c, and C-7c) and on hydrologic and ecologic systems, as well as global fluxes of energy and (likely) carbon and water. Given the importance of hydrology at the base of ice sheets, improved understanding of the thermal flux from Earth's interior to their bases would improve estimates of ice-sheet stability and vulnerability as related to sea-level rise (Climate Objectives C-1a to C-1d).

Question S-6: How much water is traveling deep underground and how does it affect geologic processes and water supplies?

Water flowing beneath Earth's surface helps sustain life. Growing populations and climate change are rapidly claiming surface-water supplies, which are the easiest and cheapest to manage and exploit. Consequently, it is becoming increasingly important to measure, monitor, and manage aquifer systems in a sustainable way or else risk human health in many parts of the world. Furthermore, deep groundwater is central to geological processes including earthquake generation, rock formation, and landscape evolution. High pore pressures are an often invoked yet seldom measured catalyst for tectonic and hydrologic processes, such as faulting, volcanic eruptions, and subsurface flow dynamics. As a result the geological challenges and societal needs for deep groundwater monitoring are well aligned. Synoptic global observations from space play a key role in addressing this worldwide challenge.

Objective S-6a: Determine the fluid pressures, storage, and flow in confined aquifers at spatial resolution of 100 m and pressure of 1 kPa (0.1 m head).

- *Priority—Very Important:* Overproduction of groundwater aquifers not only risks loss of immediately available water but also can lead to permanent loss of storage capacity. If drawdown leads to irreversible permeability and porosity changes, the aquifer may no longer be able to be recharged, even if rainfall is plentiful.
- *Relevant quantities:* The relevant measurements include vertical surface deformation from InSAR and GPS, as well as estimates of surface water (including snowpack) and surface-to-groundwater fluxes,

as observed in large basins using gravity (see Figure 10.3). For predictive measurements, forecasts of water use, precipitation, and runoff are required.

- *Length and time scales over which responses should be quantified:* Broad areal coverage that spans watersheds at a scale fine enough to resolve inhomogeneities in aquifer structure (km scale) are needed. Temporal sampling needs to resolve any seasonal effects. In areas prone to InSAR decorrelation weekly or better sampling is needed to identify reliable scattering points.

Objective S-6b: Measure all significant fluxes in and out of the groundwater system across the recharge area.

- *Priority—Important:* Groundwater flow is coupled to recharge and withdrawal forcings: when it rains, water is commonly captured in underground reservoirs; it is later available for use in drier periods. Modeling flow throughout the water cycle for any region requires measuring or estimating all relevant fluxes between the various elements of the system (e.g., Jasechko et al., 2016).
- *Relevant quantities:* The relevant measurements include precipitation, streamflow, recharge and extraction rates, water use by humans, plus any natural discharges, evapotranspiration, and soil moisture.
- *Length and time scales over which responses should be quantified:* Areal coverage that spans watersheds at a scale fine enough to resolve inhomogeneities in aquifer structure, plus areas of precipitation catchment or surface flow relevant to aquifers are needed. For most of these characteristics, 100 m to km scale is sufficient. Monitoring individual producing wells requires sampling at 10 m postings or less. Stream gauges need to be deployed in streams with flow rates that are not constant or predictable over an annual cycle.

Objective S-6c: Determine the transport and storage properties in situ within a factor of 3 for shallow aquifers and an order of magnitude for deeper systems.

- *Priority—Important:* Remotely sensed hydraulic head data, combined with observations from in situ wells, are needed to solve for aquifer conductivity and storage parameters. Once the calibrations are known and flow is determined to be in an elastic range, detailed spatially resolved aquifer descriptors can be retrieved. These parameters then form the basis of the groundwater model.
- *Relevant quantities:* The relevant measurements include vertical surface deformation from InSAR and GPS, plus ground-based head data at multiple wells in the watershed. Such measurements require production records from some wells and drawdown tests at several.
- *Length and time scales over which responses should be quantified:* Areal coverage that spans watersheds and basins at a scale fine enough to resolve inhomogeneities in aquifer structure are needed. Monitoring individual producing wells requires sampling at 10 m postings or less. For the drawdown tests, data are needed on the scale of hours over days to estimate conductivity. Basin-wide temporal sampling needs to resolve any seasonal effects.

Objective S-6d: Determine the impact of water-related human activities and natural water flow on earthquakes.

- *Priority—Important:* Wastewater disposal and water injections for enhanced geothermal systems (e.g., Figure 10.21) induce earthquakes in regions where such activity has historically been minimal. Determining whether natural or anthropogenic subsurface flow can raise earthquake hazard potentials in seismically active areas requires a means to estimate pressure changes at depth and to relate those changes to stress distributions.

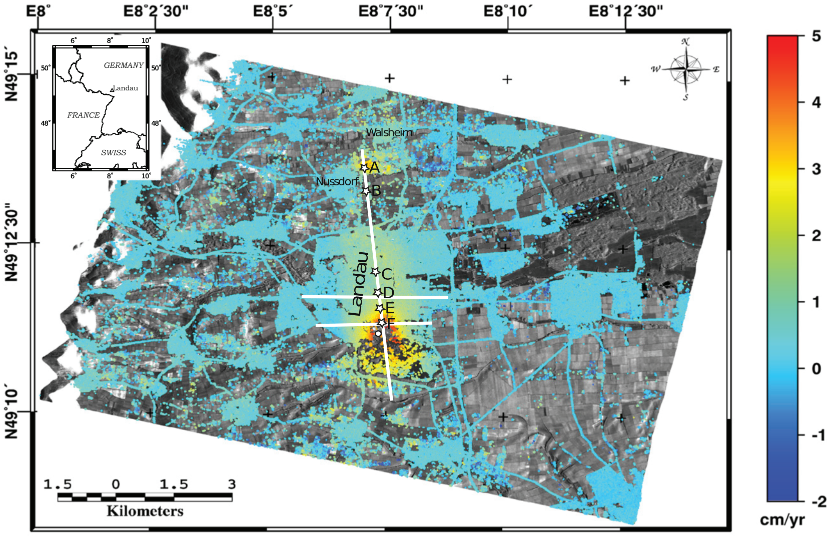

FIGURE 10.21 Surface uplift detected by InSAR and associated with deep fluid injection by a geothermal power plant near Landau, Germany. Fluid extraction and injection during geothermal production also produces earthquakes. The uplift shows where the fluid pressures are high and helps constrain the specific forces that are leading to the earthquakes. SOURCE: Heimlich et al. (2015).

- *Relevant quantities:* The relevant measurements include vertical surface deformation from InSAR and GPS, as well as the locations of any preexisting faults that might be triggered by changes in pressure. For predictive measurements wastewater reinjection estimates are required.
- *Length and time scales over which responses should be quantified:* Areal coverage that spans production zones and basins at a scale fine enough to resolve inhomogeneities in reservoir structure are needed. Monitoring individual producing wells requires sampling at 10 m postings or less. Temporal sampling needs to resolve any production or reinjection effects.

Linkages of S-6 Objectives to Other Panels and Integrating Themes

Water is clearly an integral part of multiple Earth systems, and it is central to the hydrology, climate, weather, and ecosystems panels. Although surface water fluxes are moderately well characterized, deep water is one of the most difficult components of the water cycle to measure (Hydrology Objective H-3b). As has become apparent in the past two decades satellite-based measurements, particularly data from InSAR and GRACE that measure deformation and water loads, respectively, shed light on the deep, confined reservoirs in Earth's interior—information that can advance a wide range of science objectives (Hydrology Objective H-4c). Although the spatial resolution of GRACE is currently limited, repeat gravity measurements can quantify seasonal to annual changes in the total mass of water in large groundwater basins (e.g., Figure 10.3), as well as estimate the snow-water equivalent at the end of the snow-accumulation season (Hydrology Objective H-1c). Higher resolution geodesy and gravity measurements will enable better quantification of groundwater change, help address Hydrology and Ecosystem objectives (H-1c, H-4c, E-1d, E-2b, and E-5b), and are clearly related to water fluxes and extreme events, particularly drought (Hydrology Objective H-4c).

Question S-7: How do we improve discovery and management of energy, mineral, and soil resources?

Extraction of natural resources, including ores and water, is critical for providing food, energy, and industrial raw materials needed for modern civilization. Moreover, the quality of soils (their geochemistry, nutrients, permeability, thickness, and durability) are determinative ingredients for agriculture and ecology, and thereby modulate sustainability. The surface expressions of the chemical compositions of many resources, including soils, are visible in the spectrum of reflected and emitted energy signatures. These signatures can be effectively monitored with high spatial resolution data collected from spaceborne instruments. Production of subsurface resources (e.g., water or hydrocarbons) can cause surface deformation that can be monitored from space using InSAR. In situ calibration wells provide important verification points. For example, discovery and management of offshore hydrocarbon resources benefit from frequent high-resolution images of sea-surface oil slicks (Figure 10.22).

The primary need is for high-resolution sensors in the optical, thermal, and infrared portions of the spectrum. Once the raw measurements are corrected for atmospheric influences, it is possible to infer surface chemical composition by comparing the reflectance spectra to a library of known materials. Challenges include having sufficient spectral information (bands) at fine enough resolution to permit the identification of target minerals, despite the interference of the atmosphere, while fitting within bandwidth limits.

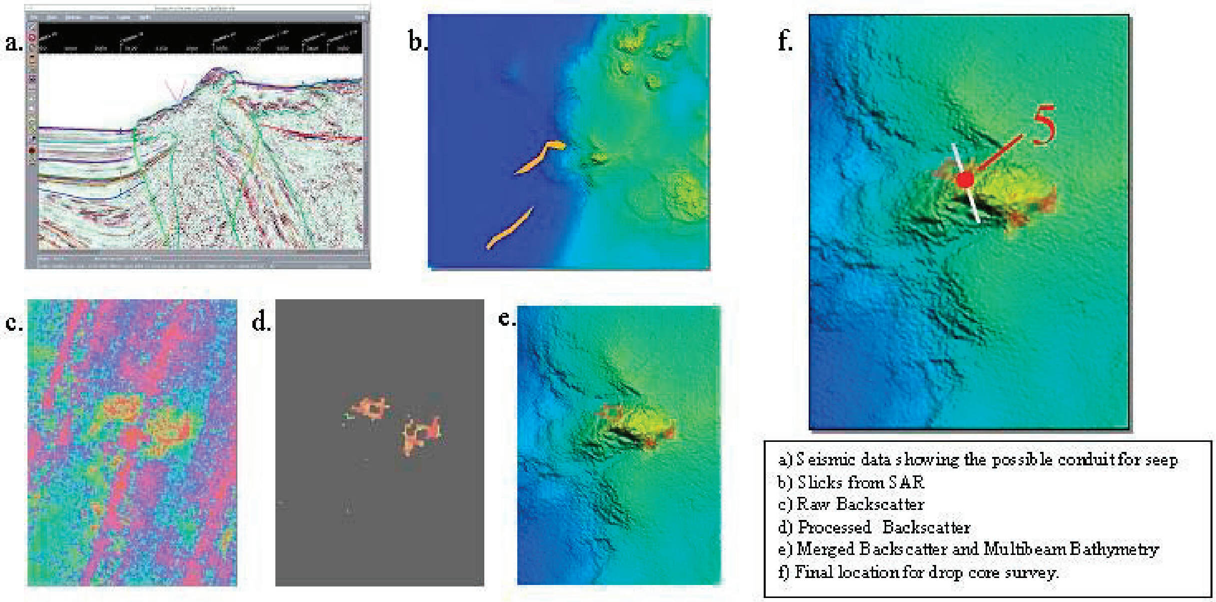

FIGURE 10.22 Natural seeps of oil from the seafloor (A) migrate to the sea surface, where they produce slicks that, under the right conditions of wind speed and sea state, can be observed with high-resolution SAR (B) and multispectral optical images. These reconnaissance data provide an important starting point for exploration. B: Persistent slicks on the ocean surface against the backdrop of multibeam bathymetry. C and D: Sonar backscatter and filtered backscatter, respectively, overlain on bathymetry (panel E). The source location of the seeps was identified using a seismic line (panel A) and a drop core (red dot in panel F). The workflow of using SAR imagery, multibeam, seismic, and drop core is generally considered the best way to identify naturally occurring seeps in the marine environment. SOURCE: Dolan et al. (2004).

Objective S-7a: Map topography, surface mineralogic composition and distribution, thermal properties, soil properties/water content, and solar irradiance for improved development and management of energy, mineral, agricultural, and natural resources.

- *Priority—Important:* Resource management is an important application area that is furthered through the use of government-collected data sets.
- *Relevant quantities:* The relevant measurements include 1 m spatial resolution optical visible data, 30 m or better hyperspectral VSWIR imaging, and TIR data. Because many satellites provide meter-scale optical/infrared spectrum data, this objective can likely be met through simple data sharing agreements among data providers. However, development of hyperspectral VSWIR and TIR data is required. Additional needs include 30 m or better resolution bare-earth topography and vertical surface deformation from InSAR and GPS.
- *Length and time scales over which responses should be quantified:* The length and time scales of most of these measurements are highly variable, depending on the circumstances. Deformation rates can be rather high in areas of active production (>10 mm/yr), although the aerial extent of reservoirs is usually less than a few hundred meters. Consequently, 5-50 m spatial resolution is needed for deformation monitoring. Temporal variations in land cover and infrastructure development generally occur over weeks to years, and so the 30-60 m multi- and hyperspectral data need to be acquired at least biweekly.

Linkages of S-7 Objectives to Other Panels and Integrating Themes

Earth materials provide a vital framework for the biosphere and human society. The composition, hydrological properties, and geobiochemistry of soils are fundamental to the health of ecosystems and hydrologic networks. These properties determine runoff, infiltration, erosion, nutrient fluxes, and much of the structure of plant and animal communities—key components of the integrating themes of energy and water cycles (Hydrology Objectives H-1a and H-4a; Ecology Objectives E-1b, E-3a, and E-5b). The irregular spatial distribution of key mineral and energy resources and their subsequent extraction commonly introduces localized challenges related to water, energy, ecosystem quality, and sustainability—important attributes of both the Hydrology and Ecosystem panels' objectives.

Enabling Measurements

A wide variety of spaceborne measurements are needed to help achieve the science and applications objectives described earlier. Some of these measurements support multiple objectives, although requirements may differ for each objective. A description of each measurement type—including how the measurement is made, the maturity of the measurement technology, trade-offs (e.g., temporal and spatial resolution, technological approaches), and extent to which the measurement is new—appears in the following sections.

Terrestrial Reference Frame (1 mm Positional Accuracy; 0.1 mm/yr Rate Accuracy)

The Terrestrial Reference Frame serves as the reference frame for all Earth science satellite observations. The terrestrial reference frame includes motion of the geocenter relative to the frame.

- *Measurement basis:* In the United States terrestrial reference frame activities are organized by NASA and strongly supported by international partners and the International Earth Rotation Service. The networks used for the terrestrial reference frame are a sparse global network of VLBI and SLR stations that are collocated with GPS/GNSS instruments. A much denser, well-distributed global GPS/GNSS network (~200 sites) is needed for precise orbit determination with low latency. GPS/GNSS is also used to tie the global tide gauge network to the reference frame. A precise determination of the terrestrial reference frame requires the complementary measurements from all three systems (VLBI, GPS, and SLR). However, only SLR has a demonstrated capability to measure geocenter motion at monthly time scales.

- *Measurement maturity:* VLBI, SLR, and GPS were developed over many decades by NASA and its partners. They are mature, but many existing facilities that support VLBI, SLR, and GPS tracking are aging and require upgrades or replacements to be able to reach the required accuracy and stability goals. In addition, investment is needed for extending analysis from its current emphasis on GPS to include signals from the other GNSS constellations: GLONASS, GALILEO, and BEIDOU. This expansion requires investment in both new receivers (which track all GNSS signals) and software development.
- *Trade-space definition:* It will be important that the VLBI/SLR/GNSS sites have a good global distribution with an adequate number of southern hemisphere stations; this is a current shortcoming of the legacy networks. Running a network with an adequate number of stations every day would reduce the impact of individual station problems and maintain better accuracy of global parameter estimates like Earth orientation parameters. On the precision side simulations indicate that polar motion and Earth orientation from a 30-site, next-generation network will be 2-3 times more precise than the best research and development experiment ("CONT") campaigns (14-17 stations).
- *Continuity versus new:* The accuracy of the terrestrial reference frame requires long time series at globally distributed VLBI/SLR/GPS stations. Because of the dynamic nature of processes from Earth's surface and interior, continuity of the measurements is implicitly necessary. The equipment at the existing terrestrial reference frame sites has to be maintained and, in many cases, upgraded. This requirement is true for all three techniques. For VLBI and SLR the majority of the development cost for building new ground stations has been expended. Completion of the deployment of the new systems and funding for ongoing operational costs will be required to achieve the goals as defined earlier. Note that the great majority of VLBI and SLR sites are operated by international collaborators.

  New work is needed to tie the three ground systems together, in terms of both modeling the measurements and making new in situ measurements. Many of the GPS/GNSS sites were installed when daily downloads were state of the art. New real-time telemetry is needed, with higher sampling rates, so that the GPS/GNSS data can be used in early warning systems for earthquakes, volcanoes, and tsunamis, as well as to image atmospheric water-vapor events. Support for new GPS/GNSS stations in undersampled regions, such as Africa and South America, as well as new hardware providing access to the signals from the European, Russian, and Chinese systems are also needed. New efforts are required to tie tide-gauge records into the terrestrial reference frame. These efforts could include the use of reflected GPS/GNSS signals for water-level sensing when possible (see Box 2.1).

Land-Surface Deformation

Surface deformation requirements for the panel's science objectives are highly variable (Table 10.3). Some applications require spatial resolution of <5 m with measurement precision of ≤10 mm and weekly or more frequent sampling. Other applications need lower spatial resolution of 100-500 m with seasonal or better sampling. Very frequent observations are sometimes needed to capture the rapid deformation following some earthquakes and volcanic eruptions. These event-dependent requirements can sometimes be achieved by tasking all relevant international space assets.

- *Measurement basis:* Two different but complementary technologies can be used to measure surface deformation. Ground-based GPS receivers can be deployed in point locations to continuously measure three components of surface deformation at mm accuracy at decadal scales. A prominent example is the U.S. Plate Boundary Observatory (Holt and Shcherbenko, 2013), which consists of about 1100 permanent sites deployed at 10-100 km spacing over western North America. Typically, the receiving units provide samples every 15 seconds, but they can acquire data at up to 20 Hz to function as strong motion seismometers (Box 2.1). Over 10,000 other continuous GPS sites around the world are operated by governments and organizations. These sites provide the measurements of global plate motions needed both for scientific studies and for defining the moving reference frame. The GPS receiving units (and satellites) are tied to the terrestrial reference frame, and so they can achieve better than 1 mm position and 1 mm/yr velocity accuracies, respectively. All of the measurement requirements listed in Table 10.3, except the spatial resolution, could be achieved with GNSS.

  The second technology used to measure surface deformation is repeat-pass InSAR deployed on a satellite, an aircraft, or fixed on the ground. A single interferogram represents the deformation of the surface of Earth in the line of the boresight of the radar between the reference and repeat acquisition times. The best spatial resolution of the measurement is half the length of the antenna (~5 m). The single InSAR accuracy is mostly limited by the two-way delay (20-200 mm) of the microwaves as they propagate through the troposphere. Any small-scale disruption of the surface owing to, for example, vegetation growth will decorrelate the measurement. Hence, the time between the reference and repeat acquisitions is limited to years or weeks depending on the properties of the surface. Other large-scale error sources associated with orbital and ionospheric effects produce errors >100 mm at length scales >100 km. The ionospheric errors can be corrected using a two-frequency radar as planned for NISAR. Therefore, a single interferogram represents a scalar, relative deformation measurement. Two or more components of deformation can be achieved by observations from ascending and descending orbits. High precision of 1 mm/yr can be achieved through 50 or more repeated

TABLE 10.3 Land-Surface Deformation Requirements for Different Science Objectives

Objective	Spatial Resolution	Precision	Frequency	Duration
S-1a	**10 m**	**10 mm**	**Event dependent**	
S-1b	**10 m**	**10 mm**	**12 days**	**10+ yr**
S-1c	50 m	1 mm/yr	<Seasonal	
S-2a	**10 m**	**10 mm**	**Event dependent**	
S-2b	10 m	1 mm/yr	Event dependent	
S-2c	100 m	1 mm/yr	Event dependent	5+ yr
S-3a	**100 m**	**10 mm/yr**	**<Seasonal**	
S-3b	**<50 m**	**5-10 mm**	**Weekly**	**10+ yr**
S-4a	**<5 m**	**5-10 mm**	**Weekly**	**10+ yr**
S-5a	100 m	10 mm		
S-6a	5 m	10 mm	Weekly	
S-6b	5 m	3 mm/yr	Weekly	
S-7a	5 m	10 mm	Weekly	

NOTE: Requirements for the Most Important objectives are marked in bold.

measurements taken over a year. The radar can also be mounted on an aircraft or on the ground to monitor motions of intermediate scale (<10 km) and small (<5 km) scale, respectively.

- *Measurement maturity:* GPS is a mature 3D measurement technique. Improvements over the next decade will come from the inclusion of new GNSS signals and availability in real time. GPS relies on a well-defined terrestrial reference frame. However, GPS/GNSS networks are supported by multiple U.S. agencies and international partners, and so their long-term existence cannot be guaranteed.

  Radar interferometry is a mature measurement with well-established processing workflows and decades of scientific results to demonstrate its utility. Spaceborne radar interferometry has been performed using a number of non-U.S. platforms; a joint U.S.-Indian mission (NISAR) is scheduled for launch in 2021. Additionally, less accurate airborne InSAR is part of the NASA portfolio of measurements. The international constellation of radar satellites approaches the needed postings and vertical precisions specified earlier, but not at the temporal sampling needed to reduce atmospheric propagation artifacts. The newer Sentinel-1 series satellites are beginning to offer a typical cadence of 24 days in tectonically active areas and could provide 6-day repeated measurements in the case of a major geological disaster. NISAR has a much more capable radar that can achieve high spatial resolution over a wide swath on a 12-day cadence with two look directions. In addition, it offers a second channel for ionospheric correction, which will dramatically increase the accuracy of the measurements over length scales greater than 20 km. NISAR is designed for a 3-year lifetime, but no engineering barriers prevent collection of 10 years of usable data. Some recent radar satellites have operated successfully for 2 decades, whereas others have lasted only 6 years.
- *Trade-space definition:* Most of the preceding needs can be met by continuing existing capabilities but at denser temporal sampling. A NISAR follow-on mission is required to maintain a set of continuous L-band observations. A follow-on mission should offer as fast a repeat (more frequent than 12 days) and as high a spatial resolution as possible. NISAR's 12-day repeat was driven by the need to cover the equatorial regions for ecosystems (cryosphere requested a 1-day repeat). If that equatorial restriction could be relaxed, more frequent (even 3 day) L-band repeat could be obtained, which is ideal for fast-moving targets like ice streams and frequent revisit for earthquakes. A follow-on mission would be cheaper than the original NISAR owing to technology inheritance and reduction of risk.

  An alternative to a NISAR follow-on is to fly a constellation of SAR satellites with a simpler and cheaper architecture and, hence, perhaps less capability (e.g., no polarimetry, narrower swath), in order to provide global coverage, fast repeat, left/right looks, and free data access. The optimal configuration for science users would be a constellation that allows rapid repeats, both for quick response and for minimizing phase errors through multiple observations. This strategy would likely mean abandoning global coverage every orbit so that each platform could operate with a lower duty cycle and, hence, produce less total data. No other existing mission comes close to that goal, although Sentinel-1 could if its data acquisition policy is changed.

  For groundwater-related topographic change, airborne laser elevation maps can be added as needed. Especially in sparsely vegetated areas, most applications would benefit from the availability of the TanDEM-X digital elevation model (DEM)—a matter of cost/negotiation.
- *Continuity versus new:* The NISAR mission scheduled for launch will provide the requisite resolution. However, continuation of these types of measurements past the NISAR mission will be necessary to establish the appropriate baselines for understanding continuous landscape deformation. Additionally, the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) mission is currently active, although increased spatial and temporal coverage could be enabled by a constellation of autonomous imaging vehicles on a site-specific basis.

The surface deformation needs are the enhanced capabilities promised by NISAR, but with increased temporal sampling. Development of an international constellation of similar or identical satellites operated as an array is needed.

High-Resolution Bare-Earth Topography

Global maps of bare-earth topography serve multiple critical roles, including (1) providing a pre-event (e.g., earthquake, volcano, landslide, tsunami) reference surface; (2) imaging changes owing to these processes (Objectives S-1a, S-1b, S-1c, S-1d); (3) assessing areas of potential landslides and volcanic lahars (Objective S-2c); (4) forecasting coastal inundation or emergence owing to local sea-level change (Objective S-3b), and (5) relating topographic forms to the processes (e.g., erosion, landslides) that created and modified them (Objective S-4a). However, high-resolution, bare-earth topography is currently available for less than 1 percent of the terrestrial surface. Moreover, nearly all high-resolution topographic maps have been created with airborne lidar, which imposes significant practical limits on the extent of coverage. Although lidar-based topographic mapping from space on a contiguous and high-resolution grid poses a major technological challenge, it is a necessary and logical next step that promises to transform understanding of landscape evolution and the interactions of processes that shape them.

- *Measurement basis:* The topographic depiction needs sufficient spatial resolution to discriminate landscape-forming elements from one another, such as hillslopes, river channels, floodplains, and landslides. Moreover, the baseline depiction needs sufficiently high resolution to allow changes in the distribution of these landscape elements and related surface processes to be measured. Numerous studies over the last two decades have shown that digital topography with spatial resolution of considerably less than 5 m (and preferably ~1 m with ~10-fold greater vertical resolution) is required to resolve these differences and quantify these changes. However, changes in Earth's landscapes occur at vastly different rates. Thus, the most practical and cost-effective strategy for acquiring the necessary time series may be the acquisition of a global, baseline high-resolution data set that would be revisited as necessary in select areas (e.g., following a major flood, earthquake, volcanic eruption, or wildfire). Because high-resolution data cannot yet be acquired efficiently from space, an airborne platform is currently used. The rapid development and (now) widespread deployment of drone-based technologies could enable the autonomous collection of these high-resolution data, potentially by a constellation of vehicles. However, collecting 1 m topography using drones at a global scale faces obstacles of sovereignty.
- *Measurement maturity:* Airborne lidar is a mature technology that has been commercially deployed and is commonly used. Data processing workflows have been developed and refined, particularly for bare-earth topography, canopy structure, and aboveground biomass, although some human intervention is necessary to achieve research-grade data sets. Autonomous vehicle maturity lags behind that of the measurement itself, but widespread commercial and scientific applications will likely continue to produce rapid advances in this area in the coming decade. Space-based, global coverage remains an important but unrealized goal at present.
- *Trade-space definition:* Resolution requirements for these data are determined by the scale of the individual landscape elements that are changing, the magnitude of those changes, and the noise characteristics of the data. Many studies suggest that changes in landscape processes are resolvable only at meter scales, such that 10 m data (10 m × 10 m pixels) are insufficient. Furthermore, many landscape metrics, such as hillslope or channel gradients, are derivative quantities sensitive to systematic data noise. Last, all global elevation data sets contain elevation information contaminated

by the effects of aboveground vegetation. In most places the lack of a true bare-earth description of Earth's landscapes inhibits quantification of change across landscapes and between landscape elements. For these reasons, the value of the proposed topography degrades appreciably both at spatial resolutions exceeding several meters and with the inclusion of confounding elements such as vegetation.

- *Continuity versus new:* Technology development is needed to permit sustained, high-resolution (≤5 m horizontal, ≤1m vertical), bare-earth topographic mapping from space. This mapping needs to be spatially continuous (interpolation between highly resolved, but narrow strips is inadequate), and it also needs to be locally to regionally repeatable/refreshed based on anticipated or actual disruptive events.

Moderate-Resolution Topography (10 m Horizontal, 1 m Vertical; Low Earth Orbit)

Topography is needed to be able to calibrate many geophysical data sets (Questions S-1, S-2, S-3, S-5), provide a coarse description of spatially variable change of Earth's surface (Questions S-2, S-4), and predict surface-water flow patterns (Question S-6).

- *Measurement basis:* Water-flow predictions require knowing where water is and how it is routed across landscapes. Such data are important for measuring surface topography, which retains the surface water that ultimately feeds aquifer systems. Topographic data with 30 m postings at several meter accuracy provide a useful starting point.
- *Measurement maturity:* Several technologies have been deployed that are capable of generating the requisite data resolution.
- *Trade-space definition:* The TanDEM-X DEM is not available for general scientific use. This lack of availability is a matter of organization and collaboration, rather than fundamental scientific and engineering capabilities. The trade-offs in topographic accuracy are relatively straightforward. Notably, topographic data, such as TanDEM-X, provide the topography of the vegetation canopy, which is only a coarse approximation of Earth's actual surface. Commercial optical stereo data could provide a freely available DEM (e.g., Arctic DEM) with resolution and accuracy that exceeds that of TanDEM-X, albeit with the same limitations of failing to resolve the bare Earth wherever vegetation is present.
- *Continuity versus new:* The relevant data exist.

Hyperspectral UV/VNIR/SWIR/TIR (~ 30 m Spatial Scale; Revisit Between 1 and 7 Days)

Hyperspectral image data support Objectives S-1a, S-1c, S-2a, S-2b, S-4a, S-4c, and S-7a. Current Landsat-class observations are made in 7-10 wavelength bands. However, imaging spectroscopy with spectral resolutions of 10-20 nm (i.e., hundreds of wavelength bands) is possible with current technology and is critical for discriminating mineral, rock, gas, and vegetation species. This level of imaging spectroscopy is required in the full wavelength range from the UV to the TIR (0.3-12.5 microns). For general mapping and change detection, acquisition of these data at the 7-day time scale is adequate. To capture higher frequency events and phenomena, high spatial resolution data are required at the 1-3 day time scale. The higher spatial resolution, coupled with the higher temporal frequency, will provide the ability to monitor many transient events at volcanoes, capture small-scale phenomena proximal to the vent, and detect trends and precursory activity. These data will fuel a fundamental leap forward in the ability to understand volcanic activity and forecast future eruptions. Furthermore, the compositional information derived from data at finer spectral and temporal scales will support a variety of science and applications objectives—for example, (1) determining the gas species and ash particle size distribution in volcanic plumes; (2) mapping resources and surficial deposits related to natural processes, geologic disasters, and anthropogenic activity; (3) determining the magnitude and surface change resulting from landslides; (4) estimating the scale of river avulsion and erosion/deposition events; and (5) assessing the impact of human activities.

- *Measurement basis:* NASA has a long history of multi- to hyperspectral imaging of Earth's surface. The Landsat program of satellites has provided data at the sub-100-m spatial scale in the visible/near infrared (VNIR) and shortwave infrared (SWIR) since the 1970s. TIR imaging at approximately the same spatial scale became possible in the 1980s, although with only one or two wavelength bands. The ASTER sensor, launched in 1999 and still operating, provides improved spatial and spectral resolution in the VNIR/SWIR region and, for the first time, five spectral channels in the TIR. This multispectral TIR capability allows derivation of compositional information and improved temperature detection. Other sensors such as Hyperion, a hyperspectral VNIR/SWIR instrument on the EO-1 spacecraft, showed that collection of useful hyperspectral data from Earth orbit was possible. The Sentinel-2 multispectral spacecraft series with 13 spectral bands (4 VNIR bands at 10 meters, 6 SWIR bands at 20 meters, and 3 TIR bands at 60 meters spatial resolution) provides 5-day repeat coverage and thus fulfills several of the measurement requirements. Last, the previous decadal survey recommended a data continuity mission called Hyperspectral Infrared Imager (HyspIRI), which combines hyperspectral VNIR/SWIR with multispectral TIR. The mission would greatly expand the current imaging capabilities of ASTER and Sentinel-2 and replicate any data planned for future Landsat missions. However, the mission concept was not approved for Phase-A development.
- *Measurement maturity:* The UV/VNIR/SWIR/TIR measurement capability is mature in general and relatively low cost. New developments in optics and detector technology enabled by the NASA Instrument Incubator program and the Planetary Science Division has made deployment of such sensors on small satellites possible, thus enabling a constellation solution. Three or four satellites in opposing polar orbits with Landsat-like resolution would image the equator every 4-5 days and the polar regions less than once a day. If the sensors had the capabilities of HyspIRI, those numbers would decrease to ~1 image every day at the equator and every 2 hours closer to the poles. Satellites in geostationary orbits provide even greater temporal resolution data (~15-60 min), which is useful for detecting larger events with much shorter time scales and to support rapid responses to new eruptions. However, the spatial resolution is poor (many km pixels), which limits detection capability. Furthermore, spaceborne detection of CO_2 and water vapor in volcanic emissions remains a challenge.
- *Trade-space definition:* A thorough study of the trade space for a sensor class having capabilities approaching these requirements has been completed by the HyspIRI Study Group. Data from such a class of sensor would not only provide Landsat-quality data but would also improve all derived science data products. HyspIRI's TIR sensor would have greatly improved temporal revisit times (5 days at the equator versus 16 days for ASTER and Landsat), but not enough to detect high-frequency change or mitigate the obscuration of clouds in persistently cloudy regions. The multispectral TIR is slightly improved from that of ASTER, but it would not provide the spectral resolution of VNIR and SWIR data: the resolution required for detailed measurements of specific minerals or gas constituents, or to unravel complexly mixed temperatures. Furthermore, these sensors could be decoupled and placed on smaller satellites in opposing orbits, thus allowing the improved temporal resolution required.
- *Continuity versus new:* Except for Sentinel-2, the legacy instruments currently acquiring multispectral data are well past their design lifetimes. Landsat 8 is operational, but the TIR sensor is already

degraded. ASTER continues to operate 10-plus years past its planned 5-year mission, although the SWIR sensor failed in 2009. Commercial sensors are improving spectral capability (e.g., the latest Worldview-3 satellite or those operated by Planet Lab), but they do not provide TIR data, have the repeat time needed for longer term monitoring and postevent observation, or have a global mapping scope. These same issues pertain to planned hyperspectral missions such as Environmental Mapping and Analysis Program (EnMAP) and Hyperspectral Imager Suite (HISUI). Therefore, a critical gap is looming for moderate spatial resolution (~30 m) multi- to hyperspectral image data. These data bridge scales between the low spatial resolution imaging sensors designed primarily for weather observations and the high spatial resolution commercial imagers. The measurements made by the Landsat class of sensors will continue, but these data are not adequate to enable the needed step-change forward in the science. Global imaging spectroscopy from space with much higher temporal fidelity and spectral resolution than planned would provide this capability.

High-Resolution (Sub-m) Global Optical and Multispectral Observations

High-resolution optical data provide the most cost-effective means of determining where landscape change is happening or is likely to happen (Questions S-1, S-2, S-3, S-4).

- *Measurement basis:* Acquisition of high-resolution (<5 m horizontal-spacing postings) optical imagery can assist in mapping the extent of damage in areas where natural hazards have adversely affected humans and infrastructure (Question S-2). In areas devoid of vegetation, stereo high-resolution optical/multispectral satellite observations may be used to construct elevation models (<2 m horizontal-spacing postings) that can be used to quantify landscape change, including coastal inundation (Questions S-3, S-4). Both change detection and stereo applications require subpixel geolocation accuracy. Additionally, near-infrared observations may divulge important, spatially dense (<1.5 m multispectral resolution) information about the extent of vegetation cover and properties of the surface, such as relative vegetative health over seasonal repeat times. Such broad coverage, high-resolution data could be used to guide repeat, high-resolution surveys to areas where landscape change is most apparent. Such resurveys can also be used to quantify changes in the location and activity of humans. Localized activity could then be associated with imaged landscape changes to determine the impact of human activity on landscapes across global-scale watersheds.
- *Measurement maturity:* High-resolution spaceborne optical and near-infrared imaging is demonstrated and mature. Commercial satellites already in place (WorldView-2/3, WorldView-4) meet the operational requirements.
- *Trade-space definition:* The required technology is operational and has been commercialized.
- *Continuity versus new:* Continuity is an important requirement, but commercial viability likely will lead to future continuity of these data.

Time-Variable Gravity—Mass Change

Time-variable gravity measurements are important for revealing deformation associated with seismic activity (Objectives S-1b, S-2b), quantifying the rates of sea-level change and its driving processes; Objective S-3a), documenting seasonal snow- and ice-loading and melt losses in large catchments and mountain ranges (Objective S-4a), and quantifying significant fluxes in and out of large groundwater systems across the recharge area (Objectives S-6b, S-6c).

- *Measurement basis:* The GRACE (2002-2017), and Gravity Field and Steady-State Ocean Circulation Explorer (GOCE; 2009-2013) missions have been used to investigate Earth's mean and time-varying gravity across a spectrum of spatiotemporal wavelengths. GRACE yields time-variable gravity at a resolution of approximately 300 km at the equator and with an accuracy of about 2 cm water equivalent. At higher latitudes the resolution is approximately twice as good owing to the spatial convergence of the satellite tracks. Although this resolution and accuracy is sufficient to quantify large-scale mass changes (i.e., ice-sheet mass balance, global ocean mass, water storage in the largest hydrological basins), it is rather coarse for most water problems, because most watersheds are too small to be resolved with 200-300 km resolution. Moreover, the time-variable gravity data from GRACE is insufficient to detect mass changes of individual glaciers on the Greenland and Antarctica ice sheets. Improving spatial resolution to 100-200 km at the equator and reducing error from 2 cm to 1 cm water equivalent thickness would allow its application to studies of smaller hydrological basins, smaller glaciers, and smaller magnitude earthquakes.
- *Measurement maturity:* Deriving gravity by precisely measuring the change between satellite positions has become a mature measurement approach. The measurement accuracy of GRACE-FO is anticipated to be slightly better than GRACE because it will use better accelerometers, star trackers, refined geophysical background models, and an experimental laser interferometer that has the potential to improve ranging accuracy by 20 times or more. However, the limiting error source in time-variable gravity is aliasing of gravity signals that vary faster than the monthly averaging, and that cannot yet be modeled accurately.

  Achieving spatial scales of 100-200 km and an accuracy of <1 cm water equivalent RMS would require additional GRACE-FO satellite pairs or new technology such as an advanced gravity gradiometer. This innovation would allow the gravity fields to be resolved at higher temporal resolution in order to measure (not model) the high-variability mass signals. Flying at lower orbits may also be required, but technology (i.e., a drag-free thruster system) would have to be developed to reduce contamination from atmospheric drag. Flying in such a low orbit would also reduce the lifetime of such a mission.
- *Trade-space definition:* Flying a gravity mission similar to GRACE-FO toward the end of the next decade would incrementally improve spatial and temporal resolution of gravity measurements. Such a mission would allow both the continued observation of Greenland and Antarctica total mass balances and the quantification of their contribution to accelerating sea-level rise. Enhanced resolution would both allow measurements of water-storage change in very large (>500,000 km^2) hydrological drainage basins, including snow and ice in major mountain ranges, and contribute to measurements of very large (>M8) earthquakes. However, to make significant improvements that would advance studies of earthquakes, glacial isostatic adjustment, and glacier-scale processes would require constellations of gravity satellites, development of new gradiometer technology, or both (Pail et al., 2015). One potential way to advance would be to fly a large gravity mission like GRACE-FO with more advanced instruments, along with several lower-cost CubeSat missions in order to form a constellation.
- *Continuity versus new:* Future gravity missions are needed to maintain at least the continuity of the GRACE/GRACE-FO gravity measurement, primarily for global mean sea-level change studies. However, investing in constellations of gravity missions in optimal complementary orbits or improved gradiometers would likely reduce errors and resolution, increase temporal resolution, and allow time-variable gravity measurements that would considerably improve our understanding of earthquakes and glacial isostatic adjustment as well as cryospheric and hydrologic change.

Radar Altimetry—Sea-Surface Height

Radar altimetry is essential for measuring sea-surface height, which is critical for sea-level change studies (Objective S-3a). It is also important for measuring surface water distribution (Objective S-6a), and for measuring an accurate mean sea surface, from which high-resolution (<10 km) ocean gravity can be derived (Objective S-5a).

- *Measurement basis:* Radar altimeters operating in the Ku-band (with an additional C-band to estimate ionosphere path delays) have been used to measure sea-surface height with good precision (2 cm RMS accuracy at ~50 km resolution) since 1993. More recently, improved accuracy has been demonstrated for a series of Ka-band altimeters flown over the same ground track with overlapping missions (TOPEX/Poseidon, Jason-1, Jason-2, Jason-3). This approach has proven vital for linking records for climate studies. However, this level of accuracy also requires precise GPS receivers for orbit determination and microwave radiometers to correct for water vapor path delays. The planned SWOT mission will use Ka-band interferometric radar to improve accuracy to less than 1 cm over a swath with 2-5 km resolution. Coupled with topography, this resolution would allow definition of the surface forcing term for the water-flow model in a watershed, as well as detection of surface water area at smaller scales than is possible with traditional radar altimetry.
- *Measurement maturity:* Nadir Ku-band has been flown since the early 1990s, and the first Ka-band radar altimeter was launched in 2013. Thus, the measurement is mature. Radar interferometry is also mature, although its use for observing sea-surface height and surface water is still experimental and needs to be demonstrated with SWOT.
- *Trade-space definition:* Until SWOT demonstrates the predicted level of accuracy and resolution, traditional Ku- or Ka-band radar altimeters will be needed to maintain the observations necessary for quantifying global and regional sea-level change. Improvements in reducing the radar and radiometer footprints to get similar accuracy over the deep ocean all the way to the coastline would be a benefit. A continuation of the global tide-gauge network is also required to detect biases and drifts that have been common in the historical record. Many of these bias changes and drifts are the result of problems with the microwave radiometer correction. Adding an internal calibration mode in the radiometer loop would improve the stability of the sea surface height measurement.

  To utilize SWOT for hydrological studies, remote measurement of the forcing terms require instruments observing precipitation, runoff, soil moisture, and evapotranspiration. Many satellites feed the precipitation models, and these can often provide forecasts of incoming fluxes. Streams are often monitored with gages that yield surface runoff.
- *Continuity versus new:* At a minimum, continuity of at least one nadir-pointing altimeter with an accuracy at least as good as Jason-3 is critical for global and regional sea-level change studies. If SWOT science goals are met, then future missions based on that design would lead to significant improvements.

Magnetic Field Vector (Low Earth Orbit)

Measurements of the magnetic field at satellite altitude are sensitive to spatial and temporal variations in the core field (Objective S-5a), electrical conductivity of the mantle (S-5b), and the large-scale crustal field (Objective S-5c). Higher resolution technology under development has the potential to map smaller scale structures of the crustal field down to about 100 km wavelength (Objective S-5c).

- *Measurement basis:* In situ magnetic field vector with 0.1 nT per component precision and 0.5 nT per component absolute accuracy at length scales of 100 km to global. To achieve the science objectives the next generation of magnetic satellites has to carry accurate vector instrumentation at low enough cost to enable a constellation of satellites to meet science objectives. A 1-hour local time sampling of 12 satellites (each covering 2 local times) achieves optimal separation of internal and external magnetic fields. Science objectives include (1) identifying core dynamics with shorter temporal and spatial scales, (2) mapping electrical conductivity and water content of the mantle and lithosphere, (3) monitoring magnetic variations of tidal and steady ocean flow, (4) mapping the Curie isotherm depth to determine lithospheric heat flow, and (5) improving the accuracy of geomagnetic reference models for navigation, attitude control, and resource management. This constellation would also address ionospheric, magnetospheric, and heliospheric science objectives. New technology under development (guidestar laser measurements from polar orbiting satellite) will potentially offer much higher precision.
- *Measurement maturity:* After the successful Oersted, Challenging Mini-satellite Payload (CHAMP), Scientific Application Satellite-C (SAC-C), and Swarm magnetic missions, spaceborne vector magnetometry can be considered a mature technology. Accurate monitoring systems require vector magnetometers with omnidirectional accuracy, precise attitude determination, and an absolute reference for calibration. For a constellation of magnetic satellites the primary technological challenges lie in miniaturizing the systems, including the large star camera baffles, eliminating thermomechanical distortions in the attitude determination systems, and minimizing stray magnetic fields from thermoelectric currents and adjacent instruments.[3]
- *Trade-space definition:* A single polar orbiting satellite would enable the secular variation of the geomagnetic field to be monitored with sufficient accuracy for global geomagnetic reference models for navigation, attitude control, and resource management. A constellation of vector magnetic satellites would also enable progress in the science objectives listed earlier.
- *Continuity versus new:* Geomagnetic field models require continuous time series of measurements to track the secular variation of the geomagnetic field. The study of core processes also requires continuous coverage. The 3-year gap between CHAMP and Swarm caused a significant degradation in the accuracy of geomagnetic field models and limited our ability to understand processes and waves in Earth's core. Ideally, at least one geomagnetic satellite would be in orbit at all times. A one-time constellation of satellites with limited life span would enable progress toward additional science objectives.

Magnetic Field Intensity (Suborbital)

Mapping small-scale magnetic field variations caused by crustal magnetization is important for deriving the compositional and thermal structure of the continents (Objective S-5c). Over the oceans a complete mapping of the magnetic field would reveal the magnetic reversals over the past 200 million years as well as the plate tectonic history of the old ocean basins where shipboard surveys are sparse.

- *Measurement basis:* In situ magnetic field intensity with 0.01 nT precision and 10 nT absolute accuracy at length scales ranging from 1 km to 1,000 km.
- *Measurement maturity:* Magnetic intensity measurements have been made from aircraft for over 70 years. Unmanned aerial vehicles present a new opportunity for magnetometry.

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[3] New technology in development at NASA is discussed at https://arxiv.org/abs/1610.05385.

- *Trade-space definition:* The objective of airborne magnetic surveys is to map the crustal magnetic field, which does not change over time. The primary challenge is to survey remote areas, in particular the southern oceans.
- *Continuity versus new:* The crustal magnetic field has to be surveyed only once. Repeat measurements offer limited benefit.

Soil Moisture

The amount of water in the soil and on the surface as snow is a key part of the water balance and has major ecological impacts (Objectives S-4b, S-6b). Remote sensing estimation of these terms is also needed to develop the water-flow model.

- *Measurement basis:* The SMAP radar failure makes it difficult to achieve the spatial resolution needed to adequately estimate the surface forcing term for hydrologic models. A spaceborne radiometer without an active sensor that allows upscaling of the soil moisture measurements cannot achieve adequate resolution. Hence, an active radar with km resolution at daily sampling is needed. Daily sampling is needed to capture precipitation events.
- *Measurement maturity:* The technology has been developed, but needs to be made reliable and available.
- *Trade-space definition:* The amount of water stored in the soil (soil moisture) and the amount lost through evapotranspiration are relatively difficult to estimate. Soil Moisture Active-Passive (SMAP) would have yielded soil moisture, and other microwave radiometers can give soil moisture at 10 km resolution. Recent work using radar backscatter to augment the SMAP radiometric data suggests that soil moisture may be determinable at the km scale, a much more helpful measurement than the coarser radiometric-only satellites.
- *Continuity versus new:* Soil moisture approaches could consist of flying a reengineered SMAP mission that combines both active and passive L-band instruments operating at L-band. An orbital P-band radar, more equivalent to the Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) aircraft system, might be advantageous for capturing root-zone soil moisture, once that system is shown to be sufficiently accurate. This approach would likely entail a dual polarization on the receive system to compensate for the Faraday rotation from the ionosphere, which could compromise the active radar calibration accuracy.

Ice Thickness

Knowledge of ice thickness for outlet glaciers around Greenland and Antarctica is essential for documenting where ice sheets are vulnerable to change in coming decades. Thickness is also vital for models used to forecast potential impacts of grounded ice melt/discharge to sea-level rise (Objective S-3a).

- *Measurement basis:* The only way to meet the required accuracy/resolution (250 m horizontal resolution near grounding line, uncertainty <10 m vertical) is from suborbital (aircraft) radar that penetrates the ice and is reflected off the bedrock.
- *Measurement maturity:* Systems to measure ice thickness are robust, and many are already flown. However, more coordinated flights are necessary to observe important regions.

- *Trade-space definition:* Any measurement of a region never observed is an improvement over no measurement. At the very least, measurements need to be made over areas where demonstrated glacier thinning is occurring.
- *Continuity versus new:* No new technology is needed, just coordination of observations to cover the edges of both Greenland and Antarctica.

Ice Velocity

Knowledge of ice velocity for the Greenland and Antarctica ice sheets is vital for computing the ice discharge from the outlet glaciers (Objective S-3a).

- *Measurement basis:* Ice velocity with a 250 m resolution (less than the width of most glaciers) and an accuracy of better than ±1 m/yr RMS can be measured from space using optical and SAR pixel tracking for fast-moving ice streams, and InSAR to provide higher precision for slower moving ice. This capability has been demonstrated in the past, although InSAR measurements have not always been available at the monthly time scale required. Moreover, because many of the sensors have inclinations of ≤81 degrees, they cannot sample the main ice streams in Antarctica.
- *Measurement maturity:* Optical and SAR pixel tracking as well as InSAR are robust and mature measurement types.
- *Trade-space definition:* Continuous observations are necessary, and so one-off missions or long gaps between missions will reduce measurement usefulness. The Sentinel-1 series of SAR measurements will provide multidecadal measurements of ice-stream velocity over the lower latitude areas of Greenland and the Antarctic peninsula, although they lack the high-latitude coverage of the major Antarctic ice streams. Because the signal-to-noise ratio is low over ice sheets, small CubeSat SAR/InSAR missions with very short (1-day) repeat intervals may be able to meet the requirements and provide sufficient temporal resolution to monitor grounding line retreat as well as to detect rapid velocity changes.
- *Continuity versus new:* NISAR should meet the low-latitude requirements when it is launched, but future InSAR missions are necessary to ensure continued and higher latitude observations.

Ice Topography and Change

Although similar to the bare-earth topography measurement, knowledge of topography change over the Greenland and Antarctica ice sheets and other ice caps and glaciers is different in that a time series, not a single estimate, is required to estimate ice-sheet mass balance (Objective S-3a).

- *Measurement basis:* Satellite laser altimetry or lidar, such as from the previous ICESat or the future ICESat-2 mission, can likely achieve the required resolution and accuracy—spatial resolution on the scale of the area of a glacier (100 m × 100 m), accuracy in the mean of better than 10 cm RMS—and be able to resolve yearly changes with an accuracy better than 25 cm/yr.
- *Measurement maturity:* ICESat-2 is being flown to test the capability of a photon-counting lidar system. Airborne lidars have been used for much of the last decade over Greenland and Antarctica as part of Operation Icebridge.
- *Trade-space definition:* Extended time series of observations are necessary, and so one-off missions or long gaps between missions will reduce the usefulness of the data. Lidar-based ice-topography change has higher resolution than satellite gravity, making it a better tool for observing the mass

balance of individual glacier systems. However, this calculation requires an estimate of snow density and the amount of firn on the ice in order to deduce mass change from the surface topography change. The trend in ice topography is also sensitive to errors in glacial isostatic adjustment models.

- *Continuity versus new:* A mission beyond ICESat-2 is required to meet the goals of continuous observations of ice topography change in order to study glacier-scale dynamics. Improved systems to reduce error in height and improve spatial coverage would be beneficial.

Snow Density

Snow density is required to correct ice topography change measurements in order to derive ice mass change (Objective S-3a).

- *Measurement basis:* Snow density can currently be estimated from passive microwave radiometers and models with a resolution of several hundred kilometers and an accuracy of 4-5 cm RMS in terms of snow-water equivalent. Experiments have also used SAR data to obtain snow density with an accuracy of 0.03 g/cm^3 averaged over broad regions of the Himalayas.
- *Measurement maturity:* Estimation of snow density from passive microwave radiometers and models is mature, but is only accurate at spatial scales larger than ice topography measurements. Use of SAR data is still mainly experimental, but shows promise of higher accuracy and smaller horizontal resolution.
- *Trade-space definition:* To be most useful for ice topography data, the resolution needs to be close to that of the satellite lidar systems (~10 km × 10 km). However, if snow and firn is isotropic on the ice sheet, lower spatial resolutions could be used.
- *Continuity versus new:* No specific satellite instruments are needed; the calculations can be made from instruments used for other objectives.

Surface Melt

Surface melt is useful for determining where the surface of the ice sheet is melting (Objective S-3a).

- *Measurement basis:* The areal extent of surface melt can be deduced from visible imagery from space, but provides no quantitative information on the amount of mass lost.
- *Measurement maturity:* Current optical imagery is sufficient to detect and measure extent of surface melt. Thus, the technique is mature.
- *Trade-space definition:* A high-resolution image (~1 m pixel size) would be most useful. Daily observations of the ice sheet would be useful, but at least weekly would be sufficient.
- *Continuity versus new:* No new instruments are needed, just continuation of optical sensors or accessibility to commercial optical data.

RESULTING SOCIETAL BENEFIT

Implementing the program outlined earlier would create numerous societal benefits. At short time scales the greatest benefit likely derives from hazard mitigation: a goal that requires the ability to forecast, quantify, and lessen the impact of major impulsive events. At longer time scales, the ability to characterize the evolution of Earth's surface as a function of interactions among topography, weather, climate, ecology, hydrology, and society provides a basis to delineate the combinations of initial conditions and external forcing (natural and anthropogenic) that drive both abrupt and incremental landscape change, ranging from landslides and floods to topsoil loss and groundwater depletion. The observations proposed here promise to lead to a marked improvement in quantifying the processes that drive landscape change and impact habitability. Notable societal benefits for implementing each major science question include the following:

- Forecasting natural disasters, including the timing and size of earthquakes and any associated tsunamis, the timing and duration of volcanic eruptions, and the timing and location of landslides. The most costly natural disaster in world history was the 2011 M9.0 Tohoku earthquake and tsunami, but even smaller events, such as the 2010 Eyjafjallajökull volcanic eruption in Iceland, take a toll on society. Satellite-based measurements are the only practical means for monitoring geological hazards around the world: key information for making forecasts.
- Responding rapidly to natural disasters and mitigating their consequences. The "library" of high-resolution space-based observations of disaster-prone areas permits rapid quantification of the impacts of geological disasters on landscapes and societal infrastructure, both during the event and in its aftermath. Detectable impacts may be caused by impulsive events, such as earthquakes or volcanic eruptions, or by more sustained events, such as drought or extensive wildfires.
- Understanding and forecasting how sea level will change along coastlines, where ~600 million people currently live. Sea-level rise on the coast is a product of changes in ocean volume and mass, as well as vertical land motion. Remote sensing measurements of sea-surface height and ice-sheet characteristics are essential for understanding the drivers and rates of sea-level change. Space- and land-based geodesy permit quantification of the amount and rate of uplift or subsidence of the land surface. When these data are combined with high-resolution coastal topography, the magnitude of both incremental inundation and storm-driven flooding can be forecast and potentially mitigated.
- Quantifying global, decadal landscape change and how that change affects the groundwater, soil, and biological resources on which society depends. Most landscapes are shaped incrementally by fluvial, hillslope, coastal, cryospheric, and ecological processes. The use of high-resolution time series underlies the ability to delineate trends of change and to develop societal strategies to mitigate or arrest changes that threaten societal health and sustainability.
- Monitoring, understanding, and forecasting spatial and temporal variations of Earth's magnetic field. Global navigation and protection from excessive cosmic radiation depend on the shape, strength, and persistence of Earth's magnetic field. A constellation of satellites with vector magnetometers can measure spatial and temporal variations in the magnetic field needed to update global geomagnetic field models.
- Quantifying mantle convection to understand how it drives plate motions and generates earthquakes and volcanic eruptions. Mantle tractions drive lithospheric strain accumulation that loads faults, causes earthquakes, and triggers volcanism. Space- and land-based geodetic measurements, combined with seismic models, are used to predict mantle motions. A more accurate terrestrial reference frame and a detailed long-term land surface deformation field serve to quantify the level of mantle coupling. Together, this information will underpin improved forecasts of crustal deformation and the resultant seismic and volcanic hazards, and inform strategies to enhance resilience to destructive earthquakes and eruptions.
- Understanding temporal variations of subsurface water storage and transport. Global population growth and increasing extraction of groundwater for agricultural, municipal, and industrial uses are depleting this truly vital resource. Both geodesy and gravity measurements enable systematic tracking of the location and pace of groundwater extraction, which is growing in importance, given the mismatch between the rapid rate of withdrawal and the slow infiltration that replenishes groundwater supplies.

- Improving the discovery and management of energy, mineral, and soil resources. The chemical composition of these resources can be mapped using high-resolution spectral imaging, and data from moderate-resolution multispectral satellites and SAR satellites can be used to detect and monitor surface oil spills, dispersal plumes, contaminants, soil loss, nutrient depletion, and ecological change.

Overall, many Earth surface and interior processes are caused or influenced by anthropogenic activity. Today, tectonically inactive areas are riddled with earthquakes owing to wastewater injection, and invasive species and wildfires are adversely affecting landscape stability, nutrient availability, and overall sustainability. Together, detailed topography, temporally dense time series of high-resolution imagery, and highly resolved geodetic measurements are key elements for defining rates of change, forecasting developing hazards, and creating new strategies to reduce harmful societal impacts.

REFERENCES

Ablain, M., J.F. Legeais, P. Prandi, M. Marcos, L. Fenoglio-Marc, H.B. Dieng, J. Benveniste, and A. Cazenave. 2017. Satellite altimetry-based sea level at global and regional scales. *Surveys in Geophysics* 38(1):7-31.

Bettinelli, P., J.P. Avouac, M. Flouzat, L. Bollinger, G. Ramillien, S. Rajaure, and S. Sapkota. 2008. Seasonal variations of seismicity and geodetic strain in the Himalaya induced by surface hydrology. *Earth and Planetary Science Letters* 266(3-4):332-344.

Booth, A.M., S.R. LaHusen, A.R. Duvall, and D.R. Montgomery. 2017. Holocene history of deep-seated landsliding in the North Fork Stillaguamish River valley from surface roughness analysis, radiocarbon dating, and numerical landscape evolution modeling. *Journal of Geophysical Research: Earth Surface* 122(2):456-472.

Brantley, S.L., M.B. Goldhaber, and K.V. Ragnarsdottir. 2007. Crossing disciplines and scales to understand the critical zone. *Elements* 3(5):307-314.

Bürgmann, R., G. Hilley, A. Ferretti, and F. Novali. 2006. Resolving vertical tectonics in the San Francisco Bay Area from permanent scatterer InSAR and GPS analysis. *Geology* 34(3):221-224.

Carn, S.A., L. Clarisse, and A.J. Prata. 2016. Multi-decadal satellite measurements of global volcanic degassing. *Journal of Volcanology and Geothermal Research* 311(1):99-134.

Chambers, D.P., A. Cazenave, N. Champollion, H. Dieng, W. Llovel, R. Forsberg, K. von Schuckmann, and Y. Wada. 2017. Evaluation of the global mean sea level budget between 1993 and 2014. *Surveys in Geophysics* 38(1):309-327.

Chu, W., T.T. Creyts, and R.E. Bell. 2016. Rerouting of subglacial water flow between neighboring glaciers in West Greenland. *Journal of Geophysical Research: Earth Surface* 121(5):925-938.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, et al. 2013. Sea level change. In *Climate Change 2013: The Physical Science Basis* (eds. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley). Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Davis, J.L., Y. Fialko, W.E. Holt, M.M. Miller, S.E. Owen, and M.E. Pritchard. 2012. A foundation for innovation: Grand challenges in geodesy. In *Report from the Long-Range Science Goals for Geodesy Community Workshop*, UNAVCO, Boulder, CO.

Davis, J.L., L.H. Kellogg, J.R. Arrowsmith, B.A. Buffett, C.G. Constable, A. Donnellan, E.R. Ivins, et al. 2016. "Challenges and Opportunities for Research in ESI (CORE)." Report from the NASA Earth Surface and Interior (ESI) Focus Area Workshop, November 2-3, 2015, Arlington, VA.

DeCelles, P.G., and K.A. Giles. 1996. Foreland basin systems. *Basin Research* 8:105-123.

Dolan, P., D. Burggraf, K. Soofi, R. Fitzsimmons, E. Aydemir, O. Senneseth, and L. Strickland. 2004. "Challenges to Exploration in Frontier Basins—The Barbados Accretionary Prism." Presented at the AAPG International Conference and Exhibition, October 24-27, Cancun, Mexico.

Gouhier, M., and D. Coppola. 2011. Satellite-based evidence for a large hydrothermal system at Piton de la Fournaise volcano (Reunion Island). *Geophysical Research Letters* 38(2):L02302.

Han, S.C., R. Riva, J. Sauber, and E. Okal. 2013. Source parameter inversion for recent great earthquakes from a decade-long observation of global gravity fields. *Journal of Geophysical Research Solid Earth* 118(3):1240-1267.

Han, S.C., J.M. Sauber, and F. Pollitz. 2014. Broad-scale postseismic gravity change following the 2011 Tohoku-Oki earthquake and implications for deformation by viscoelastic relaxation and afterslip. *Geophysical Research Letters* 41(16):5797-5805.

Han, S.C., J.M. Sauber, and F. Pollitz. 2015. "Postseismic Gravity Changes Caused by Persistent Viscoelastic Relaxation after a Series of Great Earthquakes since 2004." Presented at the GRACE Science Team Meeting, September 21-23, Austin, TX.

Harris, N.L., S. Brown, S.C. Hagen, S.S. Saatchi, S. Petrova, W. Salas, M.C. Hansen, P.V. Potapov, and A. Lotsch. 2012. Baseline map of carbon emissions from deforestation tropical regions. *Science* 336:1573-1576.

Haugerud, R.A., D.J. Harding, S.Y. Johnson, J.L. Harless, C.S. Weaver, and B.L. Sherrod. 2003. High-resolution lidar topography of the Puget Lowland, Washington. *GSA Today* 13:4-10.

Heimlich, C., N. Gourmelen, F. Masson, J. Schmittbuhl, S.W. Kim, and J. Azzola. 2015. Uplift around the geothermal power plant of Landau (Germany) as observed by InSAR monitoring. *Geothermal Energy* 3(1):2.

Henney, L., L. Rodríguez, and I. Watson. 2012. A comparison of SO_2 retrieval techniques using mini-UV spectrometers and ASTER imagery at Lascar volcano, Chile. *Bulletin of Volcanology* 74:589-594.

Hilley, G.E., R. Bürgmann, A. Ferrietti, F. Novali, and F. Rocca. 2004. Dynamics of slow-moving landslides from permanent scatterer analysis. *Science* 304:1952-1955.

Holt, W.E., and G. Shcherbenko. 2013. Toward a continuous monitoring of the horizontal displacement gradient tensor field in southern California using cGPS observations from plate boundary observatory (PBO). *Seismological Research Letters* 84(3):455-467.

Hurst, M.D., S.M. Mudd, M. Attal, and G. Hilley. 2013. Hillslopes record the growth and decay of landscapes. *Science* 341:868-871.

Jasechko, S., J.W. Kirchner, J.M. Welker, and J.J. McDonnell. 2016. Substantial proportion of global streamflow less than three months old. *Nature Geoscience* 9:126-129.

Kirby, E., and K.X. Whipple. 2012. Expression of active tectonics in erosional landscapes. *Journal of Structural Geology* 44:54-75.

Kopp, R.E., F.J. Simons, J.X. Mitrovica, A.C. Maloof, and M. Oppenheimer. 2009. Probabilistic assessment of sea level during the last interglacial stage. *Nature* 462:863-867.

Kreemer, C., G. Blewitt, and E.C. Klein. 2014. A geodetic plate motion and global strain rate model. *Geochemistry, Geophysics, Geosystems* 15(10):3849-3889.

Kump, L.R., S.L. Brantley, and M.A. Arthur. 2000. Chemical weathering, atmospheric CO_2, and climate. *Annual Review of Earth and Planetary Sciences* 28:611-667.

Lamb, M.P., J.S. Scheingross, W.H. Amidon, E. Swanson, and A. Limaye. 2011. A model for fire-induced sediment yield by dry ravel in steep landscapes. *Journal of Geophysical Research* 116:F03006.

Lange, H., G. Casassa, E. Ivins, L. Schröder, M. Fritsche, A. Richter, A. Groh, and R. Dietrich. 2014. Observed crustal uplift near the Southern Patagonian Icefield constrains improved viscoelastic Earth models. *Geophysical Research Letters* 41:805-812.

Lay, T., R.C. Aster, D.W. Forsyth, B. Romanowicz, R.M. Allen, V.F. Cormier, and J. Gomberg. 2009. *Seismological Grand Challenges in Understanding Earth's Dynamic Systems*. Report to the National Science Foundation. Washington, DC: IRIS Consortium.

Leuliette, E.W., and R.S. Nerem. 2016. Contributions of Greenland and Antarctica to global and regional sea level change. *Oceanography* 29(4):154-159.

Lipman, P.W., and D.R. Mullineaux, eds. 1981. *The 1980 Eruptions of Mount St. Helens, Washington (No. 1250)*. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey.

Milne, G.A., and J.X. Mitrovica. 2008. Searching for eustasy in deglacial sea-level histories. *Quaternary Science Reviews* 27(25-26):2292-2302.

Molnar, P., and P. England. 1990. Late Cenozoic uplift of mountain ranges and global climate change: Chicken or egg? *Nature* 346:29-34.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2017. *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing*. Washington, DC: The National Academies Press.

Nerem, R.S., B.D. Beckley, J.T. Fasullo, B.D. Hamlington, D. Masters, and G.T. Mitchum. 2018. Climate-change-driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the National Academy of Sciences* 115(9):2022-2025.

NRC (National Research Council). 2010a. *Landscapes on the Edge: New Horizons for Research on Earth's Surface*. Washington, DC: The National Academies Press.

NRC. 2010b. *Precise Geodetic Infrastructure: National Requirements for a Shared Resource*. Washington, DC: The National Academies Press.

NRC. 2012a. *New Research Opportunities in the Earth Sciences*. Washington, DC: The National Academies Press.

NRC. 2012b. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Washington, DC: The National Academies Press.

Pail, R., R. Bingham, C. Braitenberg, H. Dobslaw, A. Eicker, A. Güntner, M. Horwath, E. Ivins, L. Longuevergne, I. Panet, and B. Wouters. 2015. Science and user needs for observing global mass transport to understand global change and to benefit society. *Surveys in Geophysics* 36(6):743-772.

Peltier, W.R., and R.G. Fairbanks. 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. *Quaternary Science Reviews* 25:3322-3337.

Porder, S., G.P. Asner, and P.M. Vitousek. 2005. Ground-based and remotely sensed nutrient availability across a tropical landscape. *Proceedings of the National Academy of Sciences* 102(31):10909-10912.

Prata, A.J., and J. Kerkmann. 2007. Simultaneous retrieval of volcanic ash and SO_2 using MSG-SEVIRI measurements. *Geophysical Research Letters* 34(5):L05813.

Pritchard, H.D., R.J. Arthern, D.G. Vaughan, and L.A. Edwards. 2009. Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. *Nature* 461:971-975.

Pritchard, M.E., and M. Simons. 2004. An InSAR-based survey of volcanic deformation in the central Andes. *Geochemistry, Geophysics, Geosystems* 5(2).

Reath, K.A., M.S. Ramsey, J. Dehn, and P.W. Webley. 2016. Predicting eruptions from precursory activity using remote sensing data hybridization. *Journal of Volcanology and Geothermal Research* 321:18-30.

Savage, J.C., and W. Thatcher. 1992. Interseismic deformation at the Nankai Trough, Japan, subduction zone. *Journal of Geophysical Research: Solid Earth* 97(B7):11117-11135.

Smith, B.E., H.A. Fricker, I.R. Joughin, and S. Tulaczyk. 2009. An inventory of active subglacial lakes in Antarctica detected by ICESat (2003-2008). *Journal of Glaciology* 55(192):573-595.

Stanley, T., and D.B. Kirschbaum. 2017. A heuristic approach to global landslide susceptibility mapping. *Natural Hazards* 87(1):145-164.

Syvitski, J., A.J. Kettner, I. Overeem, E.W.H. Hutton, M.T. Hannon, G.R. Brakenridge, J. Day, C. Vörösmarty, Y. Saito, L. Giosan, and R.J. Nicholls. 2007. Sinking deltas due to human activities. *Nature Geoscience* 2:681-686.

Voigt, S., F. Giulio-Tonolo, J. Lyons, J. Kučera, B. Jones, T. Schneiderhan, G. Platzeck, et al. 2016. Global trends in satellite-based emergency mapping. *Science* 353(6296):247-252.

Willett, S.D. 1999. Orogeny and orography: The effects of erosion on the structure of mountain belts. *Journal of Geophysical Research: Solid Earth* 104(B12):28957-28981.

Willett, S.D., S.W. McCoy, J.T. Perron, L. Goren, and C. Chen. 2014. Dynamic reorganization of river basins. *Science* 343(6175).

Zoback, M.L., E. Geist, J. Pallister, D.P. Hill, S. Young, and W. McCausland. 2013. Advances in natural hazard science and assessment, 1963-2013. *Geological Society of America Special Paper* 501:81-154.

Appendixes

A

Program of Record

Table A.1 summarizes the Program of Record (POR) used by the survey steering committee to determine which observations are expected to be available from existing or confirmed plans for instruments/missions during the 2017-2027 time frame. As discussed in Chapter 3, the committee's Observing System Priorities (Table 3.3) resulted from prioritizing augmentations to the POR to address unmet observation needs.

The POR entries for NASA and NOAA were confirmed by those agencies. Entries for non-U.S. agencies reflect plans the committee believes to be reliable, but that were not confirmed by those agencies. The committee also notes that continuing support for POR elements that have been launched, and completion of those elements not yet launched, is critical to the program recommended in this report.

TABLE A.1 ESAS Consolidated Program of Record (POR)

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
NASA + NOAA								
Aqua		AMSU-A	Absorption-band MW radiometer/spectrometer	NASA, JAXA, INPE	Extended Operations	2002	6	>2022
		CERES	Broadband radiometer	NASA, JAXA, INPE	Operations	2002	6	>2022
		AIRS	Medium-resolution IR spectrometer	NASA, JAXA, INPE	Operations	2002	6	>2022
		MODIS	Medium-resolution spectroradiometer	NASA, JAXA, INPE	Operations	2002	6	>2022
Aura		TES	High-resolution nadir-scanning IR spectrometer	NASA, NSO, FMI, NIVR, UKSA	Operations	2004	6	>2022
		OMI	Nadir-viewing wide-field-imaging spectrometer	NASA, NSO, FMI, NIVR, UKSA	Operations	2004	6	>2022
		MLS	Passive microwave limb-sounding radiometer/spectrometer	NASA, NSO, FMI, NIVR, UKSA	Operations	2004	6	>2022
CALIPSO		CALIOP	Atmospheric lidar	NASA, CNES	Operations	2006	3	>2022
		IIR	Multipurpose imaging VIS/IR radiometer	NASA, CNES	Operations	2006	3	>2022
		WFC	Multipurpose imaging VIS/IR radiometer	NASA, CNES	Operations	2006	3	>2022
CATS-on-ISS		CATS	Atmospheric lidar	NASA	Operations	2015	3	2020
CLARREO Pathfinder-on-ISS		CLARREO Pathfinder Reflected Solar Spectrometer	Spectrometer	NASA	Development	2020	1	2022
CloudSat		CPR (CloudSat)	Cloud and precipitation radar	NASA, DoD (USA), CSA	Operations	2006	2	2018
COSMIC	FM1	GOX	GNSS radio-occultation receiver	NOAA, NSPO, UCAR	Operations	2006	2	2008
	FM2	GOX	GNSS radio-occultation receiver	NOAA, NSPO, UCAR	Operations	2006	2	2008
	FM4	GOX	GNSS radio-occultation receiver	NOAA, NSPO, UCAR	Operations	2006	2	2008
	FM5	GOX	GNSS radio-occultation receiver	NOAA, NSPO, UCAR	Operations	2006	2	2008
	FM6	GOX	GNSS radio-occultation receiver	NOAA, NSPO, UCAR	Operations	2006	2	2008
	2A (Equatorial)	TGRS	GNSS radio-occultation receiver	NOAA, NSPO, UCAR	Development	2017	5	2022
	2B (Polar)	TGRS	GNSS radio-occultation receiver	NOAA, UCAR	Development	TBD	TBD	TBD
CYGNSS	CYGNSS	DDMI (CYGNSS)	GNSS receiver	NASA, NOAA	Operations	2016	2	>2019
DMSP	F-14	SSM/T-1	Absorption-band MW radiometer/spectrometer	NOAA, USAF	Operations	1997	4	2016
		SSM/T-2	Absorption-band MW radiometer/spectrometer	NOAA, USAF	Operations	1997	4	2016
		SSM	Magnetometer	NOAA, USAF	Operations	1997	4	2016
		SSM/I	Multipurpose imaging MW radiometer	NOAA, USAF	Operations	1997	4	2016
		OLS	Multipurpose imaging VIS/IR radiometer	NOAA, USAF	Operations	1997	4	2016

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
	F-15	SSM/T-1	Absorption-band MW radiometer/spectrometer	NOAA, USAF	Operations	1999	5	2017
		SSM/T-2	Absorption-band MW radiometer/spectrometer	NOAA, USAF	Operations	1999	5	2017
		SSM	Magnetometer	NOAA, USAF	Operations	1999	5	2017
		SSM/I	Multipurpose imaging MW radiometer	NOAA, USAF	Operations	1999	5	2017
		OLS	Multipurpose imaging VIS/IR radiometer	NOAA, USAF	Operations	1999	5	2017
	F-16	SSM	Magnetometer	NOAA, USAF	Operations	2003	5	2018
		SSMIS	Multipurpose imaging MW radiometer Absorption-band MW radiometer/spectrometer	NOAA, USAF	Operations	2003	5	2018
		OLS	Multipurpose imaging VIS/IR radiometer	NOAA, USAF	Operations	2003	5	2018
	F-17	SSM	Magnetometer	NOAA, USAF	Operations	2006	5	2019
		SSM/IS	Multipurpose imaging MW radiometer	NOAA, USAF	Operations	2006	5	2019
		OLS	Multipurpose imaging VIS/IR radiometer	NOAA, USAF	Operations	2006	5	2019
	F-18	SSM	Magnetometer	NOAA, USAF	Operations	2009	5	2021
		SSMIS	Multipurpose imaging MW radiometer Absorption-band MW radiometer/spectrometer	NOAA, USAF	Operations	2009	5	2021
		OLS	Multipurpose imaging VIS/IR radiometer	NOAA, USAF	Operations	2009	5	2021
DSCOVR		Plasma-Mag	Magnetometer	NOAA, NASA	Operations	2015	5	2020
		EPIC	Multipurpose imaging VIS/IR radiometer	NOAA, NASA	Operations	2015	5	2020
		NISTAR	Solar irradiance monitor	NOAA, NASA	Operations	2015	5	2020
ECOSTRESS-on-ISS		PHyTIR	Thermal Infrared Radiometer	NASA	Development	2018	1	2019
GEDI-on-ISS		GEDI	Lidar	NASA	Development	2018	2	2020
GeoCARB		GeoCARB Instrument	Scanning IR slit spectrometer	NASA	Development	2021	5	2026
GOES	GOES-13	Imager	Multipurpose imaging VIS/IR radiometer	NOAA	Operations	2006	10	2021
		Sounder	Narrow-band channel IR radiometer	NOAA	Operations	2006	10	2021
	GOES-14	Imager	Multipurpose imaging VIS/IR radiometer	NOAA	Operations	2009	10	2024
		Sounder	Narrow-band channel IR radiometer	NOAA	Operations	2009	10	2024
	GOES-15	Imager	Multipurpose imaging VIS/IR radiometer	NOAA	Operations	2010	10	2025
		Sounder	Narrow-band channel IR radiometer	NOAA	Operations	2010	10	2025
	GOES-16	GLM	Lightning imager	NOAA, NASA	Operations	2016	10	2026

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
		Magnetometer	Magnetometer	NOAA, NASA	Operations	2016	10	2026
		ABI	Multipurpose imaging VIS/IR radiometer	NOAA, NASA	Operations	2016	10	2026
		EXIS	Solar irradiance monitor	NOAA, NASA	Operations	2016	10	2026
		SUVI	Solar irradiance monitor	NOAA, NASA	Operations	2016	10	2026
	GOES-S	GLM	Lightning imager	NOAA, NASA	Development	2018	10	2029
		Magnetometer	Magnetometer	NOAA, NASA	Development	2018	10	2029
		ABI	Multipurpose imaging VIS/IR radiometer	NOAA, NASA	Development	2018	10	2029
		EXIS	Solar irradiance monitor	NOAA, NASA	Development	2018	10	2029
		SUVI	Solar irradiance monitor	NOAA, NASA	Development	2018	10	2029
	GOES-T	GLM	Lightning imager	NOAA, NASA	Development	2020	10	2035
		Magnetometer	Magnetometer	NOAA, NASA	Development	2020	10	2035
		ABI	Multipurpose imaging VIS/IR radiometer	NOAA, NASA	Development	2020	10	2035
		EXIS	Solar irradiance monitor	NOAA, NASA	Development	2020	10	2035
		SUVI	Solar irradiance monitor	NOAA, NASA	Development	2020	10	2035
	GOES-U	GLM	Lightning imager	NOAA, NASA	Development	2025	10	2038
		Magnetometer	Magnetometer	NOAA, NASA	Development	2025	10	2038
		ABI	Multipurpose imaging VIS/IR radiometer	NOAA, NASA	Development	2025	10	2038
		EXIS	Solar irradiance monitor	NOAA, NASA	Development	2025	10	2038
		SUVI	Solar irradiance monitor	NOAA, NASA	Development	2025	10	2038
GPM		DPR	Cloud and precipitation radar	NASA, JAXA	Operations	2014	3	>2022
		GMI	Multipurpose imaging MW radiometer	NASA, JAXA	Operations	2014	3	>2022
GRACE		HAIRS	Satellite-to-satellite ranging system	NASA, GFZ, ESA	Operations	2002	5	2018
GRACE-FO		GRACE instrument	Satellite-to-satellite ranging system	NASA, GFZ	Development	2018	5	2022
		LRI	Satellite-to-satellite ranging system	NASA, GFZ	Development	2018	5	2022
		MWI	Satellite-to-satellite ranging system	NASA, GFZ	Development	2018	5	2022
ICESat-2		ATLAS	Lidar altimeter	NASA	Development	2018	3	2021
Jason-3		GPSP	GNSS receiver	EUMETSAT, NOAA, CNES, NASA	Operations	2016	5	2021

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
		LRA	Laser retroreflector	EUMETSAT, NOAA, CNES, NASA	Operations	2016	5	2021
		AMR-2	Nonscanning MW radiometer	EUMETSAT, NOAA, CNES, NASA	Operations	2016	5	2021
		POSEIDON-3B Altimeter	Radar altimeter	EUMETSAT, NOAA, CNES, NASA	Operations	2016	5	2021
		DORIS-NG	Radio-positioning system	EUMETSAT, NOAA, CNES, NASA	Operations	2016	5	2021
JPSS	JPSS-1	ATMS	Absorption-band MW radiometer/spectrometer	NOAA, EUMETSAT, NASA	Development	2017	8	2024
		CERES	Broadband radiometer	NOAA, EUMETSAT, NASA	Development	2017	8	2024
		OMPS-N	High-resolution nadir-scanning SW spectrometer	NOAA, EUMETSAT, NASA	Development	2017	8	2024
		CrIS	Medium-resolution IR spectrometer	NOAA, EUMETSAT, NASA	Development	2017	8	2024
		VIIRS	Multipurpose imaging VIS/IR radiometer	NOAA, EUMETSAT, NASA	Development	2017	8	2024
	JPSS-2	ATMS	Absorption-band MW radiometer/spectrometer	NOAA, EUMETSAT, NASA	Development	2022	8	2029
		RBI	Broadband radiometer	NOAA, EUMETSAT, NASA	Development	2022	8	2029
		OMPS-N	High-resolution nadir-scanning SW spectrometer	NOAA, EUMETSAT, NASA	Development	2022	8	2029
		OMPS-L	Limb-scanning SW spectrometer	NOAA, EUMETSAT, NASA	Development	2022	8	2029
		CrIS	Medium-resolution IR spectrometer	NOAA, EUMETSAT, NASA	Development	2022	8	2029
		VIIRS	Multipurpose imaging VIS/IR radiometer	NOAA, EUMETSAT, NASA	Development	2022	8	2029
	JPSS-3	ATMS	Absorption-band MW radiometer/spectrometer	NOAA, EUMETSAT, NASA	Development	2026	8	2033
		RBI	Broadband radiometer	NOAA, EUMETSAT, NASA	Development	2026	8	2033
		OMPS-N	High-resolution nadir-scanning SW spectrometer	NOAA, EUMETSAT, NASA	Development	2026	8	2033
		OMPS-L	Limb-scanning SW spectrometer	NOAA, EUMETSAT, NASA	Development	2026	8	2033
		CrIS	Medium-resolution IR spectrometer	NOAA, EUMETSAT, NASA	Development	2026	8	2033
		VIIRS	Multipurpose imaging VIS/IR radiometer	NOAA, EUMETSAT, NASA	Development	2026	8	2033
	JPSS-4	ATMS	Absorption-band MW radiometer/spectrometer	NOAA, EUMETSAT, NASA	Development	2031	8	2038
		RBI	Broadband radiometer	NOAA, EUMETSAT, NASA	Development	2031	8	2038
		OMPS-N	High-resolution nadir-scanning SW spectrometer	NOAA, EUMETSAT, NASA	Development	2031	8	2038

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
		OMPS-L	Limb-scanning SW spectrometer	NOAA, EUMETSAT, NASA	Development	2031	8	2038
		CrIS	Medium-resolution IR spectrometer	NOAA, EUMETSAT, NASA	Development	2031	8	2038
		VIIRS	Multipurpose imaging VIS/IR radiometer	NOAA, EUMETSAT, NASA	Development	2031	8	2038
LAGEOS	LAGEOS-1	LRA (LAGEOS)	Laser retroreflector	NASA, ASI	Operations	1976	N/A	N/A
	LAGEOS-2	LRA (LAGEOS)	Laser retroreflector	NASA, ASI	Operations	1992	N/A	N/A
Landsat	Landsat-7	ETM+	High-resolution optical imager	USGS, NASA	Operations	1999	5	2022
	Landsat-8	OLI	High-resolution optical imager	USGS, NASA	Operations	2013	5	>2022
		TIRS	Narrow-band channel IR radiometer	USGS, NASA	Operations	2013	5	>2022
	Landsat-9	OLI-2	High-resolution optical imager	NASA, USGS	Development	2020	5	>2025
		TIRS-2	Narrow-band channel IR radiometer	NASA, USGS	Development	2020	5	>2025
LIS-on-ISS		LIS	Lightning imager	NASA	Operations	2017	2	2020
MAIA		MAIA	Multichannel/direction/polarization radiometer	NASA	Development	2021	2	2023
NISAR		S-band SAR	Imaging radar (SAR)	NASA, ISRO	Development	2021	3	2024
		L-band SAR	Imaging radar (SAR)	NASA, ISRO	Development	2021	3	2024
OCO-2		Spectrometer (OCO-2)	High-resolution spectrometer	NASA	Operations	2014	2	>2022
OCO-3-on-ISS		Spectrometer (OCO-3)	High-resolution spectrometer	NASA	Development	2018	3	2021
ORS-6		COWVR	Polarimetric Imaging Radiometer	DOD	Development	2017	2	2019
OSTM (Jason-2)		GPSP	GNSS receiver	NASA, NOAA, CNES, EUMETSAT	Operations	2008	3	>2022
		LRA	Laser retroreflector	NASA, NOAA, CNES, EUMETSAT	Operations	2008	3	>2022
		AMR	Nonscanning MW radiometer	NASA, NOAA, CNES, EUMETSAT	Operations	2008	3	>2022
		POSEIDON-3	Radar altimeter	NASA, NOAA, CNES, EUMETSAT	Operations	2008	3	>2022
		DORIS-NG	Radio-positioning system	NASA, NOAA, CNES, EUMETSAT	Operations	2008	3	>2022
PACE		OCI	Medium-resolution spectroradiometer	NASA	Development	2022	3	2025
		Next Gen APS (ACE)	Multichannel/direction/polarization radiometer	NASA	Development	2022	3	2025
POES	NOAA-15	AMSU-A	Absorption-band MW radiometer/spectrometer	NOAA	Operations	1998	3	2017

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
		AMSU-B	Absorption-band MW radiometer/spectrometer	NOAA	Operations	1998	3	2017
		AVHRR/3	Multipurpose imaging VIS/IR radiometer	NOAA	Operations	1998	3	2017
		HIRS/3	Narrow-band channel IR radiometer	NOAA	Operations	1998	3	2017
	NOAA-18	AMSU-A	Absorption-band MW radiometer/spectrometer	NOAA	Operations	2005	3	2017
		MHS	Absorption-band MW radiometer/spectrometer	NOAA	Operations	2005	3	2017
		SBUV/2	High-resolution nadir-scanning SW spectrometer	NOAA	Operations	2005	3	2017
		AVHRR/3	Multipurpose imaging VIS/IR radiometer	NOAA	Operations	2005	3	2017
		HIRS/4	Narrow-band channel IR radiometer	NOAA	Operations	2005	3	2017
	NOAA-19	AMSU-A	Absorption-band MW radiometer/spectrometer	NOAA	Operations	2009	3	2019
		MHS	Absorption-band MW radiometer/spectrometer	NOAA	Operations	2009	3	2019
		SBUV/2	High-resolution nadir-scanning SW spectrometer	NOAA	Operations	2009	3	2019
		AVHRR/3	Multipurpose imaging VIS/IR radiometer	NOAA	Operations	2009	3	2019
		HIRS/4	Narrow-band channel IR radiometer	NOAA	Operations	2009	3	2019
QuikSCAT		SeaWinds	Radar scatterometer	NASA	Operations	1999	2	2017
SAGE-III-on-ISS		SAGE-III	Limb-scanning SW spectrometer	NASA	Operations	2017	3	2020
SMAP		L-band Radiometer (SMAP)	Multipurpose imaging MW radiometer	NASA, CSA	Operations	2015	3	>2022
SORCE		SIM	Solar irradiance monitor	NASA	Operations	2003	5	2018
		SOLSTICE	Solar irradiance monitor	NASA	Operations	2003	5	2018
		TIM	Solar irradiance monitor	NASA	Operations	2003	5	2018
		XPS	Solar irradiance monitor	NASA	Operations	2003	5	2018
Suomi NPP		ATMS	Absorption-band MW radiometer/spectrometer	NASA, NOAA	Operations	2011	5	>2022
		CERES	Broadband radiometer	NASA, NOAA	Operations	2011	5	>2022
		OMPS	High-resolution nadir-scanning SW spectrometer	NASA, NOAA	Operations	2011	5	>2022
		CrIS	Medium-resolution IR spectrometer	NASA, NOAA	Operations	2011	5	>2022
		VIIRS	Multipurpose imaging VIS/IR radiometer	NASA, NOAA	Operations	2011	5	>2022
SWOT		GPSP	GNSS receiver	NASA, UKSA, CNES, CSA	Development	2021	3	2024
		LRA	Laser retroreflector	NASA, UKSA, CNES, CSA	Development	2021	3	2024

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
		AMR	Nonscanning MW radiometer	NASA, UKSA, CNES, CSA	Development	2021	3	2024
		Ka-band Radar Interferometer (KaRIN)	Radar altimeter	NASA, UKSA, CNES, CSA	Development	2021	3	2024
		DORIS-NG	Radio-positioning system	NASA, UKSA, CNES, CSA	Development	2021	3	2024
TCTE		TIM	Solar irradiance monitor	NOAA, NASA	Operations	2013	1.5	2017
TEMPO		Spectrometer (TEMPO)	High-resolution nadir-scanning SW spectrometer	NASA	Development	2018	2	2020
Terra		CERES	Broadband radiometer	NASA, METI, CSA	Operations	1999	6	>2021
		ASTER	High-resolution optical imager	NASA, METI, CSA	Operations	1999	6	>2021
		MOPITT	High-resolution nadir-scanning SW spectrometer	NASA, METI, CSA	Operations	1999	6	>2021
		MODIS	Medium-resolution spectroradiometer	NASA, METI, CSA	Operations	1999	6	>2021
		MISR	Multichannel/direction/polarization radiometer	NASA, METI, CSA	Operations	1999	6	>2021
TROPICS		TROPICS	Absorption-band MW radiometer/spectrometer	NASA	Development	2021	1	2022
TSIS-1-on-ISS		TSIS-1	Solar irradiance monitor	NASA	Development	2018	5	2023
TSIS-2		TSIS-2	Solar irradiance monitor	NASA	Development	2020	5	2025
Canada								
ePOP on CASSIOPE		GAP	GNSS radio-occultation receiver	CSA	Operations	2013	2	>2017
		MGF	Magnetometer	CSA	Operations	2013	2	>2017
SCISAT-1		ACE-FTS	Limb-scanning IR spectrometer	CSA, ESA, NASA	Operations	2003	2	2019
		MAESTRO	Limb-scanning SW spectrometer	CSA, ESA, NASA	Operations	2003	2	2019
RADARSAT-2		SAR (RADARSAT-2)	Imaging radar (SAR)	CSA, MDA	Operations	2007	7	2023
RCM	RCM-1	SAR (RCM)	Imaging radar (SAR)	CSA, NRCAN, DND, DFO, AAFC, EnvCan, PSC	Development	2018	7	2025
	RCM-2	SAR (RCM)	Imaging radar (SAR)	CSA, NRCAN, DND, DFO, AAFC, EnvCan, PSC	Development	2018	7	2025
	RCM-3	SAR (RCM)	Imaging radar (SAR)	CSA, NRCAN, DND, DFO, AAFC, EnvCan, PSC	Development	2018	7	2025
ESA + EUCOM								
ADM-Aeolus		ALADIN	Doppler lidar	ESA	Development	2018	3	2021

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
BIOMASS		SAR-P	Synthetic aperature radar (P-band)	ESA	Development	2021	5	2026
CryoSat-2		Laser Reflectors	Laser retroreflector	ESA	Operations	2010	3.5	2019
		SIRAL	Radar altimeter	ESA	Operations	2010	3.5	2019
		DORIS-NG	Radio-positioning system	ESA	Operations	2010	3.5	2019
EarthCARE		ATLID	Atmospheric lidar	ESA, JAXA	Development	2018	3	2021
		BBR (EarthCARE)	Broadband radiometer	ESA, JAXA	Development	2018	3	2021
		CPR (EarthCARE)	Cloud and precipitation radar	ESA, JAXA	Development	2018	3	2021
		MSI (EarthCARE)	Multipurpose imaging VIS/IR radiometer	ESA, JAXA	Development	2018	3	2021
FLEX		FLORIS	High Resolution Imaging Spectrometer	ESA	Development	2022	3	2025
Meteosat	Meteosat-10	GERB	Broadband radiometer	EUMETSAT, ESA	Operations	2012	7	2022
		SEVIRI	Multipurpose imaging VIS/IR radiometer	EUMETSAT, ESA	Operations	2012	7	2022
	Meteosat-11	GERB	Broadband radiometer	EUMETSAT, ESA	Operations	2015	7	2025
		SEVIRI	Multipurpose imaging VIS/IR radiometer	EUMETSAT, ESA	Operations	2015	7	2025
	Meteosat-8	GERB	Broadband radiometer	EUMETSAT, ESA	Operations	2002	7	2019
		SEVIRI	Multipurpose imaging VIS/IR radiometer	EUMETSAT, ESA	Operations	2002	7	2019
	Meteosat-9	GERB	Broadband radiometer	EUMETSAT, ESA	Operations	2005	7	2021
		SEVIRI	Multipurpose imaging VIS/IR radiometer	EUMETSAT, ESA	Operations	2005	7	2021
	MTG-I1 (imaging)	LI	Lightning imager	EUMETSAT, ESA	Development	2021	8.5	2029
		FCI	Multipurpose imaging VIS/IR radiometer	EUMETSAT, ESA	Development	2021	8.5	2029
	MTG-I2 (imaging)	LI	Lightning imager	EUMETSAT, ESA	Development	2025	8.5	2033
		FCI	Multipurpose imaging VIS/IR radiometer	EUMETSAT, ESA	Development	2025	8.5	2033
	MTG-I3 (imaging)	LI	Lightning imager	EUMETSAT, ESA	Development	2029	8.5	2037
		FCI	Multipurpose imaging VIS/IR radiometer	EUMETSAT, ESA	Development	2029	8.5	2037
	MTG-I4 (imaging)	LI	Lightning imager	EUMETSAT, ESA	Development	2033	8.5	2041
		FCI	Multipurpose imaging VIS/IR radiometer	EUMETSAT, ESA	Development	2033	8.5	2041
	MTG-S1 (sounding)	UVN	High-resolution nadir-scanning SW spectrometer	EUMETSAT, COM, ESA	Development	2023	8.5	2030
		IRS	Medium-resolution IR spectrometer	EUMETSAT, COM, ESA	Development	2023	8.5	2030
	MTG-S2 (sounding)	UVN	High-resolution nadir-scanning SW spectrometer	EUMETSAT, COM, ESA	Development	2030	8.5	2039

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
		IRS	Medium-resolution IR spectrometer	EUMETSAT, COM, ESA	Development	2030	8.5	2039
Metop	Metop-A	AMSU-A	Absorption-band MW radiometer/spectrometer	EUMETSAT, NOAA, CNES, ESA	Operations	2006	5	2019
		MHS	Absorption-band MW radiometer/spectrometer	EUMETSAT, NOAA, CNES, ESA	Operations	2006	5	2019
		GRAS	GNSS radio-occultation receiver	EUMETSAT, NOAA, CNES, ESA	Operations	2006	5	2019
		GOME-2	High-resolution nadir-scanning SW spectrometer	EUMETSAT, NOAA, CNES, ESA	Operations	2006	5	2019
		IASI	Medium-resolution IR spectrometer	EUMETSAT, NOAA, CNES, ESA	Operations	2006	5	2019
		AVHRR/3	Multipurpose imaging VIS/IR radiometer	EUMETSAT, NOAA, CNES, ESA	Operations	2006	5	2019
		HIRS/4	Narrow-band channel IR radiometer	EUMETSAT, NOAA, CNES, ESA	Operations	2006	5	2019
		ASCAT	Radar scatterometer	EUMETSAT, NOAA, CNES, ESA	Operations	2006	5	2019
	Metop-B	AMSU-A	Absorption-band MW radiometer/spectrometer	EUMETSAT, NOAA, CNES, ESA	Operations	2012	5	2024
		MHS	Absorption-band MW radiometer/spectrometer	EUMETSAT, NOAA, CNES, ESA	Operations	2012	5	2024
		GRAS	GNSS radio-occultation receiver	EUMETSAT, NOAA, CNES, ESA	Operations	2012	5	2024
		GOME-2	High-resolution nadir-scanning SW spectrometer	EUMETSAT, NOAA, CNES, ESA	Operations	2012	5	2024
		IASI	Medium-resolution IR spectrometer	EUMETSAT, NOAA, CNES, ESA	Operations	2012	5	2024
		AVHRR/3	Multipurpose imaging VIS/IR radiometer	EUMETSAT, NOAA, CNES, ESA	Operations	2012	5	2024
		HIRS/4	Narrow-band channel IR radiometer	EUMETSAT, NOAA, CNES, ESA	Operations	2012	5	2024
		ASCAT	Radar scatterometer	EUMETSAT, NOAA, CNES, ESA	Operations	2012	5	2024
	Metop-C	AMSU-A	Absorption-band MW radiometer/spectrometer	EUMETSAT, NOAA, CNES, ESA	Development	2018	5	2023
		MHS	Absorption-band MW radiometer/spectrometer	EUMETSAT, NOAA, CNES, ESA	Development	2018	5	2023
		GRAS	GNSS radio-occultation receiver	EUMETSAT, NOAA, CNES, ESA	Development	2018	5	2023
		GOME-2	High-resolution nadir-scanning SW spectrometer	EUMETSAT, NOAA, CNES, ESA	Development	2018	5	2023
		IASI	Medium-resolution IR spectrometer	EUMETSAT, NOAA, CNES, ESA	Development	2018	5	2023
		AVHRR/3	Multipurpose imaging VIS/IR radiometer	EUMETSAT, NOAA, CNES, ESA	Development	2018	5	2023
		ASCAT	Radar scatterometer	EUMETSAT, NOAA, CNES, ESA	Development	2018	5	2023

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
	Metop-SG A1	MWS	Absorption-band MW radiometer/spectrometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2021	7.5	2028
		RO	GNSS radio-occultation receiver	EUMETSAT, DLR, COM, CNES, ESA	Development	2021	7.5	2028
		UVNS (Sentinel-5)	High-resolution nadir-scanning SW spectrometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2021	7.5	2028
		IASI-NG	Medium-resolution IR spectrometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2021	7.5	2028
		3MI	Multichannel/direction/polarization radiometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2021	7.5	2028
		METimage	Multipurpose imaging VIS/IR radiometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2021	7.5	2028
	Metop-SG A2	MWS	Absorption-band MW radiometer/spectrometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2028	7.5	2035
		RO	GNSS radio-occultation receiver	EUMETSAT, DLR, COM, CNES, ESA	Development	2028	7.5	2035
		UVNS (Sentinel-5)	High-resolution nadir-scanning SW spectrometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2028	7.5	2035
		IASI-NG	Medium-resolution IR spectrometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2028	7.5	2035
		3MI	Multichannel/direction/polarization radiometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2028	7.5	2035
		METimage	Multipurpose imaging VIS/IR radiometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2028	7.5	2035
	Metop-SG A3	MWS	Absorption-band MW radiometer/spectrometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2035	7.5	2042
		RO	GNSS radio-occultation receiver	EUMETSAT, DLR, COM, CNES, ESA	Development	2035	7.5	2042
		UVNS (Sentinel-5)	High-resolution nadir-scanning SW spectrometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2035	7.5	2042
		IASI-NG	Medium-resolution IR spectrometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2035	7.5	2042
		3MI	Multichannel/direction/polarization radiometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2035	7.5	2042
		METimage	Multipurpose imaging VIS/IR radiometer	EUMETSAT, DLR, COM, CNES, ESA	Development	2035	7.5	2042
	Metop-SG B1	RO	GNSS radio-occultation receiver	EUMETSAT, CNES, ESA	Development	2022	7.5	2030
		ICI	Multipurpose imaging MW radiometer	EUMETSAT, CNES, ESA	Development	2022	7.5	2030
		MWI	Multipurpose imaging MW radiometer	EUMETSAT, CNES, ESA	Development	2022	7.5	2030
		SCA	Radar scatterometer	EUMETSAT, CNES, ESA	Development	2022	7.5	2030
	Metop-SG B2	RO	GNSS radio-occultation receiver	EUMETSAT, CNES, ESA	Development	2029	7.5	2037
		ICI	Multipurpose imaging MW radiometer	EUMETSAT, CNES, ESA	Development	2029	7.5	2037
		MWI	Multipurpose imaging MW radiometer	EUMETSAT, CNES, ESA	Development	2029	7.5	2037

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
		SCA	Radar scatterometer	EUMETSAT, CNES, ESA	Development	2029	7.5	2037
	Metop-SG B3	RO	GNSS radio-occultation receiver	EUMETSAT, CNES, ESA	Development	2036	7.5	2042
		ICI	Multipurpose imaging MW radiometer	EUMETSAT, CNES, ESA	Development	2036	7.5	2042
		MWI	Multipurpose imaging MW radiometer	EUMETSAT, CNES, ESA	Development	2036	7.5	2042
		SCA	Radar scatterometer	EUMETSAT, CNES, ESA	Development	2036	7.5	2042
PROBA	PROBA	CHRIS	High-resolution optical imager	ESA	Operations	2001	1	>2017
		HRC	Multipurpose imaging VIS/IR radiometer	ESA	Operations	2001	1	>2017
	PROBA-V	Vegetation	Medium-resolution spectroradiometer	ESA, BELSPO	Operations	2013	5	2019
Sentinel-1	Sentinel-1 A	C-Band SAR	Imaging radar (SAR)	ESA, COM	Operations	2014	7	2021
	Sentinel-1 B	C-Band SAR	Imaging radar (SAR)	ESA, COM	Operations	2016	7	2023
	Sentinel-1 C	C-Band SAR	Imaging radar (SAR)	ESA, COM	Development	2021	7	2028
	Sentinel-1 D	C-Band SAR	Imaging radar (SAR)	ESA, COM	Development	2023	7	2030
Sentinel-2	Sentinel-2 A	MSI (Sentinel-2)	High-resolution optical imager	ESA, COM	Operations	2015	7.25	2022
	Sentinel-2 B	MSI (Sentinel-2)	High-resolution optical imager	ESA, COM	Development	2017	7.25	2024
	Sentinel-2 C	MSI (Sentinel-2)	High-resolution optical imager	ESA, COM	Development	2021	7.25	2029
Sentinel-3	Sentinel-3 A	OLCI	Medium-resolution spectroradiometer	ESA, EUMETSAT, COM	Operations	2016	7	2023
		SLSTR	Multichannel/direction/polarization radiometer	ESA, EUMETSAT, COM	Operations	2016	7	2023
		SRAL	Radar altimeter	ESA, EUMETSAT, COM	Operations	2016	7	2023
	Sentinel-3 B	OLCI	Medium-resolution spectroradiometer	ESA, EUMETSAT, COM	Development	2018	7	2025
		SLSTR	Multichannel/direction/polarization radiometer	ESA, EUMETSAT, COM	Development	2018	7	2025
		SRAL	Radar altimeter	ESA, EUMETSAT, COM	Development	2018	7	2025
	Sentinel-3 C	OLCI	Medium-resolution spectroradiometer	ESA, EUMETSAT, COM	Development	2023	7	2029
		SLSTR	Multichannel/direction/polarization radiometer	ESA, EUMETSAT, COM	Development	2023	7	2029
		SRAL	Radar altimeter	ESA, EUMETSAT, COM	Development	2023	7	2029
Sentinel-4	Sentinel-4 A	UVN (Sentinel-4)	High-resolution nadir-scanning SW spectrometer	ESA, COM	Development	2023	8.5	2031
	Sentinel-4 B	UVN (Sentinel-4)	High-resolution nadir-scanning SW spectrometer	ESA, COM	Development	2030	8.5	2039

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
Sentinel-5	Sentinel-5 A	UVNS (Sentinel-5)	High-resolution nadir-scanning SW spectrometer	ESA, COM	Development	2021	7.5	2028
	Sentinel-5 B	UVNS (Sentinel-5)	High-resolution nadir-scanning SW spectrometer	ESA, COM	Development	2022	7.5	2030
	Sentinel-5 precursor	TROPOMI	High-resolution nadir-scanning SW spectrometer	ESA, COM, NSO	Development	2017	7	2023
Sentinel-6	Sentinel-6 A	TriG	GNSS radio-occultation receiver	ESA, EUMETSAT, NASA, NOAA, COM, CNES	Development	2020	7.5	2025
		GNSS POD Receiver	GNSS receiver	ESA, EUMETSAT, NASA, NOAA, COM, CNES	Development	2020	7.5	2025
		LRA (Sentinel-6)	Laser retroreflector	ESA, EUMETSAT, NASA, NOAA, COM, CNES	Development	2020	7.5	2025
		AMR-C	Nonscanning MW radiometer	ESA, EUMETSAT, NASA, NOAA, COM, CNES	Development	2020	7.5	2025
		Poseidon-4 Altimeter	Radar altimeter	ESA, EUMETSAT, NASA, NOAA, COM, CNES	Development	2020	7.5	2025
		DORIS-NG	Radio-positioning system	ESA, EUMETSAT, NASA, NOAA, COM, CNES	Development	2020	7.5	2025
	Sentinel-6 B	TriG	GNSS radio-occultation receiver	ESA, EUMETSAT, NASA, NOAA, COM, CNES	Development	2025	7.5	2030
		GNSS POD Receiver	GNSS receiver	ESA, EUMETSAT, NASA, NOAA, COM, CNES	Development	2025	7.5	2030
		LRA (Sentinel-6)	Laser retroreflector	ESA, EUMETSAT, NASA, NOAA, COM, CNES	Development	2025	7.5	2030
		AMR-C	Nonscanning MW radiometer	ESA, EUMETSAT, NASA, NOAA, COM, CNES	Development	2025	7.5	2030
		Poseidon-4 Altimeter	Radar altimeter	ESA, EUMETSAT, NASA, NOAA, COM, CNES	Development	2025	7.5	2030
		DORIS-NG	Radio-positioning system	ESA, EUMETSAT, NASA, NOAA, COM, CNES	Development	2025	7.5	2030
SMOS		MIRAS (SMOS)	Multipurpose imaging MW radiometer	ESA, CDTI, CNES	Operations	2009	3	2019
Swarm		GPS Receiver (Swarm)	GNSS receiver	ESA, CNES, CSA	Operations	2013	4	2018

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
		ACC	Gradiometer/accelerometer	ESA, CNES, CSA	Operations	2013	4	2018
		Laser Reflectors (ESA)	Laser retroreflector	ESA, CNES, CSA	Operations	2013	4	2018
		ASM	Magnetometer	ESA, CNES, CSA	Operations	2013	4	2018
		VFM	Magnetometer	ESA, CNES, CSA	Operations	2013	4	2018
European National Agencies								
PRISMA (hyperspectral)		PAN CAMERA	High-resolution optical imager	ASI	Development	2018	5	2023
		HYC	Medium-resolution IR spectrometer	ASI	Development	2018	5	2023
LARES		LCCRA	Laser retroreflector	ASI	Operations	2012	N/A	N/A
CSG	CSG-1	CSG SAR	Imaging radar (SAR)	ASI, MoD (Italy)	Development	2018	7	2025
	CSG-2	CSG SAR	Imaging radar (SAR)	ASI, MoD (Italy)	Development	2019	7	2025
COSMO-SkyMed	COSMO-SkyMed 1	SAR 2000	Imaging radar (SAR)	ASI, MoD (Italy)	Operations	2007	5	>2017
	COSMO-SkyMed 2	SAR 2000	Imaging radar (SAR)	ASI, MoD (Italy)	Operations	2007	5	>2017
	COSMO-SkyMed 3	SAR 2000	Imaging radar (SAR)	ASI, MoD (Italy)	Operations	2008	5	>2017
	COSMO-SkyMed 4	SAR 2000	Imaging radar (SAR)	ASI, MoD (Italy)	Operations	2010	5	>2017
Ingenio		PAN+MS (RGB+NIR)	High-resolution optical imager	CDTI, ESA	Development	2019	7	2026
		UVAS	High-resolution nadir-scanning SW spectrometer	CDTI, ESA	Development	2019	7	2026
PAZ		Paz SAR-X	Imaging radar (SAR)	CDTI, INTA, HISDESAT	Development	2017	5	2022
		Paz RO secondary	GNSS radio-occultation receiver	CDTI, INTA, HISDESAT	Development	2017	5	2022
Pleiades	Pleiades 1A	HiRI	High-resolution optical imager	CNES	Operations	2011	5	2018
	Pleiades 1B	HiRI	High-resolution optical imager	CNES	Operations	2012	5	2019
STELLA		Laser Reflectors	Laser retroreflector	CNES	Operations	1993	N/A	N/A
STARLETTE		Laser Reflectors	Laser retroreflector	CNES	Operations	1975	N/A	N/A
Diademe 1&2		RRA	Laser retroreflector	CNES	Operations	1967	N/A	N/A
CFOSAT		SCAT	Radar scatterometer	CNES, CNSA	Development	2018	3	2021
		SWIM	Radar scatterometer	CNES, CNSA	Development	2018	3	2021
MERLIN		IPDA LIDAR	Atmospheric lidar	CNES, DLR	Development	2021	3	2024
VENUS		VSC	High-resolution optical imager	CNES, ISA	Operations	2017	3.5	2021

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
MEGHA-TROPIQUES		SAPHIR	Absorption-band MW radiometer/spectrometer	CNES, ISRO	Operations	2011	3	2020
		ScaRaB	Broadband radiometer	CNES, ISRO	Operations	2011	3	2020
		ROSA	GNSS radio-occultation receiver	CNES, ISRO	Operations	2011	3	2020
		MADRAS	Multipurpose imaging MW radiometer	CNES, ISRO	Operations	2011	3	2020
SARAL		AltiKa	Radar altimeter	CNES, ISRO	Operations	2012	3	>2018
RapidEye		MSI	High-resolution optical imager	DLR	Operations	2008	7	2019
EnMAP		HSI	High-resolution optical imager	DLR	Development	2019	5	2024
TanDEM	TanDEM-L	L-Band SAR	Imaging radar (SAR)	DLR, HRC	Development	2022	10	2032
	TanDEM-X	X-Band SAR	Imaging radar (SAR)	DLR	Operations	2010	5	2020
TerraSAR-X		GPSRO (Terra-SAR)	GNSS radio-occultation receiver	DLR	Operations	2007	5	2020
		X-Band SAR	Imaging radar (SAR)	DLR	Operations	2007	5	2020
HRWS SAR		HRWS X-Band Digital Beamforming SAR	Imaging radar (SAR)	DLR	Development	2022	6	2028
DESIS-on-ISS		DESIS	Medium-resolution spectroradiometer	DLR	Development	2017	3	2020
Oersted		GPSRO (Oersted)	GNSS radio-occultation receiver	DNSC, CNES	Operations	1999	1	>2017
		CSC FVM	Magnetometer	DNSC, CNES	Operations	1999	1	>2017
		Overhauser Magnetometer	Magnetometer	DNSC, CNES	Operations	1999	1	>2017
NORSAT-1		TSI	Solar irradiance monitor	NSC	Development	2017	3	2020
Odin		SMR	Limb-scanning MW spectrometer	SNSB, TEKES, CNES, CSA, ESA	Operations	2001	2	2017
		OSIRIS	Limb-scanning SW spectrometer	SNSB, TEKES, CNES, CSA, ESA	Operations	2001	2	2017
UK-DMC2		SLIM-6-22	High-resolution optical imager	UKSA	Operations	2009	5	>2017
JAXA + JMA								
ALOS-2		PALSAR-2 (ALOS-2)	Imaging radar (SAR)	JAXA	Operations	2014	5	2019
		CIRC	Multipurpose imaging VIS/IR radiometer	JAXA	Operations	2014	5	2019
GCOM	GCOM-C	SGLI	Medium-resolution spectroradiometer	JAXA	Development	2017	5	2022
	GCOM-W	AMSR-2	Multipurpose imaging MW radiometer	JAXA	Operations	2012	5	>2017
GOSAT	GOSAT	TANSO-FTS	High-resolution nadir-scanning IR spectrometer	JAXA, MOE (Japan), NIES (Japan)	Operations	2009	5	2018

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
		TANSO-CAI	Multipurpose imaging VIS/IR radiometer	JAXA, MOE (Japan), NIES (Japan)	Operations	2009	5	2018
	GOSAT-2	TANSO-FTS-2	High-resolution nadir-scanning IR spectrometer	JAXA, MOE (Japan), NIES (Japan)	Development	2018	5	2023
		TANSO-CAI-2	Multipurpose imaging VIS/IR radiometer	JAXA, MOE (Japan), NIES (Japan)	Development	2018	5	2023
Himawari	Himawari-8	AHI	Multipurpose imaging VIS/IR radiometer	JMA	Operations	2014	15	2029
	Himawari-9	AHI	Multipurpose imaging VIS/IR radiometer	JMA	Operations	2016	15	2031
MTSAT-2	MTSAT-2	IMAGER/MTSAT-2	Multipurpose imaging VIS/IR radiometer	JMA, JCAB	Operations	2006	10	>2017
ISRO								
CARTOSAT	CARTOSAT-1	PAN (Cartosat-1)	High-resolution optical imager	ISRO	Operations	2005	5	>2017
	CARTOSAT-2	PAN (Cartosat-2)	High-resolution optical imager	ISRO	Operations	2007	5	>2017
	CARTOSAT-2A	PAN (Cartosat-2A/2B)	High-resolution optical imager	ISRO	Operations	2008	5	>2017
	CARTOSAT-2B	PAN (Cartosat-2A/2B)	High-resolution optical imager	ISRO	Operations	2010	5	>2017
	CARTOSAT-2E	HRMX	High-resolution optical imager	ISRO	Operations	2017	5	2022
		PAN (Cartosat-2C/2E)	High-resolution optical imager	ISRO	Operations	2017	5	2022
	CARTOSAT-3	MX (Cartosat-3)	High-resolution optical imager	ISRO	Development	2018	5	2023
		PAN (Cartosat-3)	High-resolution optical imager	ISRO	Development	2018	5	2023
GISAT		HRMX-TIR,	High-resolution optical imager	ISRO	Development	2018	7	2026
		HRMX-VNIR	High-resolution optical imager	ISRO	Development	2018	7	2026
		HYSI-SWIR	Medium-resolution IR spectrometer	ISRO	Development	2018	7	2026
		HYSI-VNIR	Medium-resolution IR spectrometer	ISRO	Development	2017	7	2026
INSAT	INSAT-3A	CCD camera	High-resolution optical imager	ISRO	Operations	2003	12	>2017
		VHRR	Multipurpose imaging VIS/IR radiometer	ISRO	Operations	2003	12	>2017
	INSAT-3D	Imager (INSAT)	Multipurpose imaging VIS/IR radiometer	ISRO	Operations	2013	7	2020
		Sounder (INSAT)	Narrow-band channel IR radiometer	ISRO	Operations	2013	7	2020
	INSAT-3DR	Imager (INSAT)	Multipurpose imaging VIS/IR radiometer	ISRO	Operations	2016	10	2026
		Sounder (INSAT)	Narrow-band channel IR radiometer	ISRO	Operations	2016	10	2026
KALPANA-1		VHRR	Multipurpose imaging VIS/IR radiometer	ISRO	Operations	2002	7	>2017
OCEANSAT	OCEANSAT-2	ROSA	GNSS radio-occultation receiver	ISRO	Operations	2009	5	>2017

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
		OCM	Medium-resolution spectroradiometer	ISRO	Operations	2009	5	>2017
	OCEANSAT-3	OCM (OCEANSAT-3)	Medium-resolution spectroradiometer	ISRO	Development	2018	5	2023
		SSTM-1 (OCEANSAT-3)	Multipurpose imaging VIS/IR radiometer	ISRO	Development	2018	5	2023
		Scatterometer (OCEANSAT-3)	Radar scatterometer	ISRO	Development	2018	5	2023
	OCEANSAT-3A	OCM (OCEANSAT-3)	Medium-resolution spectroradiometer	ISRO	Development	2020	5	2025
		SSTM-1 (OCEANSAT-3)	Multipurpose imaging VIS/IR radiometer	ISRO	Development	2020	5	2025
		Scatterometer (OCEANSAT-3)	Radar scatterometer	ISRO	Development	2020	5	2025
RESOURCESAT	RESOURCESAT-2	LISS-III (RESOURCESAT)	High-resolution optical imager	ISRO	Operations	2011	5	>2017
		LISS-IV	High-resolution optical imager	ISRO	Operations	2011	5	>2017
		AWiFS	Multipurpose imaging VIS/IR radiometer	ISRO	Operations	2011	5	>2017
	RESOURCESAT-2A	LISS-III (RESOURCESAT)	High-resolution optical imager	ISRO	Operations	2016	5	2021
		LISS-IV	High-resolution optical imager	ISRO	Operations	2016	5	2021
		AWiFS	Multipurpose imaging VIS/IR radiometer	ISRO	Operations	2016	5	2021
	RESOURCESAT-3	ALISS III	High-resolution optical imager	ISRO	Development	2019	5	2024
		ATCOR	High-resolution optical imager	ISRO	Development	2019	5	2024
	RESOURCESAT-3A	ALISS III	High-resolution optical imager	ISRO	Development	2020	5	2025
		ATCOR	High-resolution optical imager	ISRO	Development	2020	5	2025
	RESOURCESAT-3S	APAN	High-resolution optical imager	ISRO	Development	2019	5	2024
		LISS-V	High-resolution optical imager	ISRO	Development	2019	5	2024
	RESOURCESAT-3SA	APAN	High-resolution optical imager	ISRO	Development	2020	5	2025
		LISS-V	High-resolution optical imager	ISRO	Development	2020	5	2025
RISAT	RISAT-1	SAR (RISAT)	Imaging radar (SAR)	ISRO	Operations	2012	5	>2017
	RISAT-1A	SAR (RISAT)	Imaging radar (SAR)	ISRO	Development	2018	5	2023
	RISAT-2	SAR-X	Imaging radar (SAR)	ISRO	Operations	2009	5	>2017
SCATSAT-1		Scatterometer (Scatsat-1)	Radar scatterometer	ISRO	Operations	2016	5	2021
KARI								
COMS		GOCI	Multipurpose imaging VIS/IR radiometer	KARI, ASTRIUM, KMA, KORDI	Operations	2010	7.7	2018

TABLE A.1 Continued

Mission Family	Mission	Instrument Name	Instrument Type	Mission Agencies	Mission Status	Launch Year	Design Life	Expected End of Life
		MI	Multipurpose imaging VIS/IR radiometer	KARI, ASTRIUM, KMA, KORDI	Operations	2010	7.7	2018
CAS500-1		High-Resolution Optical Sensor	High-resolution optical imager	KARI, KAI	Development	2019	4	2023
GEO-KOMPSAT	GEO-KOMPSAT-2A	Advanced MI	Multipurpose imaging VIS/IR radiometer	KARI, KMA, ITT	Development	2018	10	2028
	GEO-KOMPSAT-2B	GEMS	Medium-resolution spectroradiometer	KARI, KORDI, NIER	Development	2019	10	2029
	GEO-KOMPSAT-2B	Advanced GOCI	Multipurpose imaging VIS/IR radiometer	KARI, KORDI, NIER	Development	2019	10	2029
KOMPSAT	KOMPSAT-3	AEISS	High-resolution optical imager	KARI, ASTRIUM	Operations	2012	4	>2017
	KOMPSAT-3A	AEISS-A	High-resolution optical imager	KARI, ASTRIUM	Operations	2015	5	2019
	KOMPSAT-5	AOPOD	GNSS radio-occultation receiver	KARI, TAS-i	Operations	2013	5	2018
		COSI	Imaging radar (SAR)	KARI, TAS-i	Operations	2013	5	2018
		LRR	Laser retroreflector	KARI, TAS-i	Operations	2013	5	2018
	KOMPSAT-6	SAR (KOMPSAT-6)	Imaging radar (SAR)	KARI	Development	2019	5	2024
STSAT-3	STSAT-3	COMIS	High-resolution optical imager	KARI	Operations	2013	2	2017

B

Science and Applications Traceability Matrix

The Science and Applications Traceability Matrix (SATM; Table B.1) provided the basis for much of the committee's deliberations and forms the foundation of its recommendations. The process for developing this matrix, including the central role of the panels, is summarized in Chapter 3.

The SATM is organized by panel and color coded, with blue-shaded columns identifying science and applications questions and objectives and green-shaded columns identifying associated observation and measurement needs to address those questions and objectives. Note that Table 3.3 is identical to the blue portion of the SATM. The content of the green columns represents panel guidance to the steering committee. The steering committee did more extensive implementation analysis (including cost analysis through the Cost Assessment and Technical Evaluation (CATE) process, where appropriate) to determine its observing system priorities (Table 3.3). As such, the green columns should not be taken as recommendations or even definitive guidance, but rather as noncomprehensive suggestions.

Columns in the SATM consist of the following:

- *Societal or Science Question.* The top-level science or applications question driving the research need.
- *Earth Science/Application Objective.* A specific objective needed to address the related science or societal question.
- *Science/Applications Importance.* The relative priority of pursuing a given objective, ranked as Most Important, Very Important, or Important (described further in Chapter 3).
- *Geophysical Observable.* The geophysical parameter to be observed in order to pursue the related objective.
- *Measurement Parameters.* The measurement specifications associated with the observable.
- *Example Measurement Approaches.* Examples of measurement methods that can be used to measure the observable to achieve the requirements of the measurement parameters. Entries in these columns reflect the judgment of the panels, but are not definitive. A thorough trade analysis was not performed to identify the best measurement approach for each observation, no instrument or

mission design was performed, and no costing was established. Note that examples in either the Program of Record (POR) or Targeted Observable (TO) subcolumns are not complete and may even be absent for a number of reasons, due to the complexity of the SATM process. Blank cells should not be considered as evidence that no relevant POR is available or new measurement (TO) is needed.

- *Method.* Candidate measurement methods.
- *POR.* Examples of POR instruments or missions that have made or will make similar measurements. The POR numbers refer to the Committee on Earth Observing Satellites (CEOS) Catalog categories, as summarized in Table B.2. Listed names are instruments or missions that have been specifically identified.
- *TO.* Entries in the ESAS 2017 Targeted Observables table (Appendix C) that may, depending on implementation approach, contribute to the needed measurement(s).

Table B.1 begins on next set of facing pages.

TABLE B.2 Committee on Earth Observing Satellites Catalog Categories

Program of Record Number	Instrument Technology
1	Absorption-band microwave (MW) radiometer/spectrometer
2	Atmospheric lidar
3	Broadband radiometer
4	Cloud and precipitation radar
5	Doppler lidar
6	Global Navigation Satellite Systems (GNSS) radio-occultation receiver
7	GNSS receiver
8	Gradiometer/accelerometer
9	High-resolution optical imager
10	High-resolution nadir-scanning infrared (IR) spectrometer
11	High-resolution nadir-scanning shortwave (SW) spectrometer
12	Imaging radar (Synthetic Aperture Radar)
13	Laser Retroreflector
14	Laser altimeter
15	Lightning imager
16	Limb-scanning IR spectrometer
17	Limb-scanning MW spectrometer
18	Limb-scanning SW spectrometer
19	Magnetometer
20	Medium-resolution IR spectrometer
21	Medium-resolution IR spectro-radiometer
22	Multichannel/direction/polarization radiometer
23	Multipurpose imaging MW radiometer
24	Multipurpose imaging visible (VIS)/IR radiometer
25	Narrow-band channel IR radiometer
26	Nonscanning MW radiometer
27	Radar altimeter
28	Radar scatterometer
29	Radio-positioning system
30	Satellite-to-satellite ranging system
31	Solar irradiance monitor

TABLE B.1 ESAS 2017 Consolidated Science and Applications Traceability Matrix

KEY: **Square brackets:** Nonspace observations or related commitments
Curly brackets: Space observations with non-NASAS/NOAA/USGS assets, such as non-U.S. or databuys

GLOBAL HYDROLOGICAL CYCLES AND WATER RESOURCES PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question/Goal	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
QUESTION H-1. **Coupling the Water and Energy Cycle.** How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?	**H-1a.** Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance from headwater catchments to continental-scale river basins.	**Most Important**	Energy and water fluxes in the boundary or surface layer: solar (direct and reflected) and longwave radiation (downwelling and emitted), sensible and latent heat exchange, and soil heat flux.	Surface solar and longwave radiation balances, which are needed to estimate the other energy balance parameters, to within 10 W/m^2 accuracy at 1 km resolution globally, four times daily.	Downscale CERES-like observations to finer spatial resolutions (1 km) and eliminate systematic errors. See H-1b and H-1c.	POR-1, 3, 10, 20, 21, 23, 24, 25	TO-17, 18
					Model and data integration with capabilities to estimate moist processes in atmosphere, land and terrestrial biosphere.	POR-1, 6, 9	TO-13
	H-1b. Quantify rates of precipitation and its phase (rain and snow/ice) worldwide at convective and orographic scales suitable to capture flash floods and beyond.	**Most Important**	Precipitation rate and phase (rain or snow).	Diurnal cycle of precipitation at 1 (desirable) or 4 km (needed) scales (rain and snow) with accuracy of 0.2 mm/hr for rainfall and 1 mm/hr for snow, at finer scales in selected areas such as mountainous regions.	Multi-frequency radar and radiometer system similar to GPM/CloudSat as well as aerosol capabilities for continued improvement in precipitation process understanding, precipitation rate observations, and long term monitoring for change detection.	POR-4, 23, 25	TO-5, 13
	H-1c. Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide at scales driven by topographic variability.	**Most Important**	Snow water equivalent (SWE).	Global SWE at 1 (desirable) or 4 km (needed) resolution every 3-5 days, to 10% accuracy for SWE values to 1 m.	Existing passive microwave for global scale okay for SWE values to ~200 mm. Problematic for deep snow in heterogeneous terrain.	POR-23	TO-16, 19
				In mountains, SWE at ~100 m resolution suitable for SWE values to 2.5 m.	In mountains, measure depth (Ka-band radar or laser altimeter) and density (SAR).	POR-17 (KaRIn, SWOT)	TO-16, 19
			Snow and glacier albedo and temperature.	Spectral albedo of subpixel snow and glaciers at weekly intervals to an accuracy to estimate absorption of solar radiation to 10%. Ice/snow surface temperature to ±1 K. At spatial resolution of 30 to 100 m.	Imaging spectrometer to understand seasonal variability. Develop methods and calibration for multispectral sensors for weekly worldwide coverage. Panchromatic multiangle radiometer. Thermal emission radiometer for temperature.	POR-22	TO-18
QUESTION H-2. **Prediction of Changes.** How do anthropogenic changes in climate, land use, water use, and water storage, interact and modify the water and energy cycles locally, regionally, and globally and what are the short- and long-term consequences?	**H-2a.** Quantify how changes in land use, water use, and water storage affect evapotranspiration rates, and how these in turn affect local and regional precipitation systems, groundwater recharge, temperature extremes, and carbon cycling.	**Very Important**	Latent heat flux at 3 (desirable) to 6 hour (useful) resolution during daytime intervals and at 1 km spatial scale with better than 10 W/m^2 accuracy.	Temperature of soil and vegetation separately, 40-100 m spatial resolution, accuracy of ±1 K, at a temporal frequency to resolve the diurnal cycle.	Emitted infrared radiation in 4 μm and 11 μm wavelength regions, possibly free flyers to get desired frequency of four times daily.	POR-3, 9, 10, 20, 24, 25	TO-13, 18
				Boundary layer vapor pressure deficit profile and near-surface humitidy, 1-10 km resolution, at least four times during daytime with better than 1 hPa accuracy. Boundary-layer wind speed over land, including heterogeneous terrain, is needed to estimate surface fluxes.	AIRS for atmospheric moisture. Add capability for near surface profile (profile within the first 100 m).	POR-1, 6, 20, 23	TO-4, 13
				Soil moisture profile to 4% volumetric accuracy in top 1 m of the soil column.	Passive microwave dual-channel L- and P-band radiometer, with polarization for four Stokes parameters, at spatial resolution 20-60 km. Active microwave dual-channel L- and P-band radar, VV, HH, and HV polarization at spatial resolution of 100 m to 1 km.	POR-23	TO-17

GLOBAL HYDROLOGICAL CYCLES AND WATER RESOURCES PANEL

SCIENCE			**MEASUREMENT**				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
				Albedo of vegetation and soil separately, to an accuracy to estimate absorption of solar radiation to 10 W/m^2, at weekly intervals at field scale 30-60 m spatial resolution.	Imaging spectrometer to develop methods and to calibrate multispectral sensors for worldwide coverage.	POR-22, 24	TO-18
	H-2b. Quantify the magnitude of anthropogenic processes that cause changes in radiative forcing, temperature, snowmelt, and ice melt, as they alter downstream water quantity and quality.	**Important**	Snow and ice albedo, contaminant type (dust, soot) and concentration, land cover. Surface temperature. Glacier, river, and lake mapping and characterization.	Spectral snow and ice albedo, optical properties and concentrations of contaminants (dust and soot), surface temperature to ±1 K.	Imaging spectrometry at resolution to capture topographic variability, typically ~30 m. Lidar to measure vegetation properties. Thermal emission radiometer for temperature, prefer to 30 m spatial resolution. 5-10 m spatial multiband imaging for worldwide coverage of land, rivers, lakes, and glaciers.	POR-3, 9, 12, 14, 22	TO-18, 20
	H-2c. Quantify how changes in land use, land cover, and water use related to agricultural activities, food production, and forest management affect water quality and especially groundwater recharge, threatening sustainability of future water supplies.	**Most Important**	Recharge rates (i.e., space-time rates of change in groundwater storage and availability) at 1 km (desired) up to 10 km (useful) scale globally at 10-day intervals with accuracy of better than ±1 mm/day	Soil moisture profile to 4% volumetric accuracy in top 1 m of the soil column.	See H-2a for Measurement Approach to soil moisture.	POR-23	TO-17
				Changes in vadose zone moisture and in groundwater storage. Changes in groundwater levels. Changes in snow water equivalent.	Gravimetric methods.	POR-30	TO-9, 17
				Land-surface deflection to 1 cm accuracy, 100 m spatial resolution.	L-band InSAR. Perhaps combined with airborne lidar.	POR-12	TO-19
			Differences between precipitation and evapotranspiration to an accuracy whereby estimates of their difference have smaller errors than the magnitude of groundwater recharge.	See H-2a for Measurement Parameters for evapotranspiration.	See H-2a for Measurement Approaches for evapotranspiration.	-	TO-17
				Rainfall at fine space (1 km) and time (15 min) resolution in selected areas to properly capture accumulation at field scales and partition between canopy intercept, infiltration and runoff.	High-resolution geostationary radar. Observationally constrained mesoscale models; typical constraints are active microwave backscattering coefficients, passive microwave brightness temperatures, and geostationary VIS/IR measurements.	-	TO-5, 9, 17
QUESTION H-3. **Availability of Freshwater and Coupling with Biological Cycles.** How do changes in the water cycle impact local and regional freshwater availability, alter the biotic life of streams, and affect ecosystems and the services these provide?	**H-3a.** Develop methods and systems for monitoring water quality for human health and ecosystem services.	**Important**	Turbidity, total suspended sols and suspended sols particle size distribution in estuaries and coastal regions, salinity to 10 psu, temperature to 1 K, and chlorophyll.	At spatial scales small enough to resolve streams, ~10 m. Appropriate scale and resolution for onsite management for water quality.	Imaging spectrometer for worldwide land coverage and to develop methods and calibrate multispectral sensors for more frequent coverage.	-	TO-3, 18
	H-3b. Monitor and understand the coupled natural and anthropogenic processes that change water quality, fluxes, and storages in and between all reservoirs (atmosphere, rivers, lakes, groundwater, and glaciers), and the response to extreme events.	**Important**	Land cover and vegetation condition, soil moisture, land use, burned area after fire, and terrain slope.	At scales small enough to resolve local areas contributing to water quality and landslides: at spatial resolution of 100 m (desirable) to 1 km (useful).	Models that link precipitation, land use, land cover, and topography to water quality.	POR-9, 10, 12, 21	TO-3, 18, 20
	H-3c. Determine structure, productivity, and health of plants to constrain estimates of evapotranspiration.	**Important**	Vegetation biophysical condition (color and water content), vapor pressure deficit between vegetation and atmosphere, soil moisture profile, leaf area index and vegetation fraction, broadband and spectral albedo of vegetation.	Water use efficiency of plants as they respond to moisture stress.	Models that link vegetation's radiative signal with processes of evapotranspiration.	POR-10	Modeling
			Structure of vegetation canopy.	Amount of woody biomass and leaf area index. 1 to 4 points sample points per square meter with 2 to 4 returns per point for moderately to heavily forested regions	Lidar, P-band radar.	POR-12, 14	TO-20

GLOBAL HYDROLOGICAL CYCLES AND WATER RESOURCES PANEL

SCIENCE			**MEASUREMENT**				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
				and areas with intensive agriculture. Vegetation fraction at 30-100 m resolution and vertical profile of vegetation (canopy-understory-bare soil)			
			Photosynthetic rate.	Solar induced fluorescence.	Imaging spectrometry within the Fraunhofer bands, but at 100 m scale.	POR-32	-
QUESTION H-4. How does the water cycle interact with other Earth system processes to change the predictability and impacts of hazardous events and hazard-chains (e.g., floods, wildfires, landslides, coastal loss, subsidence, droughts, human health, and ecosystem health), and how do we improve preparedness and mitigation of water-related extreme events?	**H-4a.** Monitor and understand hazard response in rugged terrain and land margins to heavy rainfall, temperature and evaporation extremes, and strong winds at multiple temporal and spatial scales. This socioeconomic priority depends on success of addressing H-1b and H-1c, H-2a, and H-2c.	**Very Important**	Magnitude and frequency of severe storms. Depth and extent of floods.	Precipitation, snowmelt, water depth, and water flow in soil at time and space scales consistent with events.	For precipitation and snow: Similar to SWOT but at finer spatial resolution.	See H-1b and H-1c	See H-1b and H-1c
					For River Discharge: Similar to SWOT but at finer spatial resolution.	POR-26 (SWOT)	
	H-4b. Quantify key meteorological, glaciological, and solid Earth dynamical and state variables and processes controlling flash floods, and rapid hazard chains to improve detection, prediction, and preparedness. (This is a critical socioeconomic priority that depends on success of addressing H-1b, H-1c, and H-4a).	**Important**	Rainfall intensity and volume for storms in the 95th percentile of values specific to areas, especially estimates in mountainous terrain where other measurement sources are not available, soil moisture, SWE, and glacier changes.	Precipitation, snowmelt, and flow in soil and glaciers at time and space scales consistent with events.	See measurement approaches associated with Objective H-2c.	POR-23	TO-17
	H-4c. Improve drought monitoring to forecast short-term impacts more accurately and to assess potential mitigations. This is a critical socioeconomic priority that depends on success of addressing H-1b, H-1c, and H-2c.	**Important**	Soil moisture, vegetation moisture, cumulative evapotranspiration, and SWE.	See specifications associated with Objective H-1a.	See measurement approaches associated with Objective H-1a.	POR-12, 23	TO-17
	H-4d. Understand linkages between anthropogenic modification of the land, including fire suppression, land use, and urbanization on frequency of, and response to, hazards. This is tightly linked to H-2a, H-2b, H-4a, H-4b, and H-4c.	**Important**	Susceptibility of forest and brushlands to fire, land use change, urban characteristics.	Dry fuel load.	Imaging spectrometer for worldwide land coverage and to develop methods and calibrate multispectral sensors for more frequent coverage.		TO-18
				Land use and land cover, global scale monthly at 30-100 m resolution, selected areas annually at 5-10 m resolution, surface soil moisture, surface temperature, evapotranspiration at scale of topographic variability, typically ~30 m.	For LULCC: Multispectral sensors at varying resolution to merge spatial and time scales.	POR-9, 11, 12	
					For Soil Moisture: Multispectral sensors at varying resolution to merge spatial and time scales.		TO-20
				Urban form and textures at scales to resolve distinctive features, typically 5-10 m, annually.	Imaging spectrometer for worldwide land coverage and to develop methods and calibrate multispectral sensors for more frequent coverage.	POR-9, 11, 12	TO-18, 20

WEATHER AND AIR QUALITY PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
***QUESTION W-1.* Planetary Boundary Layer Dynamics.** What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations?	**W-1a.** Determine the effects of key boundary layer processes on weather, hydrological, and air quality forecasts at minutes to subseasonal time scales.	**Most Important**	3D temperature in PBL	Horizontal resolution 20 km, vertical resolution 0.2 km, temporal resolution 3 hr, 0.3 K/0.3 K	Polar/geo IR and microwave sounders, complemented by airborne and surface observations	POR-1, 6, 20, 24, 25	TO-13
			3D humidity in PBL	Horizontal resolution 20 km, vertical resolution 0.2 km, temporal resolution 3 hr, 0.3 g/kg	Polar/geo IR and microwave sounders, complemented by airborne and surface observations	POR-1, 6, 20, 24, 25	TO-13
			3D horizontal wind vector in PBL	Horizontal resolution 20 km, vertical resolution 0.2 km, temporal resolution 3 hr, 1 m/s	Doppler wind lidar, AMVs from multiangle VIS/IR (occasionally reaching PBL), scatterometer measurements of near-surface winds over ocean	POR-25	TO-4, 11
			3D PM component and trace gas (ozone, NO_2) concentrations	Horizontal resolution 5 km, vertical resolution 0.2 km, temporal resolution 2 hr	See approaches listed under W-6 below.	POR-2, 10, 11, 22	TO-1, 12
			2D PBL height	Horizontal resolution 20 km, temporal resolution 3 hr, 0.1 km	Lidar (e.g., CALIPSO)	POR-2, 6	TO-1, 13
			2D PBL cloud LWP	Horizontal resolution 20 km, 20%	Microwave radiometer	POR-1, 23	TO-5
			2D cloud base	Horizontal resolution 20 km, 0.1 km	Lidar	POR-2, 4	TO-5
			2D precipitation	Horizontal resolution 10 km, 20%	Passive microwave (e.g., GPM), radar; complemented by rain gauges and radar over land	POR-1, 4, 23	TO-5
***QUESTION W-2.* Larger Range Environmental Predictions.** How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months?	**W-2a.**Improve the observed and modeled representation of natural, low-frequency modes of weather/climate variability (e.g., MJO, ENSO), including upscale interactions between the large-scale circulation and organization of convection and slowly varying boundary processes to extend the lead time of useful prediction skills by 50% for forecast times of 1 week to 2 months. Advances require improved: (1) Process understanding and assimilation / modeling capabilities of atmospheric convection, mesoscale organization, and atmosphere and ocean boundary layers, (2) Global initial conditions relevant to these quantities/processes. Observations needed for boundary layer, surface conditions, and convection are described in W-1, W-3, and W-4, respectively.	**Most Important**	Vertical temperature profile	Boundary layer through middle atmosphere; threshold Horizontal resolution 5 km, objective Horizontal resolution 3 km, both at 1 km Vertical resolution; threshold refresh 3 hr, objective refresh global 90 min and CONUS 60 min; measured with 1 K rms	Polar/geo IR and microwave sounders PLUS GNSS-RO	POR-1, 6, 20, 25	TO-13
			Vertical water vapor profile	Boundary layer through middle atmosphere; threshold Horizontal resolution 5 km, objective Horizontal resolution 3 km, both at 1 km Vertical resolution; threshold refresh 3 hr, objective refresh global 90 min and CONUS 60 min; measured with 10% LTH rms and 20% UTH rms	Polar/geo IR and microwave sounders PLUS GNSS-RO	POR-1, 6, 20, 25	TO-13
			Vertical profiles of horizontal vector winds	Boundary layer through middle atmosphere; threshold Horizontal resolution 5 km, objective Horizontal resolution 3 km, both at 1 km Vertical resolution; threshold refresh 3 hr, objective refresh global 90 min and CONUS 60 min; measured at 3 m/s rms	Doppler wind lidar	POR-5	TO-4
					AMVs from IR, WV, and visible imagers and hyperspectral sounders	POR-1, POR-20	TO-13
			Vertical profile of atmospheric O_3, aerosols, and dust for subseasonal	From surface through middle atmosphere mid-troposphere for aerosols and dust; through stratosphere for ozone.	Lidar, stereo visible, UV backscatter, MW limb sounding	POR-11, 17, 18	TO-12
			Vertical distributions of clouds and precipitation particles	From surface through lower stratosphere; Vertical resolution 1 km/10 km; ice water path to within 25%, LWP to within 25%	MW for LWP, submillimeter with radar for IWP; GNSS-RO (L-band) dual-pol - LHCP is new	POR-2, 4	TO-5

WEATHER AND AIR QUALITY PANEL

SCIENCE			**MEASUREMENT**				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
			Precipitation: total amount and rate	Horizontal resolution 10 km, 20%	Passive microwave (e.g., GPM), radar; complemented by rain gauges and radar over land	POR-4, 23	TO-5
			Surface pressure	To within 1 mb			TO-5
			Vertical profiles of latent heating		GPROF from TRMM, also from CloudSat, GPM	POR-23	TO-5
			Sea-ice coverage	5 km resolution; 80% coverage daily; uncertainty 10%; 10 km horizontal	Doppler scatterometer or scatterometer, SAR, high-resolution imager, [ice stations]	POR-11, 12, 21, 23, 28	TO-11
			Sea-surface temperature	0.2 K random uncertainty in 25 × 25 km area; 80% daily coverage; 3 to 5 km resolution.	IR radiometer, microwave radiometer, [complemented by in situ buoys and gliders]	POR-11, 21, 23, 24	
			Land-surface temperature	0.6 K random uncertainty in 25 × 25 km area, 80% daily coverage, 3-5 km resolution, with 1 km resolution desired.	IR radiometer (e.g., MODIS, VIIRS, AIRS, CrIS), complemented by modeling	POR-11, 21, 23	TO-18
			Snow coverage (for exposed land and ice)	An average of 1-2 samples (overpasses) per day per 100 to 200 km region; 1 to 10 km resolution; random errors of two times the resolution.	Visible imager (coverage), passive microwave, radar, and lidar (for snow depth/water equivalent)	POR-11, 21, 23	TO-16
			Soil moisture (surface to root zone)	Random errors of 10% in fraction of saturation, while 1 km resolution is desired, 25 km is useful.	Multichannel radiometer, scatterometer (e.g., SMOS, SMAP). *NOTES: C-band scatterometry has worked well in Europe, whereas in the US radiometry is more common. Both seem to work.*	POR-12, 23, 27	TO-17
			Ocean mixed layer depth (heat content), sea-surface height, and bottom pressure	Global refresh 10 days; Horizontal 25 km; 0.5 W/m^2/yr per decade.	Altimeter (e.g., Jason, SARAL), gravimeter (e.g., GRACE), [in situ profiles]	POR-27	TO-10
			Sea-ice thickness	50 cm; 10 km; 24 hr.	Altimeter (e.g., Jason, ICESat-2)	POR-14	TO-7
			Snow water equivalent	Horizon resolution of 20 km, once per day, 10%, Desire 4 km resolution, on a 3 to 5 day scale.	Passive microwave, radar, and SAR	POR-17, 23	TO-16, 19
***QUESTION W-3.* Surface Spatial Variations Impacts on Mass and Energy Transfers.** How do spatial variations in surface characteristics (influencing ocean and atmospheric dynamics, thermal inertia, and water) modify transfer between domains (air, ocean, land, cryosphere) and thereby influence weather and air quality?	**W-3a.** Determine how spatial variability in surface characteristics modifies regional cycles of energy, water and momentum (stress) to an accuracy of 10 W/m^2 in the enthalpy flux, and 0.1 N/m^2 in stress, and observe total precipitation to an average accuracy of 15% over oceans and/or 25% over land and ice surfaces averaged over a 100 × 100 km region and 2- to 3-day time period.	**Very Important**	Ocean surface vector wind or surface wind stress	An average of 1-2 samples (overpasses) per day per 100 to 200 km region; 5 to 10 km resolution; 0.02 N/m^2 for 100 km scales and 1 to 2 day averages (this is analogous to vector component wind random errors <1 m/s for the proposed sampling).	Scatterometer OR polarimetric radiometer. *NOTES: SAR could provide wind vectors but directional accuracy not sufficient to calculate curl.*	POR-28	TO-11
			Ocean surface vector current	An average of 1-2 samples (overpasses) per day per 100 to 200 km region for a high inclination orbit; 5 to 10 km resolution; Random errors ≤0.02 m/s for 100 km scales and 1 to 2 day averages (this is analogous to current random errors <0.5 m/s for the proposed sampling); Coincidence with wind observations.	Doppler scatterometer, HF radar (near coastal only, roughly 100 km from shore). *NOTES: Wide swath altimetry will be complementary but is not an alternative. SAR could provide one vector component, but the accuracy and sampling are questionable. Accurate surface currents (true surface, not subsurface) are new and unique.*		TO-11
			Subsurface current	Already exceeded by the global drifting buoy network: 1,250 drifting buoys with global ocean coverage and hourly locations.	[Surface drifting buoys drogued to 15 m depth, gliders]	TERRESTRIAL	TERRESTRIAL

WEATHER AND AIR QUALITY PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
			Sea-ice motion	3 km per day; 25 km horizontal, 24 hr.	Doppler scatterometer or scatterometer, SAR, high-resolution imager, (ice stations). *NOTES: Synergetic with observation of sea-ice age and extent, soil moisture, vegetation, snow, ocean mixed layer and surface currents.*	POR-11, 12, 21	TO-11
			Sea-ice coverage	5 km resolution; 80% coverage daily; uncertainty 10%; 10 km horizontal	Doppler scatterometer or scatterometer, SAR, high-resolution imager, [ice stations]	POR-11, 12, 21, 23, 28	TO-11
			Sea-surface temperature	0.2 K random uncertainty in 25 × 25 km area; 80% daily coverage; 3 to 5 km resolution.	IR radiometer, microwave radiometer, [complemented by in situ buoys and gliders]	POR-11, 21, 23, 24	
			Sea-ice surface temperature	0.6 K random uncertainty in 25 × 25 km area; 80% daily coverage; 3-5 km resolution.	IR radiometer (e.g., MODIS, VIIRS, AIRS, CrIS), complemented by modeling	POR-11, 21, 23	TO-18
			Land-surface temperature	0.6 K random uncertainty in 25 × 25 km area, 80% daily coverage, 3-5 km resolution, with 1 km resolution desired.	IR radiometer (e.g., MODIS, VIIRS, AIRS, CrIS), complemented by modeling	POR-11, 21, 23	TO-18
			Snow coverage (for exposed land and ice)	An average of 1-2 samples (overpasses) per day per 100 to 200 km region; 1 to 10 km resolution; random errors of boundaries of two times the resolution.	Visible imager (coverage), passive microwave, radar, and lidar (for snow depth/water equivalent)	POR-11, 21, 23	TO-16
			Soil moisture (surface to root zone)	Random errors of 10% in fraction of saturation while 1 km is desired, 25 km is useful.	Multichannel radiometer, scatterometer (e.g., SMOS, SMAP). *NOTES: C-band scatterometry has worked well in Europe, whereas in the US radiometry is more common. Both seem to work.*	POR-12, 23, 28	TO-15, 17
			Upper canopy moisture content	Random errors of 10% in fraction of saturation.	Multichannel radiometer, high frequency and high inclination angle scatterometer		TO-15, 17
			Significant wave height	5cm random error for a 25 km × 25 km area in one overpass.	Altimeter (for swell, wind wave compoent is well-estimated from surface winds), complemented by wave buoys	POR-26, 27	TO-21
			Columnar water vapor (all sky)	An average of 1-2 samples (overpasses) per day per 50 km region; 5 to 10 km resolution; clear sky RMS errors within 3 mm; NWP needs higher revisit (1-6 hr).	Polar/geo IR and microwave sounders PLUS GNSS-RO	POR-21, 23, 24	
			Cloud fraction	An average of 1-2 samples (overpasses) per day per 50 km region, 5 to 10 km resolution, random errors <1 K in brightness temperature	Polar/geo IR	POR-11, 21, 24	
			Ocean mixed layer depth (heat content), sea-surface height, and bottom pressure	Global refresh 10 days; Horizontal 7 km; 0.5 W/m^2/yr per decade.	Altimeter (e.g., JASON, SARAL), gravimeter (e.g., GRACE), [in situ profiles]	POR-27	TO-10
			Boundary-layer height (via air temperature profile)	An average of 1-2 samples (overpasses) per day per 50 km region; 5 to 10 km resolution; random errors 10 m in boundary-layer height.	Lidar (e.g., CALIPSO)	POR-2, 6	TO-1
			Land surface emissivity	Horizon resolution of 20 km; once per day; 20%. Desire 0.1 km, resolve diurnal cycle 10%	Multiangle multichannel radiometer	POR-11, 21, 24	TO-13

WEATHER AND AIR QUALITY PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question/Goal	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
			Ice surface emissivity	Horizon resolution of 20 km; once per day; 0.02.	Multichannel radiometer	POR-11, 21, 23	TO-13
			Sea-surface height	10 cm random variability; six hourly; 10 km resolution.	Wide-swath altimeter, supported by microwave water vapor radiometer	POR-26, 27	TO-21
			Sea-surface salinity	An average of 1-2 samples (overpasses) per 10 days per 100 to 200 km region; 50 km resolution; random erros of 0.2 psu in monthly average on a 100 × 100 km scale.	L-band radiometer, with co-aligned L-band scatterometer for roughness correction (e.g., SMAP, Aquarius, SMOS)	POR-12, 23	TO-15
			Sea-ice thickness	50 cm; 10 km; 24 hr.	Altimeter (e.g., JSON, ICESat-2)	POR-14	TO-7
			Snow water equivalent	Horizon resolution of 20 km; once per day; 20%. Desire 4 km resolution, on a 3-5 day scale.	Passive microwave, radar, and SAR	POR-17, 23	TO-16, 19
			Snow albedo and emissivity	Horizon resolution of 20 km; once per day; 0.01; 5 km resolution is desired.	Multichannel radiometer, microwave and IR/Vis	POR-11, 21, 22, 23, 24	TO-13
			2D surface precipitation	Ideally half hourly, but any additional sampling would be very valuable	Dual-frequencey radiometry, radar (e.g., GPM), [rain gauges and radar over land]	POR-4, 23	TO-5
			2D ocean surface color	An average of 1-2 samples (overpasses) per day per 100 to 200 km region; 5 to 10 km resolution; random errors of 10 per meter.	Radiometry (e.g., PACE), optical imager (e.g., MODIS), OLCI, SLGI)	POR-1, 21, 23, 24	TO-3
			Vegetation characteristics	Land cover type, leaf-area index, vegatation fraction, canopy height	IR and visible radiometry, MODIS, VIIRS, imaging lidar (GEDI and ICESat-2)	POR-9, 10, 12	TO-20
			Near surface air temperature and humidity	Horizon resolution of 20 km; temporal resolution of 3 hr; 0.3 K.	Microwave sounder (ocean), possibly hyperspectral IR for clear skies	POR-1, 6	TO-13
***QUESTION W-4.* Convective Storm Formulation Process.** Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?	**W-4a.** Measure the vertical motion within deep convection to within 1 m/s and heavy precipitation rates to within 1 mm/hour to improve model representation of extreme precipitation and to determine convective transport and redistribution of mass, moisture, momentum, and chemical species.	**Most Important**	Vertical velocity	Global coverage; sample area 200 × 200 km; 5 year mission; Horizontal resolution 2 km; vertical resolution 200 m; temporal resolution 1 min over a 20-30 min period; accuracy 1 m/s.	Doppler radar		TO-5
			Precipitation rate	Global coverage; sample area 200 × 200 km; 5 year mission; Horizontal resolution 1 km; temporal resolution 1-5 min; accuracy 1 mm/hr.	Microwave, radar (e.g., GPM), [ground-based gauges and radar]		TO-5
			3D condensate	Accuracy 0.1 g/kg	Submillimeter multiple frequencies 180-900 GHz		TO-5
			Vertical profiles of horizontal winds	Accuracy 1 m/s	Doppler wind lidar	POR-5	TO-4
					AMVs from IR/hyperspectral for wind estimation	POR-1, 20	TO-13
			3D water vapor	Vertical resolution 1 km; spatial resolution 500 m; temporal resolution 15 min; accuracy 0.5 g/kg.	IR, hyperspectral, [in situ: rawinsonde, aircraft]	POR-20	TO-13
***QUESTION W-5.* Air Pollution Processes and Distribution.** What processes determine the spatio-temporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?	**W-5a.** Improve the understanding of the processes that determine air pollution distributions and aid estimation of global air pollution impacts on human health and ecosystems by reducing uncertainty to <10% of vertically-resolved tropospheric fields (including surface concentrations) of speciated particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2).	**Most Important**	PM concentration and properties, including speciation	PM: Aerosol Optical Depth to infer PM from 0-2 km layer; Six observations during daylight hours to get diurnal distribution. 5 × 5 km^2 horizontal resolution. Spectral properties to infer PM speciation.	Combine advanced space-based observations, aircraft and ground-based observations with chemical transport modeling to infer surface levels. Geosynchronous orbit (GEO) to get temporal evolution and high horizontal resolution, in addition to LEO to get global coverage and allow for tracking long-range transport of pollution. A satellite at Lagrange point-1 may provide daylight-side coverage potentially hourly. PM: radiometric and polarimetric	POR-21 (MODIS), POR-22 (MISR, MAIA, 3MI), POR-24 (VIIRS), POR-11 (TEMPO)	TO-1, 2

WEATHER AND AIR QUALITY PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
					instrument (e.g., NASA EV MAIA, MISR)		
			Ozone (O_3) concentration	O_3: Chappuis and other UV bands to infer O_3 from 0-2 km layer, and supported by modeling to infer surface level. Six observations during daylight hours to get diurnal distribution. Vertical resolution 500 m within BL. Horizontal resolution 5 × 5 km^2.	UV/visible spectrometer at geo (e.g., TEMPO); commercial aircraft vertical observations during takeoff/landing	POR-11 (OMI, TEMPO, TROPOMI), POR-21 (GEMS)	
			NO_2 (nitrogen dioxide) concentration	NO_2: Lower tropospheric vertical distribution to infer NO_2 from 0-2 km layer. Six observations during daylight hours to get diurnal distribution. Vertical resolution 500 m within BL. Horizontal resolution 5 × 5 km^2.	UV/visible (e.g., Aura OMI, ESA TROPOMI, TEMPO); commercial aircraft vertical observations during takeoff/landing	POR-11 (OMI, TEMPO, TROPOMI), POR-21 (GEMS)	
***QUESTION W-6.* Air Pollution Processes and Trends.** What processes determine the long-term variations and trends in air pollution and their subsequent long-term recurring and cumulative impacts on human health, agriculture, and ecosystems?	**W-6a.** Characterize long-term trends and variations in global, vertically resolved speciated particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2) trends (within 20%/yr), which are necessary for the determination of controlling processes and estimation of health effects and impacts on agriculture and ecosystems.	**Important**	PM concentration and properties, including speciation	PM: Aerosol Optical Depth to infer PM from 0-2 km layer; Six observations during daylight hours to get diurnal distribution. 5 × 5 km^2 horizontal resolution. Spectral properties to infer PM speciation.	Combine advanced space-based observations, aircraft and ground-based observations with chemical transport modeling to infer surface levels. Geosynchronous orbit (GEO) to get temporal evolution and high horizontal resolution, in addition to LEO to get global coverage and allow for tracking long-range transport of pollution. A satellite at Lagrange point 1 may provide daylight-side coverage potentially hourly. PM: radiometric and polarimetric instrument (e.g., NASA EV MAIA, MISR)	POR-21 (MODIS), POR-22 (MISR, MAIA, 3MI), POR-24 (VIIRS), POR-11 (TEMPO)	TO-1, 2
			O_3 (ozone) concentration	O_3: Chappuis and other UV bands to infer O_3 from 0-2 km layer, and supported by modeling to infer surface level. Six observations during daylight hours to get diurnal distribution. Vertical resolution 500 m within BL. Horizontal resolution 5 × 5 km^2.	UV/visible spectrometer at geo (e.g., TEMPO); commercial aircraft vertical observations during takeoff/landing	POR-11 (OMI, TEMPO, TROPOMI), POR-21 (GEMS)	
			NO_2 (nitrogen dioxide) concentration	NO_2: Lower tropospheric vertical distribution to infer NO_2 from 0-2 km layer. Six observations during daylight hours to get diurnal distribution. Vertical resolution 500 m within BL. Horizontal resolution 5 × 5 km^2.	UV/visible (e.g., Aura OMI, ESA TROPOMI, TEMPO); commercial aircraft vertical observations during takeoff/landing	POR-11 (OMI, TEMPO, TROPOMI), POR-21 (GEMS)	
***QUESTION W-7.* Tropospheric Ozone Processes and Trends.** What processes determine observed tropospheric ozone (O_3) variations and trends and what are the concomitant impacts of these changes on atmospheric composition/chemistry and climate?	**W-7a.** Characterize tropospheric O_3 variations, including stratospheric-tropospheric exchange of O_3 and impacts on surface air quality and background levels.	**Important**	O_3 (ozone) concentration	O_3: Vertical distribution within the troposphere and lower stratosphere through a combination of ozonesondes (0.5 km vertical resolution, weekly sampling, to 70 hPa) and satellites (e.g., 0.5 km in vertical resolution in upper troposphere, lower stratosphere; 5.5 km^2 column observation with near surface (0-2 km) sensitivity).	Filter radiometer (e.g., Aura HIRDLS) for upper troposphere/lower stratosphere O_3 in conjunction with an ozonesonde network and commercial aircraft observations during takeoff/landing.	POR-11 (HIRDLS, TEMPO), POR-15 (LIS, GLM), POR-21 (GEMS)	

WEATHER AND AIR QUALITY PANEL

SCIENCE			**MEASUREMENT**				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
***QUESTION W-8.* Methane Source Trends and Processes.** What processes determine observed atmospheric methane (CH_4) variations and trends and what are the subsequent impacts of these changes on atmospheric composition/chemistry and climate?	**W-8a.** Reduce uncertainty in tropospheric CH_4 concentrations and in CH_4 emissions, including uncertainties in the factors that affect natural fluxes.	**Important**	CH_4 (methane) concentration	CH_4 column (LEO): 7 × 7 km^2 horizontal resolution; daily overpass; precision = 0.6% (upcoming TROPOMI specifications – full physics method). CH_4 column (GEO): 4 × 4 km^2 horizontal resolution; hourly observations; precision = 1.0% (GEO-CAPE specifications) Both TROPOMI and GEO-CAPE may be able to resolve large point sources on daily scales.	Passive instruments give global coverage of columns (e.g., SCIAMACHY), but stymied by clouds and low light conditions. Emissions estimated from a model using satellite-observed methane and proxies (e.g., inundation depth) for emissions.	POR-10 (GOSAT, GOSAT2), POR-11 (TROPOMI)	TO-6
				Active: pencil pixel size; along track coverage, precision = 1.0% (specifications for upcoming MERLIN)	Active lidar instruments give data in regions that passive instruments cannot, such as night, low light and/or cloudy environments (e.g., monsoons, Arctic).	POR-2 (MERLIN)	
***QUESTION W-9.* Role of Cloud Microphysical Processes.** What processes determine cloud microphysical properties and their connections to aerosols and precipitation?	**W-9a.** Characterize the microphysical processes and interactions of hydrometeors by measuring the hydrometeor distribution and precip rate to within 5%.	**Important**	3D hydrometeor concentration and drop size distribution	0.5 g/kg	Microwave, IR		TO-5
			Vertical temperature profile	Horizontal resolution: 3 km; 1 km vertical; refresh; global 90 minutes, CONUS 60 minutes.	Microwave and IR sounders, GNSS-RO	POR-1, 6, 23	TO-13
			Vertical water vapor profile	Horizontal resolution: 3 km; 1 km vertical; refresh; global 90 min CONUS 60 minutes.	Microwave and IR sounders, GNSS-RO	POR-23	TO-13
			Vertical profiles of horizontal wind vector	Horizontal resolution: 3 km; 1 km vertical; refresh; global 90 minutes and CONUS 60 minutes.	Doppler wind lidar, AMVs from IR, WV and visible imagers and sounders		TO-13
			Precipitation rate	1 mm/hr accuracy; 2 km horizontal resolution; 1 min temporal refresh over a 20-30 min period.			TO-5
			Aerosol concentration	Aerosol optical depth (300 m resolution)	Nadir and multiangle radiometers (MODIS, MISR), lidars (CALYPSO, HRSL), Sun photometers (ground based) for calibration/validation.	POR-1, 2, 4, 10, 12	TO-2, TO-1
***QUESTION W-10.* Clouds and Radiative Forcing.** How do clouds affect the radiative forcing at the surface and contribute to predictability on time scales from minutes to subseasonal?	**W-10a.** Quantify the effects of clouds of all scales on radiative fluxes, including on the boundary layer evolution. Determine the structure, evolution and physical/dynamical properties of clouds on all scales, including small-scale cumulus clouds.	**Important**	High-resolution 2D cloud fraction, helpful to also have estimates of cloud depth, and cloud droplet distribution; Ground-based radiation, water vapor, horizontal and vertical winds, temperature; Hydrometeors, temperature, moisture, winds from the boundary layer through the troposphere and into the UTLS; 3D aerosols, hydrometeors, vertical and horizontal winds, water vapor, temperature, precipitation.	Within 2% for cloud fraction over a 5 × 5 km area; spatial resolution 200 m desirable.	High-resolution visible/IR	POR-1, 11, 21, 23, 24	

MARINE AND TERRESTRIAL ECOSYSTEMS AND NATURAL RESOURCES MANAGEMENT PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question/Goal	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
QUESTION E-1. **Ecosystem Structure, Function, and Biodiversity.** What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space?	**E-1a.** Quantify the distribution of the functional traits, functional types, and composition of vegetation and marine biomass, spatially and over time.	**Very Important**	Chemical properties of vegetation, aquatic biomass, and soils	*Land, inland aquatic, costal zone, and shallow coral reef:* Spectral radiance (10 nm; 380-2500 nm); GSD = 30-45 m; Revisit = ~15 days; SNR = 400:1 VNIR/250:1 SWIR at 25% reflectance; IT of ~5 ms. *Ocean:* Spectral radiance (5 nm; 380-1050 nm); GSD = 0.25-1.0 km; Revisit = <2 days; SNR = 1000:1 at TOA clear sky ocean radiance (PACE)	High-fidelity imaging spectrometer (150-200 km swath from Sun-synchronous LEO). For ocean, imaging spectrometer with wider swath and larger pixels.	Landsat-8 and -9 plus ESA Sentinal-2a, -2b, -2c, and -2d missions 30 m multispectra 3-4 day equatorial revisit frequency POR complement TO-18. PACE for ocean.	TO-18
				Western hemisphere coastal ocean, inland waters: Geostationary; 100-300 m; 5-10 nm; 2-3 hr repeat; GSD = ~250 m	GEO spectrometers (e.g., GEO-CAPE)		TO-3
	E-1b. Quantify the three-dimensional (3D) structure of terrestrial vegetation and 3D distribution of marine biomass within the euphotic zone, spatially and over time.	**Most Important**	3D physical structure of vegetation and aquatic biomass	*Land:* Imaging waveform acquired in swaths; desired sampling = 1 ha cells with 10-25 m footprint size; global sampling every 5 years. *Ocean:* ~2 m vertical resolution subsurface to ~3 optical depths; High spectral resolution lidar (or similar) technique to retrieve vertical particle backscatter and vertical extinction profiles; ≤1 km footprint at sea surface; global	Imaging lidar (Land: 1064 nm; Ocean: 532 nm and 355 nm). *NOTES: GEDI to deploy in 2019 for two years of canopy structure and biomass sampling; Synergy with ICESat-2 (not ideal for land vegetation) to launch circa 2020; Synergy with NISAR radar mission launches in 2022; Synergy with BIOMASS P-band mission to launch in 2020.*		TO-22 and TO-20 for land lidar; TO-1 if it meets specs for ocean and TO-10 lidar
	E-1c. Quantify the physiological dynamics of terrestrial and aquatic primary producers.	**Most Important**	Primary Observable: Chemical properties of vegetation and aquatic biomass, and soils	*Land, inland aquatic, coastal zone, and shallow coral reef:* Spectral radiance (10 nm; 380-2500 nm); GSD = 30-45 m; Revisit = ~15 days; SNR = 400:1 VNIR/250:1 SWIR at 25% reflectance; IT of ~5 ms. *Ocean:* Spectral radiance (5 nm; 380-1050 nm); GSD = 0.25-1.0 km; Revisit = <2 days; SNR = 1000:1 at TOA Clear sky ocean radiance (PACE)	High-fidelity imaging spectrometer (150-200 km swath from sun-sync LEO). For ocean, imaging spectrometer with wider swath and larger pixels.	Landsat-8 and -9 plus ESA Sentinal-2a, -2b, -2c, and -2d missions 30 m multispectra 3-4 day equatorial revisit frequency. For ocean, PACE plus BioArgo (in situ).	TO-18
			Supporting observable: Solar-induced fluorescence	400-790 nm; 0.3 nm bandwidth (FWHM)	SIF spectrometer. *NOTES: SIF sensors are in orbit and are planned, but require other measurements for interpretation. Science community indicates the need for concurrent imaging spectrometer (hyperspectral) and lidar measurements*	GOME-2 POR and assume GEOCARB and FLEX will also be POR GEDI as POR lidar	TO-18
			Supporting observable: Thermal IR imaging	8-12 microns (cloudband at 1.6 microns); multispectral; GSD = 50-100 m; revisit = <15 days; day and night measurements. 150-200 km swath from Sun-synchronous LEO.	TIR imager (e.g., Landsat TIR). *NOTES: Needs to be coupled with the spectrometer to determine physiology (including ET).*	Landsat-8 and 9, MODIS, VIIRS plus ECOSTRESS are POR	TO-17
			Water particles for biomass accounting	*Western Hemisphere Coastal Waters;* Geostationary; 100-300 m; 5-10 nm; 2-3 hr repeat; GSD = ~250 m	GEO spectrometers (e.g., GEO-CAPE)		TO-3
			Net radiation and temperature for ET	Geostationary	Net radiation (e.g., GOES)	NOAA GOES-16 and GOES-S is POR	

MARINE AND TERRESTRIAL ECOSYSTEMS AND NATURAL RESOURCES MANAGEMENT PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
	E-1d. Quantify moisture status of soils.	**Important**	Soil moisture	Combined radar (L-, P-band) and radiometer	Soil moisture (e.g., SMAP, SMOS)	SMAP, SMOS	TO-17
	E-1e. Support targeted species detection and analysis (e.g., foundation species, invasive species, indicator species, etc.).	**Important**	Plant species and/or aquatic biomass classification	*Land, inland aquatic, costal zone, and shallow coral reef:* Spectral radiance (10 nm; 380-2500 nm); GSD = 30-45 m; Revisit = ~15 days; SNR = 400:1 VNIR/250:1 SWIR at 25% reflectance; IT of ~5 ms. *Land:* Lidar; 1064 nm; Imaging waveform acquired in swaths; desired sampling = 1 ha cells with 10-25 m footprint size; global sampling every 5 years.	High-fidelity imaging spectrometer (150-200 km swath from LEO, e.g., VSWIR or HyspIRI)	Landsat-8 and -9 plus ESA Sentinal-2a, -2b, -2c, and -2d missions 30 m multispectra 3-4 day equatorial revisit frequency POR and complement TO-18 for plant functional types	TO-18
				Open Ocean, Land Vegetation mapping: Spectral radiance (5 nm; 380-1050 nm); GSD = 0.25-1.0 km; Revisit = <2 days; SNR = 1000:1 at TOA clear sky ocean radiance (PACE).	High-fidelity imaging spectrometer (1500-2000 km swath from LEO, e.g., PACE)	SeaWiFS, MODIS, VIIRS and Sentinel-3 (all at reduced spectral resolution) and PACE	TO-10
				Western hemisphere coastal waters:Geostationary; 100-300 m; 5-10 nm; 2-3 hr repeat; GSD = ~250 m	GEO spectrometers (e.g., GEO-CAPE)		TO-3
***QUESTION E-2.* Fluxes Between Ecosystems, Atmosphere, Oceans, and Solid Earth.** What are the fluxes (of carbon, water, nutrients, and energy) *between* ecosystems and the atmosphere, the ocean, and solid Earth, and how and why are they changing?	**E-2a.** Quantify the fluxes of CO_2 and CH_4 globally at spatial scales of 100 to 500 km and monthly temporal resolution with uncertainty <25% between land ecosystems and atmosphere and between ocean ecosystems and atmosphere.	**Most Important**	Active and passive observations of atmospheric CO_2, CH_4, and CO concentrations	High accuracy column measurements with near-surface sensitivity, Global coverage in all seasons with 1-3 day revisit, Footprint resolution of $\leq$4 km CO_2: random error <1 ppm, systematic error <0.2 ppm CH_4: random error <10 ppb, systematic error <0.5 ppb CO: random error <10 ppb	Active and/or passive NIR observations for total column CO2, CH_4; TIR/SWIR observations of CO	GOSAT, GOSAT-2, OCO-2, OCO-3, GeoCARB, TEMPO, TROPOMI aboard Sentinel-5p	TO-6
			GPP, respiration, and decomposition, and biomass burning	Global, daily, 30 m / 300 m	Possible: VIIRS, Landsat, lidar topography, commercial sat data	Landsat-8 and -9 plus ESA Sentinal-2a, -2b, -2c, and -2d missions 30 m multispectra 3-4 day equatorial revisit frequency POR	TO-6 and TO-18
			3D winds	Global, daily, 5 km	Lidar winds		TO-4
			Air-sea delta pCO2 and air-sea gas transfer coef	global/daily, $\leq$100 km (less if apprp)	Possible: VIIRS, Aquarius FO, QuikSCAT FO	VIIRS, QuikSCAT	
	E-2b. Quantify the fluxes from land ecosystems between aquatic ecosystems.	**Important**	Riverine transport of nutrients, organic matter and other constituents to oceans and inland waters	River discharge, water quality (POC, DOC, nutrients, CDOM, turbidity); high revisit (2-3 days)	Possible: MODIS, VIIRS, Landsat, Sentinel-2 water quality	MODIS, VIIRS, Landsat, Sentinel-2 water quality	TO-3
	E-2c. Assess ecosystem subsidies from solid Earth.	**Important**	Dust inputs, soil erosion, landslides, black carbon	High spatial resolution (1 m), bare-Earth topography at 0.1 m vertical accuracy Spectral radiance (10 nm; 380-2500 nm); GSD = 30-45 m	Aircraft lidar; VSWIR	MISR	
***QUESTION E-3.* Fluxes Within Ecosystems.** What are the fluxes (of carbon, water, nutrients, and energy) within ecosystems, and how and why are they changing?	**E-3a.** Quantify the flows of energy, carbon, water, nutrients, and so on, sustaining the life cycle of terrestrial and marine ecosystems and partitioning into functional types.	**Most Important**	GPP, respiration, litterfall and decomposition, nonPS vegetation, functional types	Global, daily, 30 m / 300 m Daily SIF measurements	MODIS, VIIRS, Landsat, lidar topography, commercial sat data SIF from GOSAT, GOME-2, and FLEX	Landsat-8 and -9 plus ESA Sentinal-2a, -2b, -2c, and -2d missions 30 m multispectra 3-4 day equatorial revisit frequency POR GOSAT and GOME-2	TO-18 and TO-20
			CO_2, CO, CH_4, etc. fluxes from biomass burning	Global. Daily, 300 m.	e.g., {Sentinel-3} MODIS and VIIRS	MODIS and VIIRS POR	TO-6

MARINE AND TERRESTRIAL ECOSYSTEMS AND NATURAL RESOURCES MANAGEMENT PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question/Goal	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
			ET and root zone moisture	Globally, weekly, ~50 km.	Soil moisture (e.g., SMAP, SMOS, HDO from TES)	SMAP, TES	TO-17
			Aquatic NPP, PhytoC and Chl, NCP, Export from the euphotic zone, N_2 fixation and calcification, partitioned into functional types	Hyperspectral with spatial resolution 1 km and 1-2 day revisit for open ocean (PACE). Multi-spectral regional imaging with <200 m spatial resolution and <1 day revisit for coastal and inland waters (GEO-CAPE).	Imaging spectrometer (e.g., PACE, VIIRS); In situ ocean measurements and modeling; high-fidelity imaging spectrometer (150-200 km swath from Sun-synchronous LEO) for aquatic and coastal waters.	MODIS, VIIRS, PACE, Sentinel-3, Landsat-8 and -9 plus ESA Sentinal-2a, -2b, -2c, and -2d missions 30 m multispectra 3-4 day equatorial revisit frequency POR	TO-3 and TO-18
	E-3b. Understand how ecosystems support higher trophic levels of food webs.	**Important**	Rates of herbivory on terrestrial vegetation	See E-2a and E-3a	See E-2a and E-3a		
			Zooplankton population dynamics and secondary production	*Modeling plus new sensor concept, possibly lidar.*			
QUESTION E-4. How is carbon accounted for through carbon storage, turnover, and accumulated biomass? Have all of the major carbon sinks been quantified and how are they changing in time?	**E-4a.** Improve assessments of the global inventory of terrestrial C pools and their rate of turnover.	**Important**	Aboveground carbon density (biomass)	Global, daily 30 m / 300 m lidar; 1064 nm; Imaging waveform acquired in swaths; desired sampling = 1ha cells with 10-25 m footprint size; global sampling every 5 years.	GEDI, ICESat-2, Landsat-8, Sentinel-2, MODIS, VIIRS		TO-20 and TO-22
			Terrestrial GPP, respiration, decomposition and biomass burning	See E-2a and E-3a	See E-2a and E-3a		TO-6 and TO-18
	E-4b. Constrain ocean C storage and turnover.	**Important**	Air-sea CO2 fluxes	Hyperspectral with spatial resolution 1 km and 1-2 day revisit for open ocean.	NPP for biological contribution	PACE	
			Vertical profile of export flux and water mass ventilation ages	Hyperspectral with spatial resolution 1 km and 1-2 day revisit for open ocean.	NPP (see above) plus in situ measurements (e.g., ARGO) and particle flux modeling.	PACE (for NPP)	TO-3 and TO-10
***QUESTION E-5.* Carbon Sinks.** Are carbon sinks stable, are they changing, and why?	**E-5a.** Discover ecosystem thresholds in altering C storage.	**Important**	Roles of temperature and moisture, changes in community structure (incl. invasives), sea-level rise, ocean upwelling, etc. on C storage	See E-1 through E-4	Imaging spectrometer (e.g., PACE, MODIS, VIIRS); In situ ocean measurements and modeling	MODIS, VIIRS, PACE, Sentinel-3, Landsat-8 and -9 plus ESA Sentinal-2a, -2b, -2c, and -2d missions 30 m multispectra 3-4 day equatorial revisit frequency POR	TO-22 and TO-20 for land Lidar; TO-1 if it meets specs for ocean and TO-10 lidar
	E-5b. Discover cascading perturbations in ecosystems related to carbon storage.	**Important**	Cascading ecological perturbations (e.g., pine beetles, plankton or algal blooms, permafrost thawing, wildfire)	*Hyperspectral with spatial resolution 1 km and 1-2 day revisit for open ocean.*	Imaging spectrometer (e.g., PACE, MODIS, VIIRS); In situ ocean measurements and modeling	MODIS, VIIRS, PACE, Sentinel-3, Landsat-8 and -9 plus ESA Sentinal-2a, -2b, -2c, and -2d missions 30 m multispectra 3-4 day equatorial revisit frequency POR	TO-3, TO-18, TO-20, and TO-22
	E-5c. Understand ecosystem response to fire events.	**Important**	Wild and prescribed fires including active fire and burn area detection, GPP; 3D physical structure of vegetation; Chemical properties of vegetation	Global. Daily, 300 m.	Active fire detection using MODIS; VIIRS and the proposed TIR mission; (same as in E-1c but with eight bands); Burn area assessment using Landsat and Sentinel-2, MODIS, VIIRS and the proposed VSWIR imaging spectrometer (400 to 2500 nm) (same as in E-1e); Vegetation structure/fuel load assessment using lidar (same as in E-1b), SAR (Sentinel 1), and black carbon/smoke using CALIPSO, GEDI, GLAS, ICESat-1/2	Landsat-8 and -9 plus ESA Sentinal-2a, -2b, -2c, and -2d missions 30 m multispectra 3-4 day equatorial revisit frequency POR	TO-2, TO-6, TO-12, TO-18, and TO-22

CLIMATE VARIABILITY AND CHANGE PANEL

SCIENCE			**MEASUREMENT**				
					Example Measurement Approaches		
Societal or Science Question	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
***QUESTION C-1.* Sea-level Rise: Ocean Heat Storage and Ice Melt.** How much will sea-level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?	**C-1a.** Determine the global mean sea-level rise to within 0.5 mm/yr over the course of a decade.	**Most Important**	Sea-surface height	Space/Time Sampling: 7 km along track/10 day; Space/Time Coverage: global/10 days; Accuracy/Stability: 3 cm at 7 km and 1 mm/global/yr	Radar altimeter, with microwave water vapor radiometer and precision orbit	POR-26, 27	TO-21
			Terrestrial reference frame	Space/Time Sampling: monthly; Space/Time Coverage: global/year-decade; Accuracy/Stability: 1 mm/ 0.1 mm/yr/decade	GNSS RO	POR-7, 13 (GRACE-FO, Jason-3, LAGEOS, GRASP)	
			Ocean mass distribution	Space/Time Sampling: 300 km^2/monthly; Space/Time Coverage: global/monthly; Accuracy/Stability: 15 mm at 300 km^2, 0.1 mm/yr/decade	Gravity (e.g., GRACE FO)	POR-30	TO-9
	C-1b. Determine the change in the global oceanic heat uptake to within 0.1 W/m^2 over the course of a decade.	**Most Important**	Sea-surface height	Space/Time Sampling: 7 km along track/10 day, equivalent to 150 km^2/10 day; Space/Time Coverage: global/10 days; Accuracy/Stability: 3 mm at 7 km, 1 mm/global/yr	Radar altimeter, with microwave water vapor radiometer and precision orbit	POR-26, 27	TO-21
			Ocean mass distribution	Space/Time Sampling: 300 km^2/monthly; Space/Time Coverage: global/monthly; Accuracy/Stability: 15 mm at 300 km^2, 0.1 mm/yr/decade	Gravity (e.g., GRACE FO)	POR-30	
			Ocean temperature and salinity profile	Space/Time Sampling: 3 degrees × 3 degrees/10 day, equivalent to 150 km^2/10 day; Space/Time Coverage: global/10 days; Accuracy/Stability: 0.01 deg/0.01 psu	[in situ, such as Argo]	[Argo, Deep Argo]	TERRESTRIAL
	C-1c. Determine the changes in total ice-sheet mass balance to within 15 Gton/yr over the course of a decade and the changes in surface mass balance and glacier ice discharge with the same accuracy over the entire ice sheets, continuously, for decades to come.	**Most Important**	Ice-sheet mass	Horizontal resolution/range: 100 km / Global; Temporal sampling: Monthly; Precision: 1 cm water equivalent on scale of 200 km	Gravity (e.g., GRACE FO), NISAR/Landsat, [reanalysis], Operation IceBridge.	POR-30	
			Ice-sheet velocity	Horizontal resolution/range: 100 m / pole to pole; Temporal sampling: weekly to daily; Precision: 1 m/yr in fast flow areas, 1 cm/yr near ice divides	SAR (e.g., NISAR), Landsat	POR-12	TO-19
			Ice-sheet elevation	Vertical resolution/range: 10-20 cm; Horizontal resolution/range: 100 m/ pole to pole; Temporal sampling: weekly to daily; Precision: 10-20 cm	Operation IceBridge, ICESat-2, {WorldView satellites}, GLISTIN	POR-14	TO-20
			Ice-sheet thickness, ice-shelf thickness	Vertical resolution/range: 10 m pole to pole; Horizontal resolution/range: 100 m/ pole to pole; Temporal sampling: yearly; Precision: 10 m	Operation IceBridge, ICESat-2 (ice shelf), {WorldView satellites}	POR-14	TO-20
			Ice-sheet bed elevation, ice-shelf cavity shape	Vertical resolution/range: 30 m; Horizontal resolution/range: 100 m/ pole to pole; Temporal sampling: one time; Precision: 30 m	Operation IceBridge, EVS-2 OMG, new EVS Antarctica		TO-20
			Ice-sheet surface mass balance	Vertical resolution/range: 1 mm/yr; Horizontal resolution/range: 5 km/ pole to pole; Temporal sampling: monthly; Precision: 1 mm/yr	Gravity (e.g., GRACE FO), ICESat-2, Operation IceBridge, [re-analysis data]	POR-14, 30	TO-20
	C-1d. Determine regional sea-level change to within 1.5-2.5 mm/yr over the course of a decade (1.5 corresponds to a	**Very Important**	Sea-surface height	Space/Time Sampling: 250 m/weekly at midlatitudes; Space/Time Coverage: 20 days/global; Accuracy: 10 cm	e.g., SWOT to be launched 2021		TO-21

CLIMATE VARIABILITY AND CHANGE PANEL

SCIENCE			**MEASUREMENT**				
					Example Measurement Approaches		
Societal or Science Question	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
	~6000 km^2 region, 2.5 corresponds to a ~4000 km^2 region).		Land vertical motions	Space/Time Sampling: 100 m along coast; Space/Time Coverage: global coastline/monthly; Accuracy/stability: 1 mm/ 1 mm/yr	[ground GPS]		TERRESTRIAL
			Ocean mass distribution	Same as C-1a		POR-30	
			Wind vector	Space/Time Sampling: 25 × 25 km/weekly; Space/Time Coverage: global/weekly; Accuracy/stability: 2 m/s speed, 15 degree direction	METOP A/B, Oceansat-3, HY-2B	POR-28	TO-11
QUESTION C-2. **Climate Feedback and Sensitivity.** How can we reduce the uncertainty in the amount of future warming of Earth as a function of fossil fuel emissions, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?	**C-2a.** Reduce uncertainty in low and high cloud feedback by a factor of 2.	**Most Important**	Top of Atmosphere Shortwave (SW), Longwave (LW) and Net Radiative Fluxes for All-sky and Clear-sky conditions	Space/Time Sampling: 100 km, monthly; Space/Time Coverage: global, decadal trends; Accuracy/Stability: global SW TOA flux at 0.3% (95% confidence), global LW TOA flux at 0.6% (95% confidence); Ultimate requirement is on use for Cloud Radiative Effect for SW and LW	Earth radiation monitor (e.g., CERES), RBI for space-time-angle sampling, CLARREO-like intercalibration (to achieve decadal trend accuracy/stability)	POR-3, 24	TO-14
			Cloud fraction	Space/Time Sampling: 100 km, monthly; Space/Time Coverage: global, decadal trends; Accuracy/Stability: 0.1% relative to global mean (1σ)	Cloud imagers (e.g., MODIS/VIIRS), or lidar (e.g., CALIPSO) or HSRL	POR-24	TO-2
			Cloud optical depth	Space/Time Sampling: 100 km, monthly; Space/Time Coverage: global, decadal trends; Accuracy/Stability: 0.3% relative to global mean log optical depth (95% confidence)	Cloud imagers (e.g., MODIS/VIIRS) plus CLARREO-like intercalibration (to achieve optical depth trend accuracy/stability)	POR-24	TO-14
			Cloud infrared emissivity	Space/Time Sampling: 100 km, monthly; Space/Time Coverage: global, decadal trends	Cloud imagers (e.g., MODIS/VIIRS), or lidar (e.g., CALIPSO) or HSRL	POR-24	TO-2 or TO-14
			Cloud top height	Space/Time Sampling: 100 km, monthly; Space/Time Coverage: global, decadal trends; Accuracy/Stability: 0.04 K (1σ)	Cloud imagers (e.g., MODIS/VIIRS) plus CLARREO-like intercalibration or lidar (e.g., CALIPSO) or HSRL	POR-24	TO-2 or TO-14
			Cloud effective radiating temperature	Space/Time Sampling: 100 km, monthly; Space/Time Coverage: global, decadal trends; Accuracy/Stability: 0.04 K (1σ)	Cloud imagers (e.g., MODIS/VIIRS) plus CLARREO-like intercalibration	POR-24	TO-2 or TO-14
			Cloud phase (water, ice)	Space/Time Sampling: 100 km, monthly; Space/Time Coverage: global, decadal trends	Cloud imagers (e.g., MODIS/VIIRS), or lidar (e.g., CALIPSO) or HSRL	POR-24	TO-14
			Cloud particle size	Space/Time Sampling: 100 km, monthly; Space/Time Coverage: global, decadal trends	Cloud imagers (e.g., MODIS/VIIRS) plus CLARREO-like intercalibration	POR-24	TO-14
	C-2b. Reduce uncertainty in water vapor feedback by a factor of 2.	**Very Important**	Atmospheric water vapor and temperature profiles	Vertical Resolution/Coverage: 2 km from 0 to 15 km altitude; Space/Time Sampling: 100 km horizontal resolution/monthly average Time/Space Coverage: decadal trends/global; Accuracy/Stability: 0.03 K (1σ)	IR sounders (e.g., CrIS, IASI) plus CLARREO-like intercalibration, GNSS-RO for zonal temperature trend in 5-20 km altitude	POR-6, 20	TO-14
	C-2c. Reduce uncertainty in temperature lapse rate feedback by a factor of 2.	**Very Important**	Atmospheric temperature profile	Vertical Resolution/Coverage: 2 km from 0 to 15 km altitude; Space/Time Sampling: 2 km vertical resolution, 100 km horizontal resolution/monthly Time/Space Coverage: decadal	IR sounders (e.g., CrIS, IASI) plus CLARREO-like intercalibration, GNSS-RO for zonal temperature trend in 5-20 km altitude	POR-6, 20; Suborbital: Global Climate Observing System Reference Upper-Air Network (GRUAN), NWS Upper-Air Observations Program	TO-14

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SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
				trends/global; Accuracy/Stability: 0.03 K (1σ)			
	C-2d. Reduce uncertainty in carbon cycle feedback by a factor of 2.	**Most Important**	See Objectives C-3a, C-3c, C-3d, and C-3e	See Objective C-3a, C-3c, and C-3e			
	C-2e. Reduce uncertainty in snow/ice albedo feedback by a factor of 2.	**Important**	Surface Snow and Ice Coverage	Space/Time Sampling: 10 km horizontal resolution/monthly average; Time/Space Coverage: decadal trends regional and global; Accuracy/Stability: 1% (1σ)	MODIS/VIIRS for snow/ice cover and surface albedo. CERES for TOA albedo	POR-3, 24	
			Surface albedo and Top of Atmosphere albedo (spectral and broadband)	Space/Time Sampling: 100 km horizontal resolution/monthly average; Time/Space Coverage: decadal trends regional and global; Accuracy/Stability: 1% (1σ)	MODIS/VIIRS for snow/ice cover and surface albedo. CERES for TOA albedo	POR-3, 24	
	C-2f. Determine the decadal average in global heat storage to 0.1 W/m^2 (67% confidence) and interannual variability to 0.2 W/m^2 (67% confidence).	**Very Important**	Same as for Objective C-1b		See Objective C-1b	POR-3, 24	
			Global net radiation	Space/Time Sampling: 100 km, monthly; Space/Time Coverage: Monthly to decadal, Global; Interannual stability/drift of calibration less than 0.1 W/m^2	Earth radiation monitor (e.g., CERES), RBI for space-time-angle sampling, CLARREO-like intercalibration (to achieve decadal trend accuracy/stability)	POR-3, 24	TO-14
			Total solar irradiance	Space/Time Sampling: full solar disk, daily; Space/Time Coverage: monthly to decadal; Accuracy/Stability: 0.01%/0.01% per decade	Total solar irradiance (e.g., TSIS)	TSIS on ISS, JPSS	
	C-2g. Quantify the contribution of the upper troposphere and stratosphere (UTS) to climate feedbacks and change by determining how changes in UTS composition and temperature affect radiative forcing with a 1-sigma uncertainty of 0.05 W/m^2 over the course of the decade.	**Very Important**	Vertical profiles of temperature in UTS (upper troposphere and stratosphere), for quantifying radiative forcing	Vertical resolution and range: <1 km in UTLS, <3 km in mid-upper stratosphere; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: weekly; Precision: 1-2 K.	UV, visible, and infrared solar, lunar, and stellar occultation (e.g., ACE-FTS, GOMOS, HALOE, POAM, SAGE) High precision, high vertical resolution (<1 km), climate (trend) quality, but poor spatial coverage unless using a constellation.	POR-6, 16, 17, 18 ACE-FTS (not global), Auro MLS (not 1 km verical resolution; not self-calibrating), GPS-RO (extreme path length), MSU/SSU/AMSU (10 km vertical resolution; not self-calibrating)	TO-13
			Vertical profiles of radiatively active gas concentrations in the UTS, for quantifying radiative forcing	**Concentration of O_3:** Vertical resolution and range: <1 km in UTLS, <3 km in mid-upper stratosphere; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: weekly; Precision: 10%. **Concentration of H_2O:** Vertical resolution and range: <1 km in UTLS, <3 km in mid-upper stratosphere; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: weekly; Precision: 10%.	Infrared and microwave limb emission (e.g., HIRDLS, MIPAS, MLS, Odin SMR) Many species, 3-4 km vertical resolution, night and day, global coverage Visible limb scattering (e.g., SME, OMPS-LP, OSIRIS) Lidar (e.g., CALIPSO-CALIOP) High (meters) vertical resolution Radar (e.g., CloudSat CPR) Nadir-viewing solar reflection/scattering (e.g., AIM-CIPS, MODIS, OCO-2) Good (km) horizontal resolution	POR-6, 16, 17, 18 ACE-FTS (not global; not 1 km vertical resolution), Aura MLS (not 1 km vertical resolution; not self-calibrating), OMPS-L (not 1 km vertical resolution; not self-calibrating (?)); Suborbital measurements: Network for the Detection of Atmospheric Composition Change, Global Climate Observing System Reference Upper-Air Network (GRUAN), Southern Hemisphere Additional Ozonesondes (SHADOZ) SAGE III (ISS) (not global; 18 Feb 2017 launch)	TO-12

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SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
			Vertical profiles of UTS aerosol radiative properties, for quantifying radiative forcing	Vertical resolution and range: <1 km in UTLS; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: weekly; Precision: 30%.		POR-2, 16, 18 ACE-FTS [not global; not 1 km vertical resolution], Odin OSIRIS [not 1 km vertical resolution; not polar night; no particle size info], CALIPSO CALIOP [near end-of-life] SAGE III (ISS) [not global]	TO-1, TO-2
			Volcanic and biomass burning emissions, for process studies (sources and transport)	**Volcanic Aerosol:** Vertical resolution and range: <1 km in UTLS; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: daily during events; Precision: 30%. **Concentrations of gases from volcanic emissions:** Vertical resolution and range: <1 km in UTLS; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: daily during events; Precision: ~20%, but species dependent.		POR-2, 16, 17, 18 **Volcanic Aerosol:** CALIPSO CALIOP [near end-of-life] **Concentrations of gases from volcanic emissions:** ACE-FTS [not global; not 1 km vertical resolution], MLS [not 1 km vertical resolution; not NO$_2$] SAGE III (ISS) [not enough sampling to track the sources]	TO-1, TO-2, TO-12
			Deep convective clouds, for process studies (sources)	Vertical resolution and range: <1 km in UTLS; Horizontal range: Global; Horizontal and temporal sampling: event-specific, episodic; Precision: 30%.		POR-1, 4, 10, 17, 21, 23 Aura MLS (not 1 km vertical resolution), Aqua AIRS, Aqua AMSR-E, Aqua MODIS, CloudSat	TO-5
			Small-scale transport and the Brewer-Dobson circulation, for process studies (transport)	Vertical resolution and range: <1 km in UTLS, <3 km in mid-upper stratosphere; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: event-driven for small scale, weekly for BD; Precision: 30%.		POR-16, 17 ACE-FTS [not global; not 1 km vertical resolution], Aura MLS [not 1 km vertical resolution]	TO-12, TO-13
			Dynamical features such as the polar vortex, for process studies (transport)	Vertical resolution and range: <1 km in UTLS, <3 km in mid-upper stratoshpere; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: daily to weekly; Precision: 1-2 K (T), 30% (UV).		POR-6, 16, 17, 18 ACE-FTS [not global; not 1 km vertical resolution], Aura MLS [not 1 km vertical resolution], GPS-RO [extreme path length]	TO-12, TO-13
			Planetary and gravity waves, for process studies (transport)	Vertical resolution and range: <1 km from cloud top to stratopause; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: daily to weekly; Precision: 1-2 K (T).		POR-6, 16, 17, 18 ACE-FTS [not global; not 1 km vertical resolution], Aura MLS [not 1 km vertical resolution], GPS-RO [extreme path length]	TO-12, TO-13
			Stratospheric ozone and related constituents, for process studies (chemistry)	Vertical resolution and range: <1 km from cloud top to stratopause; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: daily to weekly; Precision: 5% (O$_3$), 10% (others).		POR-16, 17, 18 ACE-FTS [not global; not 1 km vertical resolution], Aura MLS [not 1 km vertical resolution; only some of the constituents]); Suborbital measurements: Network for the Detection of Atmospheric Composition	TO-12

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
						Change, Global Climate Observing System Reference Upper-Air Network (GRUAN), Southern Hemisphere Additional Ozonesondes (SHADOZ) SAGE III [not global; only some of the constituents]	
	C-2h. Reduce the IPCC AR5 total aerosol radiative forcing uncertainty by a factor of 2.	**Most Important**	AEROSOLS. Aerosol Size (0.05 µm and larger), vertical profiles of mass concentrations (10/cm^3 and greater), effective radius. Also needed: (1) column properties (aerosol optical depth, burden as aerosol mass concentration), (2) plume properties (e.g., characterizing aerosol type, plume height, and plume thickness), and (3) characteristics at cloud base. Physical properties: (1) ability to distinguish size of those aerosols most important to become cloud condensation nuclei (CCN, 0.1 µm radius and smaller), from those most radiatively active (0.5 µm and larger), (2) aerosol source/ chemical composition, (3) hygroscopicity, Need to separate absorption from total extinction, and obtain vertical profiles of both extinction and absorption, as well as relative humidity.	Horizontal resolution requirements: at high (1 km) to very high (<100 m); Vertical resolution requirement: Information is needed at low (column integrals) and high (<500 m) resolution. Temporal sampling: weekly; Precision: 30%. Accuracy requirements: vertically and horizontally resolved aerosol number and mass concentration (100%), effective variance (50%), and effective radius (10%) over the 0.1 to 1 µm radius range. Vertical distribution of temperature (0.2°C), humidity (uncertainty 0.3 g/kg).	Nadir viewing radiometers (e.g., MODIS); Multiangle viewing radiometers (MISR); Current technology lidar (CALIPSO); More modern technology lidar (HSRL); HSRL can be used for vertically resolved profiles that better enable (1) distinguishing aerosols and clouds, (2) increased sensitivity (detecting lower concentrations of aerosol), (3) better resolution of aerosol amounts nearer the surface (lower altitude), and (4) more accurate aerosol optical depths. Multiangle, multispectral polarimeters can provide improved column integrated information on aerosol composition such as refractive index (including absorption), particle size, and variance. The combination of HSRL and a multiangle, multispectral polarimeter has improved accuracy beyond each individual instrument.	POR-1, 2, 5, and Terrestrial. Also, POR-7, 13 (GRACE-FO, Jason-3, LAGEOS, GRASP)	TO-1, TO-2, TO-12, TO-18, TO-20
			CLOUDS. Nearby (to aerosol fields) and simultaneous measurements of cloud properties (cloud water path, thickness, altitude, condensate phase, cloud particle size, anvil extent and thickness), and precipitation characteristics. Derive estimates (with uncertainty) of cloud base vertical motions and maximum updraft velocities in cloud. Lidar (e.g., CALIOP) to separate cloud and aerosol. Determine properties of the aerosol ingested into clouds and cloud systems, and obtain a sufficiently long and diverse (in cloud types and locations) record to enable statistical interpretation of aerosol-cloud interactions. Determine drizzle frequency and amount (e.g., CloudSat).	Determination of cloud height, cloud cover, microphysical properties. Horizontal resolution: 5 degrees latitude × 10 degrees longitude/Global. Temporal sampling: weekly. Precision: 30%. Improving the confidence levels through increased accuracy in various cloud fields: • LWC 50% ->20% • IWC 70% -> 20% • Cloud thickness 240 -> 75 m • Drizzle	Nadir and multi angular radiometers (MODIS, MISR); Lidars (CALIPSO, HSRL); W-band radar reflectivity profiles (e.g., CloudSat) that accounts for light rain/ snow; microwave brightness temperatures; shortwave reflectances in the near IR and visible bands; stereo photogrammetric methods that build on and advance measurements pioneered by the MISR instrument on the Terra satellite.	POR-1, 2, 4, 5, 10, 20, 23, 24	TO-1, TO-2, TO-5, TO-13
			ENVIRONMENT. Meteorological properties in vicinity of aerosols	Atmospheric water vapor and temperature profiles: vertical	See C-12. IR sounders (e.g., CrIS, IASI) plus CLARREO-like	POR-5, 6, 7, 10, 20, 24	TO-1, TO-13, TO-14

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SCIENCE			MEASUREMENT				
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Societal or Science Question	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
			and clouds (temperature, winds, humidity) to characterize the environment in which the cloud is forming.	resolution/coverage: 2 km from 0 to 15 km altitude. Space/Time Sampling: 25 km horizontal resolution/monthly avg. Time/Space Coverage: decadal trends/global. Accuracy/Stability: 0.03 K (1σ) 3D Winds (see E-2, from Weather Panel, and C-3f) Surface winds (see C-4a): (U10, windspeed and direction) 20 km spatial resolution; 3 hr revisit; 0.5 m/s instantaneous uncertainty, 0.1 m/s monthly uncertainty, decadal stability to 0.05 m/s/decade; direction to 15 degrees instantaneous, monthly to 10 deg.	intercalibration, GNSS-RO for zonal temperature trend in 5-20 km altitude		
***QUESTION C-3.* Carbon Cycle, Including Carbon Dioxide and Methane.** How large are the variations in the global carbon cycle and what are the associated climate and ecosystem impacts in the context of past and projected anthropogenic carbon emissions?	**C-3a.** Quantify CO_2 fluxes at spatial scales of 100-500 km and monthly temporal resolution with uncertainty <25% to enable regional-scale process attribution explaining year-to-year variability by net uptake of carbon by terrestrial ecosystems (i.e., determine how much carbon uptake results from processes such as CO_2 and nitrogen fertilization, forest regrowth, and changing ecosystem demography.)	**Very Important**	Biomass and biomass change	See E-3a	See E-3a		
			GPP, respiration, and decomposition, and biomass burning	See E-3a	See E-3a		
			Atmospheric CO_2	Random error: XCO_2: goal = 1 ppm, threshold = 3 ppm; Systematic error: XCO_2: goal = 0.2 ppm, threshold = 0.5 ppm; Mission duration: 3-5 years provides a snapshot of current conditions; Trends and interannual variability will require systematic measurements >10 yr	NearIR for total column plus thermal for separation of boundary layer and upper, ground-based and aircraft in situ measurements for linking to WMO calibration scales ground-truth	Orbital: POR-11 (OCO2, OCO-3-on-ISS), POR-24 (GOSAT, GOSAT-2), GeoCARB; Suborbital: NOAA Global Greenhouse Gas Reference Network, Total Carbon Column Observing Network	TO-6
			Solar-induced flourescence	See E-1c	Ecosystem Panel, European FLEX Mission 2020, GOME-2, OCO-2	POR-11, POR-32 (FLEX)	
			Leaf Area Index, Enhanced Vegetation Index, Normalized Difference Vegetation Index	Similar to or better than MODIS			
			Atmospheric CO	Similar to or better than MOPITT		POR-11, Geo-CARB	TO-6
	C-3b. Reliably detect and quantify emissions from large sources of CO_2 and CH_4, including from urban areas, from known point sources such as power plants, and from previously unknown or transient sources such as CH_4 leaks from oil and gas operations.	**Important**	Atmospheric CO_2 and/or CH_4	Geostationary or other mapping capability. Measurement comparability <0.2 ppm for CO_2 0.5 ppb for CH_4 over time scales of decades will be needed to track changes in emissions. Spatial scale <1 km.	Geo or other mapping	Geo-CARB	TO-6
	C-3c. Provide early warning of carbon loss from large and vulnerable reservoirs such as tropical forests and permafrost.	**Important**	Atmospheric CO_2 and/or CH_4	Random error: XCO_2: goal = 1 ppm, threshold = 3 ppm; Systematic error: XCO_2: goal = 0.2 ppm, threshold = 0.5 ppm; Random Error: XCH_4 goal = 6 ppb, threshold = 12 ppb; Systematic error: goal = 2.5 ppb, threshold = 5 ppb	Geo or other mapping	POR-2 (ASCENDS, MERLIN), Geo-CARB	TO-6
			Biomass change	See E-3a	See E-3a		
	C-3d. Provide regional-scale process attribution for carbon uptake by ocean to within 25%	**Important**	Surface roughness—air sea gas transfer coefficient	See W-3a (i.e., ocean surface vector wind/surface wind stress)	See E-9		
			Winds	See W-3a, E-2	(from Weather Panel)		

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Societal or Science Question	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
	(especially in coastal regions and the Southern Ocean).		Atmospheric CO_2	Note ocean uptake signals of order 0.1 ppm and cannot be measured with current satellite sensor technology	No existing or proposed spaceborne XCO_2 sensor is capable of detecting ocean flux signals to enable useful flux quantification		
			Ocean color	(from Ecosystem panel)	(from Ecosystem panel)	POR-21 (PACE), POR-24 (VIIRS)	TO-18
			Salinity	(from Ecosystems or Weather Panel)	(from Ecosystems or Weather Panel)	POR-23	
	C-3e. Quantify CH_4 fluxes from wetlands at spatial scales of 300 km × 300 km and monthly temporal resolution with uncertainty better than 3 mg CH_4 m^{-2} day^{-1} in order to establish predictive process, based understanding of dependence on environmental drivers such as temperature, carbon availability, and inundation.	**Important**	CH_4 fluxes	Random Error: goal = 6 ppb threshold = 12 ppb; Systematic error: goal = 2.5 ppb, threshold = 5 ppb; Mission duration: 3-5 years provides a snapshot of current conditions; Spatial coverage: Tropics, Boreal		POR-2 (MERLIN), POR-11 (TropOMI), GeoCARB	TO-6
	C-3f. Improve atmospheric transport for data assimilation/inverse modeling.	**Important**	3D Winds	See E-2	See W-1 and W-3		
			PBL depth	See W-1	See W-1		
			Convective transport	See W-4	See W-4		
			Surface pressure	See W-2, to within 1 mb	See W-2		TO-5
	C-3g. Quantify the tropospheric oxidizing capacity of OH, critical for air quality and dominant sink for CH_4 and other GHGs.	**Important**	Abundance of gases lost by reaction with OH, such as HCFC-22, HFC-32 and HFC-152a	Vertical resolution and range: 1 km / mid-upper troposphere; Horizontal resolution/range: 50 km / global; Temporal sampling: Weekly; Precision: HCFC-22: ~10% (20 ppt), HFC-32: ~30% (3 ppt), HFC-152a: ~50% (4 ppt). Profiles of CO in the mid to upper global troposphere would provide useful information. This objective must have a strong suborbital component to be achieved.	There are the appropriate sample approaches: a) UV, visible, and infrared solar, lunar, and stellar occultation (e.g., ACE-FTS, GOMOS, HALOE, POAM, SAGE); b) Infrared and microwave limb emission (e.g., HIRDLS, MIPAS, MLS, Odin SMR).	Orbital: ACE-FTS, MLS, MOPITT, Odin SMR, SAGE III, TANSO-FTS. Suborbital: NASA ATom and other airborne surveys of tropospheric OH that include the tropical troposphere; continued ground-based observations of methyl chloroform and other well mixed gases with well defined emission source strength that are primarily lost by reaction with tropospheric OH.	
***QUESTION C-4.* Atmosphere-Ocean Flux Quantifications.** How will the Earth system respond to changes in air-sea interactions?	**C-4a.** Improve the estimates of global air-sea fluxes of heat, momentum, water vapor (i.e., moisture) and other gases (e.g., CO_2 and CH_4) to the following global accuracy in the mean on local or regional scales: (1) radiative fluxes to 5 W/m^2, (2) sensible and latent heat fluxes to 5 W/m^2, (3) winds to 0.1 m/s, and (4) CO_2 and CH_4 to within 25%, with appropriate decadal stabilities.	**Very Important**	Surface vector winds	(U10, windspeed and direction) 20 km spatial resolution; 3 hr revisit; 0.5 m/s instantaneous uncertainty, 0.1 m/s monthly uncertainty, decadal stability to 0.05 m/s/decade; direction to 15 degrees instantaneous, monthly to 10 degrees	Scatterometer, Doppler scatterometer, passive microwave, SAR (possible new versions based on GPM microwave imager, or Compact Ocean Wind Vector Radiometer; Vector winds highly desirable for momentum fluxes)	POR-28; SSM/I, SSM/IS, AMSR-2, GMI, MWI. Move POR-7 CYGNSS (Mission ID 740, Instrument ID 1669, Unique ID 740-1669) to POR-33	TO-11 (if scatterometer and tuned to stress)
			10 m air humidity and temperature and SST	(BL atmos) 20 km horizontal resolution; 500 m vertical resolution with 10 m at surface; 3 hr revisit; monthly 0.2°C uncertainty (temperature), 0.3 g/kg (humidity)	For temperature and humidity: IR and microwave sounders (e.g., AIRS, AMSU, ATMS), GNSS-RO	POR-1, (6)	TO-13
			Sea-surface temperature (skin)	0.2 K random uncertainty in 25 × 25 km area; 80% daily coverage; 3 to 5 km resolution.	IR or microwave radiometery	POR-23 AMSR-2 (Mission ID 459, Instrument ID 883, Unique ID 459-883) with caveats (see notes)	
			Radiative fluxes	Global and regional bias of 5 W/m^2, spatial resolution of 25 km, temporal	Like CERES on Terra/Aqua	POR-3	

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Societal or Science Question	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
				sampling 3 hr. Accuracy of 5 W/m^2, decadal stability of 0.3 W/m^2/decade.			
			Surface currents	An average of 1-2 samples (overpasses) per day per 100 to 200 km region for a high inclination orbit; 5 to 10 km resolution; Random errors ≤0.02 m/s for 100 km scales and 1 to 2 day averages (this is analogous to current random errors <0.5 m/s for the proposed sampling); Coincidence with vector wind observations.	Altimeter (e.g., Jason-3) or Doppler scatterometer for surface current		
			Wave heights	(Hs, significant wave height) 25 km spatial resolution; 3 hr revisit; 0.5 m uncertainty	Altimeter (e.g., Jason-3) for significant wave height	POR-26, 27	TO-21
			XCO_2 and XCH_4 (dry air mole fraction of these species)	25% uncertainty monthly average			
	C-4b. Better quantify the role of surface waves in determining wind stress; demonstrate the validity of Monin-Obukhov similarity theory and other flux-profile relationships at high wind speeds over the ocean.	**Important**	Wave heights	(Hs, significant wave height) 25 km spatial resolution; 3 hr revisit; 0.5 m uncertainty	(Hs, significant wave height) Jason altimeter	POR-26, 27	TO-21
			Surface layer profiles of temperature and humidity	(BL atmos) 20 km horizontal resolution; 10 m vertical resolution with 10 m at surface and near-surface; 3 hr revisit; monthly 0.2°C uncertainty (temperature), 0.3 g/kg (humidity)	(BL Atmos) For temperature and humidity: IR and microwave sounders (e.g., AIRS, AMSU, ATMS), GNSS-RO	POR-1	TO-13
			BL wind profiles	(U10, windspeed and direction) 20 km spatial resolution; 3 hr revisit; 0.5 m/s instantaneous uncertainty	(U10, windspeed or stress) Scatterometer, Doppler scatteroemter, passive microwave, SAR; possible new versions based on GPM microwave imager, or Compact Ocean Wind Vector Radiometer; Vector winds highly desirable for momentum fluxes	POR-23, 28, 33	TO-11 (if scatterometer and tuned to stress)
	C-4c. Improve bulk flux parameterizations, particularly in extreme conditions and high-latitude regions reducing uncertainty in the bulk transfer coefficients by a factor of 2.	**Important**	Turbulent heat fluxes: direct covariance flux estimates of latent and sensible heat flux and simultaneous independent measurements of surface layer air temperature and humidity, sea-surface temperature, surface-relative surface layer winds. Momentum flux: direct covariance flux estimates of stress and simultaneous independent measurements of surface layer air temperature, sea-surface temperature, surface-relative surface layer winds, directional wave spectra. Gas fluxes: direct covariance flux estimates of gas fluxes and measurements of surface layer air temperature, sea-surface temperature, surface-relative surface layer winds, and gas partial-	Accuracy: Direct covariance flux estimates 20% (stress), 30% uncertainty (heat, moisture, gases) on a point-by-point basis; Wind speed at 0.5 m/s instantaneous uncertainty; 0.2 K instantaneous uncertainty in surface layer air and sea-surface temperature; 0.3 g/kg instantaneous uncertainty in surface layer humidity; gas partial pressure difference to 4 µatm. Wave steepness data needs resolution of waves at 50 to 200 m wavelengths. Increased data needed at a variety of regimes: momentum/turbulent heat flux: wind speeds globally greater than 15 m/s; momentum/turbulent heat flux at stable conditions (air-sea temperature difference >2°C); momentum flux: measurements in strongly coupled swell-dominated regions; gas exchange at all wind speeds, all stability conditions; all wind speeds for gas exchanges. All momentum/heat/moisture/gas fluxes:	Satellite observations: improved drag coefficients: simultaneous but independent surface stess and wind speed measurements (e.g., scatterometer for stress; wind speeds from passive microwave, scatterometers; wave steepness from SAR. Other turbulent direct covariance fluxes needed for bulk flux parameterizations unobtainable from satellite. In situ: direct covariance flux measurements and simultaneous independent bulk measurements, wave information, for all fluxes from buoys, expendable platforms at sufficient elevation	Satellite: SAR, POR-(1), CFOSAT In situ: OceanSITES buoys, OOI buoys, ships of opportunity, towers, individual research experiments and associated assets	TO-11 (if scatterometer and tuned to stress)

CLIMATE VARIABILITY AND CHANGE PANEL

SCIENCE			**MEASUREMENT**				
					Example Measurement Approaches		
Societal or Science Question	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
			pressure gradients between atmospheric and ocean surface layers	measurements needed in marginal ice zone regions.			
	C-4d. Evaluate the effect of surface CO_2 gas exchange, oceanic storage, and impact on ecosystems, and improve the confidence in the estimates and reduce uncertainties by a factor of 2.	**Important**	Surface CO_2 gas exchange: Wind speeds; partial pressure CO_2 in equilibrium with surface water air above	Surface CO_2 gas exchange: 25% uncertainty monthly average	Wind speeds: scatterometer, Doppler scatterometer, passive microwave, SAR CO_2 partial pressures: in situ measurements	POR-28; SSM/I, SSM/IS, AMSR-2, GMI, MWI. Move POR-7 CYGNSS (Mission ID 740, Instrument ID 1669, Unique ID 740-1669) to POR-33	TO-11
***QUESTION C-5.* Aerosols and Aerosol Cloud Interactions.** A. How do changes in aerosols (including their interactions with clouds, which constitute the largest uncertainty in total climate forcing) affect Earth's radiation budget and offset the warming due to greenhouse gases? B. How can we better quantify the magnitude and variability of the emissions of natural aerosols, and the anthropogenic aerosol signal that modifies the natural one, so that we can better understand the response of climate to its various forcings?	**C-5a.** Improve estimates of the emissions of natural and anthropogenic aerosols and their precursors via observational constraints.	**Very Important**	Vertical profiles of aerosol mass concentrations, and including particle size (effective radius). Boundary layer concentrations are most relevant for sources; vertical profiles are most relevant for removal processes (settling and precipitation removal). Also needed: (1) dust, smoke, and other aerosol plume properties (e.g., characterizing height and thickness), and (2) characteristics in the column to assess removal rates. Precipitation phases and rates. Surface properties: (1) soil moisture; (2) topography; (3) soil type and vegetation coverage; (4) ocean surface characteristics (bubbles, waves); (5) sea-surface temperature. Surface vector winds. Fire radiative power, vegetation type and plume lofting height for fire mass consumption rate, smoke properties and plume height. Aerosol precursor gases that include NO_x, SO_2, DMS, VOCs, NH_4, and co-emitted gases that include CO and CO_2.	Aerosol mass: Horizontal resolution requirements: at high (1 km) to very high (<100 m); Vertical resolution requirement: Information is needed at low (column integrals) and high (<500 m) resolution. Temporal sampling: weekly; Precision: 30%. Accuracy requirements: vertically and horizontally resolved aerosol mass concentration (100%) and effective variance (50%). (U10, windspeed and direction) 20 km spatial resolution; 3 hr revisit; 0.5 m/s instantaneous uncertainty, 0.1 m/s monthly uncertainty, decadal stability to 0.05 m/s/decade; direction to 15 degrees instantaneous, monthly to 10 degrees. (Hs, significant wave height) 25 km spatial resolution; 3 hr revisit; 0.5 m uncertainty. SST: 0.2 K random uncertainty in 25 × 25 km area; 80% daily coverage; 3 to 5 km resolution. Gas measurements: NO_x, SO_2, DMS, VOCs, NH_4, CO, and CO_2.	See C-2h for Aerosol Measurement Approaches, C-4a for air-sea exchange that includes these below, Ecosystem for vegetation, biomass burning, dust, and possibly gases C-40. Scatterometer, Doppler scatterometer, passive microwave, SAR (possible new versions based on GPM microwave imager, or Compact Ocean Wind Vector Radiometer; Vector winds highly desirable for momentum fluxes) SST: C-42. IR and/or microwave radiometry C-44B. Altimeter (e.g., Jason-3) for significant wave height	POR-2, 5, 7, 9, 10, 11, 12, 14, 20, 21, 22, 24, 25, 28, 32	TO-1, TO-2, TO-3, TO-4, TO-6, TO-10, TO-11, TO-15, TO-17, TO-18, TO-22
	C-5b. Characterize the properties and distribution in the atmosphere of natural and anthropogenic aerosols, including properties that affect their ability to interact with and modify clouds and radiation.	**Important**	AEROSOLS: (1) extinction, absorption, AOD, AAOD (spectrally resolved), polarization, single scattering albedo, (2) size and shape, (3) vertical and horizontal distribution, (4) hydroscopicity, composition (probably not from space implies need for ground and airborne help), (5) ancillary useful variables (CO, isoprene, relative humidity, etc.).	This is a refinement of Objective C-5a. As noted, level of detail probably requires complementary data to space-based measurements, the latter of which are more suited to characterizing emissions and transport rather than detailed characteristics of the aerosols			
	C-5c. Quantify the effect that aerosol has on cloud formation, cloud height, and cloud properties (reflectivity, lifetime,	**Very Important**	CLOUDS: (1) cloud cover, optical depth, reflectivity, (2) vertical and horizontal distribution (plus cloud overlap plus morphology including	See Objective C-2h	Nadir and multiangular radiometers (MODIS, MISR); lidars (CALIPSO, HSRL); microwave brightness temperatures; shortwave reflectances in	POR-1, 2, 4, 10, 12, 14, 20, 23, 24, 25	TO-1, TO-5, TO-14

CLIMATE VARIABILITY AND CHANGE PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
	cloud phase), including semi-direct effects.		organization and convective/stratiform character), (3) colocation with precipitation, aerosls, aerosol sources, vertical velocity, (4) condensate state, number, phase, (5) within cloud variability.		the near IR and visible bands; stereo photogrammetric methods that builds on and advances measurements pioneered by the MISR instrument on the Terra satellite.		
	C-5d. Quantify the effect of aerosol-induced cloud changes on radiative fluxes (reduction in uncertainty by a factor of 2) and impact on climate (circulation, precipitation).	**Important**	**Forcing and response:** (1) radiative fluxes, (2) precipitation, (3) climate variables (winds, temperature, etc.).	See Objective C-2h	Nadir and multi angular radiometers (MODIS, MISR); Lidars (CALIPSO, HSRL); microwave brightness temperatures; shortwave reflectances in the near IR and visible bands; stereo photogrammetric methods that builds on and advances measurements pioneered by the MISR instrument on the Terra satellite.	POR-1, 23, 5, 6, 7, 10, 20, 23, 24, 25, 28, 31	TO-1, TO-5, TO-14
***QUESTION C-6.* Seasonal to Decadal Predictions, Including Changes and Extremes (C-6 and C-7).** Can we significantly improve seasonal to decadal forecasts of societally relevant climate variables? [see footnote 1]	**C-6a.** Decrease uncertainty, by a factor of 2, in quantification of surface and subsurface ocean states for initialization of seasonal-to-decadal forecasts.	**Very Important**	Sea-surface height	Spatial: 1-3 km; Temporal: approximately weekly	3 nadir-looking altimeters working together (e.g., SWOT)	POR-27	
			Sea-surface salinity	Spatial: 5-10 km; Temporal: 2-3 days; Uncertainty 0.1-0.2 psu	Aquarius-like (SMOS, SMAP)	POR-23	
			Sea-ice thickness	Freeboard height (from which thickness is derived); <3 cm uncertainty; Spatial: few km; Temporal: 10 days	Altimetry (e.g., ICESat-2, CryoSat-2)	POR-13, 14, 27, 29	
			Sea-ice fraction	Spatial: 1 km; Temporal: daily	Microwave imagers (e.g., AMSR)	POR-1, 23	TO-11
			Sea-surface temperature	Spatial: 1-3 km; Temporal: resolved diurnal cycle	Microwave, IR imagers	POR-1, 9, 10, 24	
			Surface vector winds	Spatial: few km; Temporal: daily	Scatterometer (e.g., QuikSCAT)	POR-23, 28	TO-11 (if scatterometer and tuned to stress)
			Subsurface temperatures	Spatial: 1 km horizontial, 1 m vertical; Temporal: daily; Accuracy: 0.07°C	Lidar		
			Surface currents	Spatial: 5-10 km, wide swath; Temporal: 1-2/day; Random errors ≤1 m/s	Doppler scatterometer		TO-11
			Ocean mass	Spatial:100 km; Accuracy: 2 cm	Gravity (e.g., GRACE-FO)	POR-30	
	C-6b. Decrease uncertainty, by a factor of 2, in quantification of land surface states for initialization of seasonal forecasts.	**Important**	Soil moisture	Daily at 10 km, to within 0.04 volumetric percent	L-band radar and radiometer (e.g., SMAP)	POR-12, 23	
			Freeze-thaw state	Weekly at 10 km	Passive microwave radiometers, scatterometers, SAR	POR-12, 23	
			Total water storage	Weekly at 100 km, to within 0.04 volumetric percent on average	Gravity (e.g., GRACE-FO)	POR-30	
			Vegetation phenology (FPAR)	Weekly at 10 km, to within 0.05	MODIS, AVHRR-like vegetation measurements	POR-9, 21, 24	
			Snow water equivalent	Daily at 10 km, to within 1 cm SWE	Combination of sensors, e.g., later altimetry, polarimetric imaging radar, microwave imaging radar, radiometers	POR-1, 9, 12, 14, 23, 24, 25, 28	
	C-6c. Decrease uncertainty, by a factor of 2, in quantification of stratospheric states for initialization of seasonal-to-decadal forecasts.	**Important**	Polar vortex winds	Spatial: 5 degrees latitude/longitude; Temporal: daily	Radiometers and limb-sensing instrument for vertical resolution (infer observable using geostrophic approximation)	POR-16, 17, 18	
QUESTION C-7. How are decadal-scale global atmospheric and ocean circulation patterns changing, and what are the effects of	**C-7a.** Quantify the changes in the atmospheric and oceanic circulation patterns, reducing the uncertainty by a factor of 2, with desired confidence levels	**Very Important**	COMMON TO ALL C-7: Observables to characterize the modes of circulation and trends in the global dynamical, thermodynamical, and water	COMMON TO ALL C-7: Sampling that allows the resolution of processes on spatial scales better than 0.5 degrees latitude-longitude. This would also	COMMON TO ALL C-7: Nadir-viewing and limb soundings in the visible, infrared, microwave. Lidar-in-space. Wind profiler. Aerosols, water	POR-1, 3, 4, 5, 9, 11, 12, 16, 21, 23, 24, 25, 26, 27, 28, 31	TO-1, 2, 4, 5, 9, 11, 12, 13, 15, 16, 17, 18, 20, 21

CLIMATE VARIABILITY AND CHANGE PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
these changes on seasonal climate processes, extreme events, and longer term environmental change?	of 67% (likely in IPCC parlance).		systems: land and ocean surface temperature, vertical profile of atmospheric temperature and moisture, clouds, 3D wind profiles, surface to 5 km depth ocean temperature, salinity and currents. *For ENSO and interannual time scales*: SST, subsurface ocean properties, tropical winds. *For AMOC, and decadal time scales in particular:* SST and salinity to infer water density and ocean currents to determin stream functions. *For changes in the position and intensity of the jets*: (1) vertically resolved temperature in the UT/LS, to specify tropopause height, (2) precipitation at surface, as confirmation of Hadley cell location, (3) O_3 and H_2O in the UT/LS with higher vertical resolution, to enable definition of chemical tropopause, (4) vertical distribution of stratospheric and tropospheric aerosols. *For regional climate quanitification*: observations of tracer transport (e.g., aerosols), moisture and cloud properties. SST, SSS, SSH, subsurface ocean temperatures and salinity; sea-ice extent, thickness, thermodynamic state, and albedo.	enable comparisons of the simulation fidelity between increasing high-resolution (better than 0.5 degrees latitude-longitude) models over the next decade and the observations. Measurement Requirements: Vertical Resolution and Range: ~1 km. (surface to lower stratosphere). *Measurement Requirements.* Horizontal resolution/range: 1/2° latitude × 1/2° longitude / Global; Temporal Sampling: minimum daily; Precision: 20%; Sufficient accuracy to address the regional variability and detection-attribution of forced climate change at the 67% confidence level or better, and to be used in conjunction with model simulations and reanalyses.	vapor, cloud, and sea-ice remote sensing.		
	C-7b. Quantify the linkage between natural (e.g., volcanic) and anthropogenic (greenhouse gases, aerosols, land-use) forcings and oscillations in the climate system (e.g., MJO, NAO, ENSO, QBO). Reduce the uncertainty by a factor of 2. Confidence levels desired: 67%.	**Important**				POR-1, 2, 3, 4, 5, 11, 15, 16, 17, 22, 24, 31	TO-1, 2, 3, 4, 5, 6, 9, 11, 12, 13, 14, 15, 16, 17, 18, 20
	C-7c. Quantify the linkage between global climate sensitivity and circulation change on regional scales including the occurrence of extremes and abrupt changes. Quantify the expansion of the Hadley cell to within 0.5 degrees latitude per decade (67% confidence desired); changes in the strength of AMOC to within 5% per decade (67% confidence desired); changes in ENSO spatial patterns, amplitude, and phase (67% confidence desired).	**Very Important**				POR-1, 3, 4, 12, 23, 24, 25, 26, 28, 31	TO-1, 4, 5, 13, 14
	C-7d. Quantify the linkage between the dynamical and thermodynamic state of the ocean upon atmospheric weather patterns on decadal time scales. Reduce the uncertainty by a factor of 2 (relative to decadal prediction uncertainty in IPCC, 2013). Confidence level: 67% (likely).	**Important**				POR-1, 3, 4, 12, 21, 25, 26, 27, 28, 29	TO-1, 4, 5, 11, 13, 15, 20
	C-7e. Provide observational verification of models used for climate projections. Are the models simulating the observed evolution of the large-scale patterns in the atmosphere and ocean circulation, such as the frequency and magnitude of ENSO events, strength of AMOC, and the poleward expansion of the subtropical jet (to a 67% level correspondence with the observational data).	**Important**				POR-1, 3, 4, 5, 11, 12, 16, 17, 21, 23, 24, 25, 26, 28, 31	TO-1, 4, 5, 6, 9, 11, 12, 13, 15, 16, 17, 18, 20

CLIMATE VARIABILITY AND CHANGE PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
***QUESTION C-8.* Causes and Effects of Polar Amplification.** What will be the consequences of amplified climate change already observed in the Arctic and projected for Antarctica on global trends of sea-level rise, atmospheric circulation, extreme weather events, global ocean circulation, and carbon fluxes?	**C-8a.** Improve our understanding of the drivers behind polar amplification by quantifying the relative impact of snow/ice-albedo feedback versus changes in atmospheric and oceanic circulation, water vapor, and lapse rate feedback.	**Very Important**	Sea-ice concentration/extent/type	Daily at 10 km resolution	Continuity of multichannel passive microwave (e.g., SSMI, SSMIS), sea-ice classification with dual pol SAR (e.g., ENVISAT, Radarsat) or scatterometers.		TO-11, 15, 17
			Sea-ice thickness	Daily at 1 km resolution	Laser and radar altimetry (e.g., ICESat-2, CryoSat)		
			Atmospheric boundary layer (surface temperature profiles, surface-air fluxes, water vapor, clouds).	Daily at 25 km spatial resolution, 200 m vertical resolution in the planetary boundary layer	Sounders and imagers at high horizontal resolution		
			Atmospheric soundings (tropopause and lower stratosphere)				
			Snow cover extent	Daily at 10 km resolution	Continuity of multichannel passive microwave (e.g., SSMI, SSMIS)		
	C-8b. Improve understanding of high-latitude variability and midlatitude weather linkages (impact on midlatitude extreme weather and changes in storm tracks from increased polar temperatures, loss of ice and snow cover extent, and changes in sea level from increased melting of ice sheets and glaciers).	**Very Important**	Sea-ice concentration/extent/type	Daily at 10 km resolution, within 5%	See Objective C-8a		
			Sea-ice thickness	Daily at 1 km resolution, within 20 cm	See Objective C-8a		
			Atmospheric boundary layer (surface temperature profiles, surface-air fluxes, water vapor, clouds).	Daily at 25 km spatial resolution, 200 m vertical resolution in the planetary boundary layer	See Objective C-8a		
			Atmospheric soundings (tropopause and lower stratosphere)		See Objective C-8a		
			Snow cover extent	Daily at 10 km resolution	See Objective C-8a		
			Sea-surface temperatures	Daily at a few kilometers, within 0.1 K	Microwave, IR instr (e.g., VIIRS, MODIS)		
			Snow depth on land and sea ice	Daily at 1 km, within 10 km, within 20cm	Collocated Ku/Ka-band radar altimeter		
			Snow water equivalent	Daily at 10 km, to within 1 cm SWE	Combination of sensors (e.g., laser altimetry, polarimetric imaging radar, microwave imaging radar, radiometers)		
	C-8c. Improve regional-scale seasonal to decadal predictability of Arctic and Antarctic sea-ice cover, including sea-ice fraction (within 5%), ice thickness (within 20 cm), location of the ice edge (within 1 km), timing of ice retreat and ice advance (within 5 days).	**Very Important**	Sea-ice concentration/extent/type	Daily at 10 km resolution within 5%	See Objective C-8a		
			Sea-ice thickness	Daily at 1 km resolution, within 20 cm	See Objective C-8a		
			Snow on sea ice	Daily at 100 m resolution, within 5 cm	Collocated Ku/Ka-band radar altimeter, IceBridge		
			Sea-ice motion and deformation	3-day and weekly, 10 km resolution within 10 km	Continuity of multichannel passive microwave (e.g., SSMI, SSMIS)		
			Melt pond fraction	Daily, 1 km resolution	Visible imagery (e.g., MODIS, VIIRS)		
			Sea-surface temperatures	Daily at a few kilometers, within 0.1 K	Microwave, IR instr (e.g., VIIRS, MODIS)		
			Snow cover extent	Daily at 10 km resolution, within 10 km	See Objective C-8a		
			Atmospheric boundary layer (surface temperature profiles, surface-air fluxes, water vapor, clouds).	Daily at 25 km spatial resolution, 200 m vertical resolution in the planetary boundary layer	See Objective C-8a		
	C-8d. Determine the changes in Southern Ocean carbon uptake due to climate change and associated atmosphere/ocean circulations.	**Very Important**	Atmospheric pCO_2 (i.e., within the atmospheric boundary layer)	Monthly at 100 km by 100 km spatial scales. Air-sea pCO_2 difference accurate to ±3 to 15 µatm, implying no more than ±2 to 10 µatm uncertainty in atmospheric pCO_2. Aim for 25% total flux uncertainty.	Schimel el al. RFI#2 submission: high-resolution spectroscopic observations of reflected sunlight in near infrared CO_2 and CH_4, such as provided by OCO-2. Possibility of retrieving full flux from atmospheric inversion will require multiple satellites.		

CLIMATE VARIABILITY AND CHANGE PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
				Further modeling and OSSE work will help to confirm requirements.	Kawa et al. RFI#2: lidar retrieval (e.g., ASCENDS) Singh et al. RFI#2: 2-µm lidar (e.g., IPDA lidar) Regression methods: use altimetery for sea-surface height, ocean color for biological productivity/upper ocean upwelling		
			Upper ocean pCO_2 (i.e., within the mixed layer)	Monthly at 100 km by 100 km spatial scales	Mannino et al RFI#2: ocean color (e.g., GEO-CAPE: high-temporal measurements of top of the atmosphere radiances from 350-900 nm (minimum of 25 bands; SNR > 1000) plus 1240 nm (SNR > 250) and 1640 nm (SNR > 180) with ~1000 biogeochemical Argo floats profiling every 10 days to provide upper in situ measurements		
			Surface wind speed	Surface wind: monthly means at 100 km resolution; would prefer daily at oceanic eddy-resolving resolution	Wind: scatterometer preferred, passive microwave wind speed possible		TO-11 (if scatterometer and tuned to stress)
			SST or mixed-layer temperature	SST: monthly means at 100 km resolution; would prefer daily at eddy-resolving resolution to minimize or study eddy impacts	SST: microwave SST (microwave needed because of persistent cloud cover in region)		
	C-8e. Determine how changes in atmospheric circulation, turbulent heat fluxes, sea-ice cover, fresh water input, and ocean general circulation affect bottom water formation.	**Important**	Atmospheric boundary layer temperature	Temperature at 2 m elevation to 0.2°C, and surface-specific humidity, both at spatial scale of oceanic eddies	Humidity inferred from brightness temperature (e.g., SSM/I). Temperature inferred fromreanalysis or infrared or microwave atmospheric profiler (e.g., AIRS or AMSU) with near surface measurement capability.		
			Surface wind speed	Surface wind: monthly means at 100 km resolution; would prefer daily at oceanic eddy-resolving resolution	Wind: scatterometer preferred, passive microwave wind speed possible		
			Surface temperature, salinity, density SST, or mixed layer temperature surface salinity (not easy from space at cold temperatures) or melt water input?	SST and SSS: 2-5 day sampling intervals, at eddy scales. Goal to obtain density to 0.03 kg/m^3 or temperature to 0.2°C, consistent with threshold criteria used for mixed-layer depth definition. Freshwater input/ice melt could also be helpful on monthly time scales.	SST: microwave SST (microwave needed because of persistent cloud cover at high latitudes) SSS: surface salinity desirable. Very difficult observation at cold temperatures. Use Argo profiling floats and climatology if satellite retrievals not feasible. Freshwater input, ice melt: GRACE, sea-ice extent, ice thickness		
	C-8f. Determine how permafrost-thaw-driven land cover changes affect turbulent heat fluxes, above and belowground carbon pools, and resulting greenhouse gas fluxes (carbon dioxide, methane) in	**Important**	Freeze-thaw state	Weekly, at 100 m horizontal and 5-10 cm vertical resolution	Passive microwave radiometers, scatterometers, SAR; InSAR, C- and L-band SAR; Tomographic SAR; Airborne EM; GPR; SMAP	POR-12(PALSAR) POR-12(Sentinel-1) POR-23 (SMAP)	TO-17
			Active layer thickness	Biweekly (except in winter, when no measurement is needed) at 100 m horizontal and 5 cm vertical resolution	AirMOSS (P-band SAR); UAVSAR (L-band InSAR); Airborne-EM; OIB low-frequency radars; ground based (or airborne) GPR	POR-12 (L-band PALSAR POR-12 (NISAR)	

CLIMATE VARIABILITY AND CHANGE PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
	the Arctic, as well as their impact on Arctic amplification.		Lake and wetland fraction	Bimonthly at 100-250 m	Optical instruments (e.g., MODIS, Landsat, SPOT, Sentinel-2), active SAR instruments (C and L bands)	POR-12(PALSAR) POR-12(Sentinel-1) POR-9 (Landsat) POR-9 (Sentinel-2) POR-27 (SWOT) POR-21 (MODIS)	TO-18
			Snow water equivalent	Daily at 1 km, within 1 cm SWE	Combination of sensors: e.g., laser altimetry, polarimetric imaging radar, microwave imaging radar, radiometers	POR-23 (AMSR-2) POR-23 (SMOS)	TO-16
			Snow cover extent	Daily at 1 km resolution, within 2 days uncertainty	Need for continuity of multichannel passive microwave; optical and infrared instruments (e.g., MODIS)	POR-24 (VIIRS) POR-9 (Landsat) POR-9 (Sentinel-2) POR-21 (MODIS)	TO-18
			Surface elevation	Annually at 50 m resolution, within 2 cm uncertainty	Active SAR instruments (Interferometry), Lidar; US L-band SAR; DLR Tandem-X and Tandem-L; ICESat-ATLAS	POR-12 (L-band PALSAR) POR-12 (S-band NISAR) POR-12(C-band Sentinel-1) POR-14 (ICESat-ATLAS)	TO-19, 20
			Permafrost thickness and 3D geometry	Once every 10 years, with 100 m horizontal resolution	Tomographic SAR; Satellite-based EM; GPR; P-band SAR; OIB VHF and UHF radars	POR-12 (P-band SAR)	
			Land surface temperature (LST)	Daily, with 1 km resolution and 1 K precision	MODIS, AVHRR, Sentinel	POR-24 (VIIRS)? POR-25 (Landsat) POR-25 (NISAR TIS) POR-22 (Sentinel-3) POR-21 (MODIS)	TO-18
			Land cover state and change	Monthly, with 30 m resolution	Landsat, SPOT, Sentinel-2, HyspIRI	POR-9 (Landsat) POR-9 (Sentinel-2)	TO-18
			Permafrost methane feedback (seep flux from thaw lakes)	Weekly during lake freeze-up season (Oct-Dec), ideally at 5-10 m, acceptable 30 m resolution	Quadpole L-band SAR (e.g., PALSAR)	POR-12(L-band PALSAR)	
	C-8g. Determine the amount of pollutants (e.g., black carbon, soot from fires, and other aerosols and dust) transported into polar regions and their impacts on snow and ice melt.	**Important**	Aerosol optical depth	See requirements for AEROSOLS in C-2h, C-5a, and requirements for particulate matter (PM) in W-1a, W-5a, W-6a	Nadir viewing Radiometers (e.g., MODIS); Multiangle viewing radiometers (MISR); Current technology lidar (CALIPSO); More modern technology lidar (HSRL); HSRL can be used for vertically resolved profiles that better enable (1) distinguishing aerosols and clouds, (2) increased sensitivity (detecting lower concentrations of aerosol), (3) better resolution of aerosol amounts nearer the surface (lower altitude), and (4) more accurate aerosol optical depths. Multiangle, multispectral polarimeters can provide improved column integrated information on aerosol composition such as refractive index (including absorption), particle size, and variance. The combination of HSRL and a multiangle, multispectral polarimeter has improved accuracy beyond each individual instrument.		
			Aerosol absorption optical depth	See requirements for AEROSOLS in C-2h, C-5a			

CLIMATE VARIABILITY AND CHANGE PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
			Snow depth, cover, albedo on land, glaciers and sea ice	See requirements for H-1c			
			From C-2h: Meteorological properties in vicinity of aerosols and clouds (temperature, winds, humidity) to characterize the environment in which the cloud is forming.	See requirements for C-2h	See C-12. IR sounders (e.g., CrIS, IASI) plus CLARREO-like intercalibration, GNSS-RO for zonal temperature trend in 5-20 km altitude		
	C-8h. Quantify high-latitude low cloud representation, feedbacks, and linkages to global radiation.	**Important**	Cloud properties (cloud fraction, cloud vertical distribution, cloud liquid water content, cloud ice water content, droplet effective radius, ice particle effective diameter, number concentration, in-cloud circulations, cloud top turbulence/entrainment, vertical velocity and cloud phase)	Cloud Fraction (%) <1%; Cloud Liquid Water Content +20%; Cloud Ice Water content +20%; Cloud top and base height <75 m	Continuity of lidar/radar instruments with need for more complete sampling and vertical resolution, synergistic passive-active instruments		
			Radiation (surface upwelling and downwelling flux for longwave and shortwave; TOA fluxes), Turbulent radiative fluxes	Daily, within 5 W/m^2 for radiative fluxes, within 5-10 W/m^2 for turbulent fluxes	Continuity of TOA radiative fluxes from CERES and MODIS/VIIRS		
			Atmospheric temperature and humidity		Need for collocated and finer spatial and vertical resolution boundary layer temperature and humidity		
			Aerosol concentration and composition		Continued polar lidar needed (e.g., CALIOP), advanced lidar techniques like HSRL		
			Sea-ice fraction	Daily, 10 km resolution, accuracy of 5%			
			Sea-ice thickness	Daily at 1 km resolution, accuracy of 20 cm			
	C-8i. Quantify how increased fetch, sea-level rise and permafrost thaw increase vulnerability of coastal communities to increased coastal inundation and erosion as winds and storms intensify.	**Important**	Wave heights	(Hs, significant wave height) 25 km spatial resolution; 3 hr revisit; 0.5 m uncertainty	Radar altimeter (e.g., Jason-3) for significant wave height		
			Fetch/ice edge	Daily, at 10 km resolution, within 5 km	Passive and active microwave		
			Winds	(U10, windspeed) 10 km spatial resolution; 3 hr revisit; 2 m/s uncertainty	Scatterometer, passive microwave, SAR		TO-11 (if scatterometer and tuned to stress)
			Ocean currents	Spatial: 5-10 km, wide swath, random errors ≤1 m/s	Radar altimeter (e.g., Jason-3) for surface currents, Doppler scatterometer		
***QUESTION C-9.* Ozone and Other Trace Gases in the Stratosphere and Troposphere.** How are the abundances of ozone and other trace gases in the stratosphere and troposphere changing, and what are the implications for Earth's climate?	**C-9a.** Quantify the amount of UV-B reaching the surface, and relate to changes in stratospheric ozone and atmospheric aerosols.	**Important**	Surface UVB	Global 5º latitude/10º longitude, surface only, weekly sampling, precision 5%		GOME-2; Suborbital: Baseline Surface Radiation Network (BSRN)	TROPOMI
			Total column ozone	Global 1º latitude/2º longitude, surface only, weekly sampling for column, surface through stratosphere, precision 3 Dobson Units		POR-9, 11 SBUV-2, OMI, OMPS, GOME-2; Suborbital: Network for the Detection of Atmospheric Composition Change, Global Climate Observing System Reference Upper-Air Network (GRUAN), Southern Hemisphere Additional Ozonesondes	TROPOMI

CLIMATE VARIABILITY AND CHANGE PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question	Earth Science/Application Objective	Science/Application Importance	Geophysical Observable	Measurement Parameters	Method	POR	TO
			Vertical profiles of temperature in UTS (upper troposphere and stratosphere), for quantifying radiative forcing	Vertical resolution and range: <1 km in UTLS, <3 km in mid-upper stratosphere; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: weekly; Precision: 1-2 K.	UV, visible, and infrared solar, lunar, and stellar occultation (e.g., ACE-FTS, GOMOS, HALOE, POAM, SAGE) High precision, high vertical resolution (<1 km), climate (trend) quality, but poor spatial coverage unless a constellation is used.Infrared and microwave limb emission (e.g., HIRDLS, MIPAS, MLS, Odin SMR)Many species, 3-4 km vertical resolution, night and day, global coverage Visible limb scattering (e.g., SME, OMPS-LP, OSIRIS). Lidar (e.g., CALIPSO-CALIOP). High (meters) vertical resolution. Radar (e.g., CloudSat CPR). Nadir-viewing solar reflection/scattering (e.g., AIM-CIPS, MODIS, OCO-2). Good (km) horizontal resolution Suborbital: Ground-based and balloon/aircraft measurements of ozone and ozone depleting substances to support emissions estimation and trend determination	POR-6, 16, 17, 18ACE-FTS (not global), Auro MLS (not 1 km verical resolution; not self-calibrating), GPS-RO (extreme path length), MSU/SSU/AMSU (10 km vertical resolution; not self-calibrating); Suborbital: Global Climate Observing System Reference Upper-Air Network (GRUAN), NWS Upper-air Observations Program	TO-13
			Vertical profiles of radiatively active gas concentrations in the UTS, for quantifying radiative forcing	**Concentration of O_3:** Vertical resolution and range: <1 km in UTLS, <3 km in mid-upper stratosphere; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: weekly; Precision: 10%. **Concentration of H_2O:** Vertical resolution and range: <1 km in UTLS, <3 km in mid-upper stratosphere; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: weekly; Precision: 10%.		POR-6, 16, 17, 18 ACE-FTS (not global; not 1 km vertical resolution), Aura MLS (not 1 km vertical resolution; not self-calibrating), OMPS-L (not 1 km vertical resolution; not self-calibrating (?)); Suborbital measurements: Network for the Detection of Atmospheric Composition Change, Global Climate Observing System Reference Upper-Air Network (GRUAN), Southern Hemisphere Additional Ozonesondes (SHADOZ) SAGE III (ISS) (not global; 18 Feb 2017 launch)	TO-12
			Vertical profiles of UTS aerosol radiative properties, for quantifying radiative forcing	Vertical resolution and range: <1 km in UTLS; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: weekly; Precision: 30%.		POR-2, 16, 18 ACE-FTS [not global; not 1 km vertical resolution], Odin OSIRIS [not 1 km vertical resolution; not polar night; no particle size info], CALIPSO CALIOP [near end-of-life] SAGE III (ISS) [not global]	TO-1, 2
			Volcanic and biomass burning emissions, for process studies (sources and transport)	**Volcanic Aerosol:** Vertical resolution and range: <1 km in UTLS; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: daily during events; Precision: 30%. **Concentrations of gases from volcanic emissions:** Vertical resolution and range: <1 km in UTLS; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: daily during events; Precision: ~20%, but species dependent.		POR-2, 16, 17, 18 **Volcanic Aerosol:** CALIPSO CALIOP [near end-of-life] **Concentrations of gases from volcanic emissions:** ACE-FTS [not global; not 1 km vertical resolution], MLS [not 1 km vertical resolution; not NO_2] SAGE III (ISS) [not enough sampling to track the sources]	TO-1, 2, 12

CLIMATE VARIABILITY AND CHANGE PANEL

SCIENCE			**MEASUREMENT**				
					Example Measurement Approaches		
Societal or Science Question	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
			Deep convective clouds, for process studies (sources)	Vertical resolution and range: <1 km in UTLS; Horizontal range: Global; Horizontal and temporal sampling: event-specific, episodic; Precision: 30%.		POR-1, 4, 10, 17, 21, 23 Aura MLS (not 1 km vertical resolution), Aqua AIRS, Aqua AMSR-E, Aqua MODIS, CloudSat	TO-5
			Small-scale transport and the Brewer-Dobson circulation, for process studies (transport)	Vertical resolution and range: <1 km in UTLS, <3 km in mid-upper stratosphere; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: event-driven for small scale, weekly for BD; Precision: 30%.		POR-16, 17 ACE-FTS [not global; not 1 km vertical resolution], Aura MLS [not 1 km vertical resolution]	TO-12, 13
			Dynamical features such as the polar vortex, for process studies (transport)	Vertical resolution and range: <1 km in UTLS, <3 km in mid-upper stratosphere; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: daily to weekly; Precision: 1-2 K (T), 30% (UV).		POR-6, 16, 17, 18 ACE-FTS [not global; not 1 km vertical resolution], Aura MLS [not 1 km vertical resolution], GPS-RO [extreme path length]	TO-12, 13
			Planetary and gravity waves, for process studies (transport)	Vertical resolution and range: <1 km from cloud top to stratopause; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: daily to weekly; Precision: 1-2 K (T).		POR-6, 16, 17, 18 ACE-FTS [not global; not 1 km vertical resolution], Aura MLS [not 1 km vertical resolution], GPS-RO [extreme path length]	TO-12, 13
			Stratospheric ozone and related constituents, for process studies (chemistry)	Vertical resolution and range: <1 km from cloud top to stratopause; Horizontal resolution/range: 5° latitude × 10° longitude / Global; Temporal sampling: daily to weekly; Precision: 5% (O_3), 10% (others).		POR-16, 17, 18 ACE-FTS [not global; not 1 km vertical resolution], Aura MLS [not 1 km vertical resolution; only some of the constituents]; Suborbital measurements: Network for the Detection of Atmospheric Composition Change, Global Climate Observing System Reference Upper-Air Network (GRUAN), Southern Hemisphere ADditional OZonesondes (SHADOZ), Advanced Global Atmospheric Gases Experiment and NOAA Halocarbons and Other Trace Species Network SAGE III [not global; only some of the constituents]	TO-12

[1] As noted in the text, all of the indicated measurements for Questions C-6 and C-7 would be useful, but the absence or excessive coarseness of any of the measurements would not be a "deal-breaker." This question is best considered not as a motivation for a mission but rather as a beneficiary of measurements taken to address other questions. Indicating here which measurements are already being taken is, in a way, extraneous.

EARTH SURFACE AND INTERIOR PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
QUESTION S-1. How can large-scale geological hazards be accurately forecast in a socially relevant time frame?	**S-1a.** Measure the pre-, syn-, and posteruption surface deformation and products of Earth's entire active land volcano inventory at a time scale of days to weeks.	**Most Important**	Land-surface deformation	At least two components of land-surface deformation and strain localization (e.g., surface fracturing) over length scales ranging from 10 m to 1,000 km and a precision of 1 mm at a sampling frequency related to the volcanic activity. Regionally sampled global coverage.	L- or S-band InSAR with ionospheric correction, [GPS/GNSS]	POR-12 (NISAR)	TO-19
			Topography	High spatial resolution (5 m) bare-Earth topography at 1 m vertical accuracy over all volcanoes	Spacecraft swath-lidar or radar	POR-14 (ICESat-2)	TO-20
			Ground-surface composition and changes over time	Hyperspectral VNIR/SWIR (at the ~ 30 m spatial scale) and TIR data (at the ~ 60 m spatial scale) with 1-2 week revisit time, acquiring continuously for periods of weeks to months prior to an eruption to detect trends and change	High spatial-resolution imaging/spectometry—e.g., ASTER, Hyperion, HyspIRI (last decadal survey), Landsat (high spatial). OMI, AIRS (high temporal)	POR-9 (ASTER, OLI, ETM+), POR-21 (MODIS), POR-24 (VIIRS, SEVIRI)	TO-18
			Gas emissions, plume composition, particle size and temporal changes	Hyperspectral UV, NIR, SWIR, and TIR data (at ~1-10 km spatial scale) with daily revisit time. Multi- to hyperspectral VNIR/SWIR (at ~30 m) and TIR data (at ~60 m) with ~1 week revisit time. Acquiring continuously prior to and during eruptions to detect trends and measure eruptive emissions. Active (lidar and radar) and passive (MISR) data to characterize plume altitude	Global hyperspectral UV (e.g., OMI, OMPS) and TIR (e.g., AIRS, IASI) for SO_2, H_2S and ash; high-resolution NIR for CO_2 (e.g., OCO-2). High spatial-resolution (e.g., ASTER, HyspIRI) for small plumes. Space-borne lidar and radar (e.g., CALIPSO, CloudSat), multiangle visible-NIR imagers (e.g., MISR)	POR-9 (ASTER), POR-11 (OMPS, OMI), POR-20 (AIRS), POR-21 (MODIS)	TO-1, 2, 18
			Thermal output	Multispectral TIR data (including a 3-5 micron channel) at 100 m spatial resolution acquired at a temporal frequency of 1-24 hours to detect high-frequency changes in thermal output before and after an event	Moderate-resolution imaging/spectometry—e.g., ASTER, Landsat (high spatial) but at the high temporal scale of GOES, MODIS, AVHRR	POR-9 (ASTER), POR-21 (MODIS), POR-25 (ASTER, TIRS)	TO-18
	S-1b. Measure and forecast interseismic, preseismic, coseismic, and postseismic activity over tectonically active areas on time scales ranging from hours to decades.	**Most Important**	Land-surface deformation	At least two components of land-surface deformation 10 m to 1,000 km resolution and precision of 1-10 mm at a sampling frequency related to seismic/tectonic activity. Ideally, resolution of 1 mm/week. Need more than 10 years of observations to measure interseismic deformation	L- or S-band InSAR with ionospheric correction, [GPS/GNSS].	POR-12 (NISAR)	TO-19
			Large spatial scale gravity change	Gravity change for large events (GRACE and follow-on missions)	Gravity (e.g., GRACE-2)	POR-30 (GRACE-FO)	TO-9
			Reference frame	Stable terrestrial reference frame at 1 mm/yr accuracy	[VLBI, SLR, GPS/GNSS]	POR-7, 13 (Jason-3, LAGEOS)	
			Topography	High spatial resolution (1 m), bare-Earth topography at 0.1 m vertical accuracy over selected tectonic areas	[aircraft/UAV lidar]	POR-14 (ICESat-2)	TO-20
			Land cover change	High spatial resolution (1 m) stereo optical imagery	{Commercial optical}	POR-9 (Pleiades)	COMMERCIAL
	S-1c. Forecast and monitor landslides, especially those near population centers.	**Very Important**	Land-surface deformation	At least two components of land-surface deformation at <50 m spatial resolution and 1 mm/yr at a temporal frequency <seasonal (InSAR and GPS/GNSS)	L- or S-band InSAR, [GPS/GNSS] {Complements ground-based seismic data}	POR-12 (NISAR)	TO-19
			High-resolution topography	Spatial resolution 1-5 m, vertical 0.5 m	[aircraft/UAV lidar]	POR-14 (ICESat-2)	TO-20
			Precipitation	Every 3 hours	Precipitation monitor (e.g., GPM)	POR-4 (GPM, CloudSat)	TO-5
			Permafrost melt	Radar, optical imaging, and InSAR	{Radarsat-2, commercial 1 m optical}	POR-12, 23 (RADARSAT-2, SMAP, SMOS)	TO-17

EARTH SURFACE AND INTERIOR PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
			High spatial resolution time series of distribution of vegetation and rock/soil composition	Hyperspectral VNIR/SWIR and TIR data at 30-45 m spatial resolution and ~ weekly temporal resolution	Moderate-resolution imaging/spectometry—e.g., ASTER, Landsat, Hyperion but at slightly improved spatial resolution and much improved temporal resolution	POR-9 (ASTER, Landsat, Hyperion, Sentinel-2)	TO-18
	S-1d. Forecast, model, and measure tsunami generation, propagation, and run-up for major seafloor events.	**Important**	Topography and shallow bathymetry	High spatial resolution (1 m), bare-Earth topography at 0.1 m vertical accuracy over selected tectonic areas	[aircraft/UAV lidar]	POR-14 (ICESat-2)	TO-20
			Sea-surface tsunami waves	Wave height (0.1 m), period (seconds, minutes?)	Swath altimetry—e.g., SWOT {GPS/GNSS buoys, ocean altimetry, complements seafloor pressure changes}	POR-7, 27 (SWOT)	TO-21
			Ionospheric waves	Ionospheric imaging at 10 km spatial resolution and 10 minute sampling from GPS/GNSS arrays	Radio occultation—e.g., GPS/GNSS, COSMIC	POR-6, 7 (COSMIC)	
			Global bathymetry and seamless nearshore bathymetry	Global marine gravity from swath radar altimetry (SWOT)	Swath altimetry	POR-27 (SWOT)	TO-21
			Optical, radar, and InSAR change detection on demand with low-latency processing and distribution	Enable high spatial resolution spaceborne or aircraft asset that can provide timely information to relief efforts	{Commercial 1 m optical, GPS/GNSS}	POR-9 (Pleiades, RADARSAT-2)	COMMERCIAL
			Rapid characterization of the magnitude of earthquakes	1 Hz deformation time series	{Terrestrial seismic and GPS/GNSS networks}	POR-7, 13 (GNSS, GRACE-FO, Jason-3, LAGEOS, GRASP)	TERRESTRIAL
			All high-resolution visible to thermal IR imagery	Provide rapid acquisitions at the hours to 1-day time frame using either a constellation of small-sats and/or interconnectivity to other orbital assets in a sensor-web approach	Create new small-sat constellations to complement ground-based seismic, gas, thermal, scanning lidar monitoring systems. Expand on current orbital sensor webs such as ACE and the ASTER Urgent Request Protocol. *NOTES: This is likely a NASA-specific focus, but could be partially satisfied with commercial participation.*	POR-9 (Pleiades, Sentinel-2)	COMMERCIAL
QUESTION S-2. How do geological disasters directly impact the Earth system and society following an event?	**S-2a.** Rapidly capture the transient processes following disasters for improved predictive modeling as well as response and mitigation through optimal retasking and analysis of space data.	**Most Important**	All high-resolution visible to thermal IR imagery	Provide rapid acquisitions at the hours to 1-day time frame using either a constellation of small-sats and/or interconnectivity to other orbital assets in a sensor-web approach	Create new small-sat constellations to complement ground-based seismic, gas, thermal, scanning lidar monitoring systems. Expand on current orbital sensor webs such as ACE and the ASTER Urgent Request Protocol. *NOTES: This is likely a NASA-specific focus, but could be partially satisfied with commercial participation.*	POR-9 (Pleiades, Sentinel-2)	COMMERCIAL
			Provide rapid deformation map acquisitions and interconnectivity to other sensors	At least two components of land-surface deformation over 10 m to 1000 km length scales at 10 mm precision and ASAP after the event. Adequate resolution of 1 cm/week for afterslip applications	InSAR	POR-12 (NISAR)	TO-19
	S-2b. Assess surface deformation (<10 mm), extent of surface change (<100 m spatial resolution) and atmospheric contamination, and	**Very Important**	Land-surface deformation	At least two components of land-surface deformation and surface fracturing over length scales ranging from 10 m to 1,000 km and temporal resolution of 1 mm/yr at a sampling frequency related to the volcanic	L- or S-band InSAR with ionospheric correction, [GPS/GNSS]	POR-12 (NISAR)	TO-19

EARTH SURFACE AND INTERIOR PANEL

SCIENCE			**MEASUREMENT**				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
	the composition and temperature of volcanic products following a volcanic eruption (hourly to daily temporal sampling).			activity (InSAR and GPS/GNSS) everywhere.			
			Volume, composition, and temperature of all eruptive products and their changes over time	Hyperspectral VNIR/SWIR and TIR data at 30-45 m spatial resolution and ~ weekly temporal resolution, SAR backscatter data	Moderate-resolution imaging/spectometry—ASTER, Landsat, high-repeat time airborne/UAV data	POR-9 (ASTER), POR-21 (MODIS), POR-25 (ASTER, TIRS)	TO-18
			Mass and energy fluxes across solid Earth/atmospheric boundary	Hyperspectral VNIR/SWIR and TIR data at 30-45 m spatial resolution and ~ weekly temporal resolution, High-rate SNR GPS/GNSS data	Moderate-resolution imaging/spectometry—ASTER, Landsat, high-repeat time airborne/UAV data	POR-9 (ASTER), POR-21 (MODIS), POR-25 (ASTER, TIRS)	TO-18
			[Geospatial and numerical model development of future/continued hazard potential]	Hyperspectral VNIR/SWIR and TIR data at 30-45 m spatial resolution and ~ weekly temporal resolution. SAR backscatter data at >30 m (or better spatial resolution). Bare-Earth topography. High-rate SNR GPS/GNSS data. Synergy to past/future Landsat-style systems. Expanded GIS and integration with current databases.	Moderate-resolution imaging/spectometry—e.g., ASTER, Landsat, high-repeat time airborne/UAV data, [current plume dispersion, lahar and lava flow modeling]	POR-9 (ASTER), POR-21 (MODIS), POR-25 (ASTER, TIRS)	TO-18
	S-2c. Assess co- and postseismic ground deformation (spatial resolution of 100 m and an accuracy of 10 mm) and damage to infrastructure following an earthquake.	**Very Important**	Land-surface deformation	At least two components of land-surface deformation at 100 m spatial resolution and 1 mm/yr at a temporal frequency related to the tectonic activity (InSAR and GPS/GNSS). Need more than 10 years of interseismic observations and 5 years of post seismic observations	L- or S-band InSAR with ionospheric correction, [GPS/GNSS]	POR-12 (NISAR)	TO-19
			Large spatial scale gravity change	Gravity change for large events	Gravity (e.g., GRACE-2)	POR-30 (GRACE-FO)	TO-9
			Reference frame	Stable terrestrial reference frame at 1 mm/yr accuracy	[VLBI, SLR, GNSS]	POR-7, 13 (GRACE-FO, Jason-3, LAGEOS)	TO-9
			Topography	High spatial resolution (1 m), bare-Earth topography at 0.1 m vertical accuracy over selected tectonic areas	[aircraft/UAV lidar]	POR-14 (ICESat-2)	TO-20
			Optical imaging	Map surface rupture, liquefaction features and damage at spatial scales better than 5 m.	{Worldview}, [aircraft/drone imaging]	POR-9 (Pleiades)	COMMERCIAL, AIRBORNE
QUESTION S-3. How will local sea-level change along coastlines around the world in the next decade to century?	**S-3a.** Quantify the rates of sea-level change and its driving processes at global, regional, and local scales, with uncertainty <0.1 mm/yr for global mean sea-level equivalent and <0.5 mm/yr sea-level equivalent at resolution of 10 km.	**Most Important**	Surface melt	Weekly during melt season, 1 m horizontal resolution	Imagery (e.g., Landsat, Aster, WorldView)	POR-9 (Pleiades)	TO-18
			Ice topography	Monthly or less, uncertainty <(10 cm for mean, 25 cm/yr for change) over areas of 100 km^2	Satellite and suborbital lidar	POR-14 (ICESat-2)	TO-7
			Snow density	50 km resolution with accuracy of 2 cm RMS in terms of snow water equivalent (SWE), averaged monthly		POR-14 (ICESat-2), POR-26 (SWOT), POR-27 (CryoSat-2)	TO-16
			Gravity	Monthly, uncertainty 1 cm water-equivalent thickness at resolution of 200 km at equator	Gravity (e.g., GRACE-2)	POR-30 (GRACE-FO)	TO-9
			3D surface deformation vectors on ice sheets	Monthly, cm/yr accuracy, 100 m resolution and better than seasonal sampling	InSAR	POR-12 (NISAR)	TO-19
			Sea-surface height	Monthly, 2 cm height accuracy at 100 km resolution	Radar altimetry (e.g., Jason-3, Jason-CS, SWOT), [global tidal gauge network]	POR-26, 27 (Lason-3, SWOT)	TO-21
			Terrestrial reference frame	Stability at <0.1 mm/yr	Possible (e.g., GRASP), [maintain high quality of co-located sites (minimum of 8-10)]	POR-7, 13 (GRACE-FO, Jason-3, LAGEOS, GRASP)	

EARTH SURFACE AND INTERIOR PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
			In situ temperature/salinity	Comparable to Argo at 300 km resolution or better	N/A		
			Ice velocity	Monthly or less, uncertainty <10 cm/yr over areas of 100 km^2	InSAR	POR-12 (NISAR)	TO-19
			High-resolution topography	Vertical accuracy of 10 cm, resolution 1 m		POR-14 (ICESat-2)	TO-20
	S-3b. Determine vertical motion of land along coastlines at uncertainty <1 mm/yr.	**Most Important**	Bare-earth topography	Global measurements made once to produce high-resolution (1-m horizontal, 10-cm vertical) bare-earth topographic model. Focused regional surveys at comparable resolution used to image landscape change from the globally established baseline.	[aircraft/UAV lidar, UAV SAR?]. *NOTES: In cases where landscape changes are substantial and unobscured by vegetation, topographic models created from high-resolution stereo satellite imagery may supplement airborne lidar bare-earth elevation models.*	POR-14 (ICESat-2)	TO-20
			Land-surface deformation	5-10 mm vertical precision, <50 m horizontal, weekly	InSAR	POR-12 (NISAR)	TO-19
QUESTION S-4. What processes and interactions determine the rates of landscape change?	**S-4a.** Quantify global, decadal landscape change produced by abrupt events and by continuous reshaping of Earth's surface from surface processes, tectonics, and societal activity.	**Most Important**	Bare-earth topography	Global measurements made once to produce high-resolution (1 m horizontal, 10 cm vertical) bare-earth topographic model. Focused regional surveys at comparable resolution used to image landscape change from the globally established baseline.	[aircraft/UAV lidar, UAV SAR?]. *NOTES: In cases where landscape changes are substantial and unobscured by vegetation, topographic models created from high-resolution stereo satellite imagery may supplement airborne lidar bare-earth elevation models.*	POR-14 (ICESat-2)	TO-20
			Land-surface deformation	5-10 mm vertical precision, <50 m horizontal, weekly	L- or S-band InSAR, [UAVSAR], [GNSS].	POR-12 (NISAR)	TO-19
			High spatial resolution time series of changes in optical surface characteristics	Optical ground characteristics at <1 m resolution with weekly repeat time	{Worldview-2 / 3 satellites}	POR-9 (Pleiades)	COMMERCIAL
			Measurement of rock-, soil-, water-, and ice-mass change	Satellite gravimetry	Gravity (e.g., GRACE-2)	POR-30 (GRACE-FO)	TO-9
			Measurement of rainfall and snowfall rates	Multiple times per day via satellite constellation	Like GPM	POR-4 (GPM, CloudSat)	TO-5
			Reflectance for freeze/thaw spatial and temporal distribution	<50 m horizontal, weekly	Radar reflectivity	POR-9 (Pleiades, RADARSAT-2), POR-14 (NISAR	TO-19
	S4b. Quantify weather events, surface hydrology, and changes in ice/water content of near-surface materials that produce landscape change.	**Important**	Measurement of rainfall and snowfall rates	Multiple times per day via satellite constellation	Precipitation monitor (e.g., GPM)	POR-4 (GPM, CloudSat)	TO-5
			Reflectance for freeze/thaw spatial and temporal distribution	<50 m horizontal, weekly	Radar reflectivity	POR-12 (NISAR)	TO-19
			Optical characterization of spatial and temporal distribution of freeze/thaw	<1 m horizontal, weekly	{Worldview-2 / 3 satellites}	POR-9 (Pleiades)	COMMERCIAL
			Reflectance for snow depth/snow water equivalent	SWE at ~100 m resolution suitable for SWE values to 2.5 m.	Ka-band radar or laser altimeter (depth) and SAR (density)	POR-17 (KaRIn, SWOT)	TO-16, 19
					InSAR	POR-12 (NISAR)	TO-19
			Soil/root zone moisture content		Soil state/moisture (e.g., SMAP)	POR-12 (NISAR), POR-23 (SMAP)	TO-17
				Vadose zone soil moisture at <5 m horizontal resolution with daily repeat times	[AIRMOSS]		AIRCRAFT
	S4c. Quantify ecosystem response to and causes of landscape change.	**Important**	High spatial resolution time series of distribution of vegetation in VIS/NIR	NIR at <5 m with weekly to monthly repeat time	{Worldview-2 / 3 satellites}	POR-9 (ASTER), POR-21 (MODIS), POR-25 (ASTER, TIRS)	COMMERCIAL
			Observations of canopy structure and carbon inventory	1 m resolution canopy structure collected seasonally	[Aircraft/UAV waveform lidar]	POR-14 (ICESat-2)	TO-20

EARTH SURFACE AND INTERIOR PANEL

SCIENCE			**MEASUREMENT**				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
				25 m resolution vertical structure observations collected seasonally and globally	GEDI	POR-14 (ICESat-2)	TO-20, 22
			Bare-earth topography	Global measurements made once to produce high-resolution (1 m horizontal, 10 cm vertical) bare-earth topographic model. Focused regional surveys at comparable resolution used to image landscape change from the globally established baseline.	[aircraft/UAV lidar, UAV SAR?]. *NOTES: In cases where landscape changes are substantial and unobscured by vegetation, topographic models created from high-resolution stereo satellite imagery may supplement airborne lidar bare-earth elevation models*	POR-14 (ICESat-2)	TO-20
			Observations of ecosystem status and near-surface material composition	Hyperspectral VNIR/SWIR and TIR data at 30-45 m spatial resolution and ~ weekly temporal resolution	Moderate-resolution imaging/spectometry—e.g., Landsat, ASTER, Hyperion, but with improved spectral and temporal resolution	POR-9 (ASTER, OLI, ETM+)	TO-18
QUESTION S-5. How does energy flow from the core to Earth's surface?	**S-5a.** Determine the effects of convection within Earth's interior, specifically the dynamics of Earth's core and its changing magnetic field and the interaction between mantle convection and plate motions.	**Very Important**	Monitor secular variation in Earth's magnetic field	LEO Multi-point simultaneous magnetic field vector measurements with global coverage, 0.1 nT/component precision, 1 nT/component absolute. Multi-year continuous observations.	Magnetometers (e.g., SWARM). *NOTES: There are currently no suitable LEO vector magnetic satellite missions planned beyond Swarm.*	POR-19 (SWARM)	TO-8
			Determine exchange of angular momentum between core and mantle from changes in earth rotation parameters	Observe changes in the Earth Orientation Parameters to 5 µs for the Length of Day and 50 µas for the corresponding xp, yp pole coordinates. Observe the nutation and precession of the Earth rotation axis to 0.0001″ for each component.	[VLBI]	POR-7, 13 (GRACE-FO, Jason-3, LAGEOS, GRASP)	TO-9
			Map surface topography—moderate resolution	Measure topography to 5 m horizontal and 10 cm vertical resolution	{TerraSAR Tandem-X}		COMMERCIAL
			Map gravity field	Measure sea-surface height to 1 cm over 10 km distance	Radar altimetry (e.g., SWOT)	POR-26, 27 (SWOT)	TO-21
			Determine plate motions and deformation and track the evolution of plate boundaries	Continuous GPS/GNSS 1 mm/yr horizontal, 2 mm/yr vertical, <500 km sampling interval	[GNSS]	POR-7 (GNSS)	
				SAR interferometry, 10 mm vertical, 100 mm horizontal	L-band InSAR with ionospheric correction	POR-12 (NISAR)	TO-19
				Marine or aeromagnetic high-resolution spatial magnetic anomalies, 10 nT, 1 km horizontal resolution	[aircraft magnetometer]		AIRCRAFT
				Sea floor geodesy, 5 mm/yr horizontal, 10 mm/yr vertical	[GPS acoustics]		GPS
				Improved reference frames through geodetic observations, 1 mm accuracy, 0.1 mm/yr stability horizontal and vertical	[VLBI, SLR, GNSS]	POR-7, 13 (GRACE-FO, Jason-3, LAGEOS, GRASP)	
	S-5b. Determine the water content in the upper mantle by resolving electrical conductivity to within a factor of 2 over horizontal scales of 1,000 km.	**Important**	Mantle conductivity determined from time series of global magnetic measurements	Multi-point simultaneous magnetic field vector measurements with global coverage, 0.1 nT/component precision, 1 nT/component absolute; multi-year, continuous observations.	Magnetometers (e.g., SWARM), but with larger number of satellites. *NOTES: This objective requires multi-point measurements from a constellation of satellites taking oriented vector magnetic measurements.*	POR-8, 19 (SWARM)	TO-8
	S-5c. Quantify the heat flow through the mantle and lithosphere within 10 mW/m^2.	**Important**	Determine the heat flow through the land surface and volcanic activity	Night-time hyperspectral TIR at 30-45 m spatial resolution to determine surface heat flow to within 5 mW/m^2	Imaging (e.g., MODIS)	POR-25 (ASTER, TIRS), POR-21 (MODIS)	TO-18

EARTH SURFACE AND INTERIOR PANEL

SCIENCE			MEASUREMENT				
					Example Measurement Approaches		
Societal or Science Question/Goal	**Earth Science/Application Objective**	**Science/Application Importance**	**Geophysical Observable**	**Measurement Parameters**	**Method**	**POR**	**TO**
			Map depth of the Curie temperature isotherm	UAV spatial magnetic anomalies, 10 nT, 10 km horizontal resolution	[aircraft total field magnetics]		
QUESTION S-6. How much water is traveling deep underground, and how does it affect geological processes and water supplies?	**S-6a.** Determine the fluid pressures, storage, and flow in confined aquifers at spatial resolution of 100 m and pressure of 1 kPa (0.1 m head).	**Very Important**	Topography	Topography at 10 m resolution	{TerraSAR Tandem-X}. *NOTES: The required radar data have been collected by the TerraSAR Tandem-X mission although the data are not publically available. A negotiated data purchase may be less costly than a new NASA mission.*		COMMERCIAL
			Land-surface deformation	For seasonal variations: 1 cm/yr measured weekly at 10 m spatial sampling (which allows stacking for sub-cm secular trends)	L- or S-band InSAR, [GPS/GNSS]	POR-12 (NISAR)	TO-19
			Surface water distribution	100 m spatial, e.g., SWOT, stream gauge network, seasonally	Radar altimetry (e.g., SWOT)	POR-26, 27 (SWOT)	TO-21
	S-6b. Measure all significant fluxes in and out of the groundwater system across the recharge area.	**Important**	Soil moisture, snow/SWE, rainfall	1-5 km spatial, from SMAP, other radar, thermal inertia using TIR and VNIR data, and GPS reflections, weekly	Soil moisture (e.g., SMAP), rainfall (e.g., GPM)		TO-17
			Gravity	Monthly, uncertainty 1 cm water-equivalent thickness at resolution of 100 km	Gravity (e.g., GRACE-2)	POR-30 (GRACE-FO)	TO-9
			Topography	Vertical accuracy of 10 cm, resolution 1 m	SAR, lidar (suborbital)	POR-14 (ICESat-2)	TO-20
			Deformation from fluid fluxes (uses several above measurements)	Spatiotemporal distribution of subsidence/uplift at 3 mm vertical per year, 5 m horizontal, weekly. Coverage over active reservoirs.	L- or S-band InSAR, [GPS/GNSS]	POR-12 (NISAR)	TO-19
			Land-surface deformation	Spatiotemporal distribution of subsidence/uplift at 1 cm vertical, 5 m horizontal, weekly. Coverage over managed watersheds, other watersheds of interest	L- or S-band InSAR, [GPS/GNSS]	POR-12 (NISAR)	TO-19
	S-6c. Determine the transport and storage properties in situ within a factor of 3 for shallow aquifers and an order of magnitude for deeper systems.	**Important**	Deformation from fluid fluxes (uses several above measurements)	Spatiotemporal distribution of subsidence/uplift at 3 mm/yr vertical, 5 m horizontal, weekly. Coverage over active reservoirs.	L- or S-band InSAR, [GPS/GNSS]	POR-12 (NISAR)	TO-19
	S-6d. Determine the impact of water-related human activities and natural water flow on earthquakes.	**Important**	Vertical surface deformation	Spatiotemporal distribution of subsidence/uplift at 3 mm/yr vertical, 5 m horizontal, weekly	L- or S-band InSAR, [GPS/GNSS] {seismic data and production/injection data from regulatory agencies}	POR-12 (NISAR)	TO-19
QUESTION S-7. How do we improve discovery and management of energy, mineral, and soil resources?	**S-7a.** Map topography, surface mineralogic composition, distribution, thermal properties, soil properties/water content, and solar irradiance for improved development and management of energy, mineral, agricultural, and natural resources.	**Important**	Hyperspectral VSWIR reflectivity and TIR emissivity and surface temperature	Hyperspectral VNIR/SWIR and TIR data at 30-45 m spatial resolution and ~ weekly temporal resolution	Moderate-resolution imaging/spectometry (e.g., Landsat, Aster but with improved spectral and temporal resolution)	POR-9 (ASTER, OLI, ETM+)	TO-18
			Thermal intertia	Hyperspectral TIR data at 30-45 m spatial resolution and ~ weekly temporal resolution. Day/night measurements needed at the 12-24 hour time scale.	Imaging (e.g., MODIS, ASTER)	POR-9 (ASTER, OLI, ETM+), POR-25 (ASTER, TIRS)	TO-18
			Land-surface deformation	Spatiotemporal distribution of subsidence/uplift at 1 cm vertical, 5 m horizontal, weekly	L- or S-band InSAR with ionospheric correction, [GPS/GNSS]	POR-12 (NISAR)	TO-19
			Topography	Topographic data at 30 m postings, 25 cm vertical	{TerraSAR Tandem-X}		COMMERCIAL
			Solar irradiance	Real-time measurement of solar irradiance at better than 1 km resolution and 15-min cadence for managing solar power assisted energy grids.	Solar irradiance (e.g., GOES)		

C

Targeted Observables Table

Table C.1 provides a summary of all Targeted Observables considered by the committee. This list of observables resulted from a review of the Program of Record (POR; Appendix A) to determine which observations needed to support priority science and applications objectives (Appendix B) could not be met by the existing/planned observational system. These entries are thus candidates for new flight opportunities during the ESAS 2017 decade. A summary version of this table, with priority Targeted Observables allocated to flight program elements, is provided in Table 3.3.

As with the Science and Applications Traceability Matrix (SATM; Appendix B), columns related to *science and applications questions* or *objectives* are shaded in blue, and columns related to *observations* are shaded in green.

Columns in the Targeted Observables table consist of the following:

- *Targeted Observable.* A number designation and name for the Targeted Observable.
- *Science and Applications Summary.* High-level description of the science and applications to be addressed by the Targeted Observable.
- *Science and Applications Priorities.* Cross-referenced matrices of the science and applications objectives linked to the Targeted Observable. Color-coding indicates whether objectives are ranked as Most Important (MI), Very Important (VI), or Important (I). Note that objectives here may or may not be fully addressed by the Targeted Observable, depending on implementation details and the availability of additional supporting measurements required by any given objective. Each panel is represented by a letter: **H**ydrology, **W**eather and Air Quality, **E**osytems, **C**limate, and **S**olid Earth.
- *Related ESAS 2007 and POR.* References to related missions recommended in the ESAS 2007 report and missions or instruments in the Program of Record.
- *Identified Need/Gap.* A short description of the identified need or gap in the Program of Record that was considered as a candidate priority for new flight opportunities in the ESAS 2017 decade.
- *Candidate Measurement Approach.* One or more potential measurement approaches to address the identified need or gap in the Program of Record.
- *ESAS 2017 Disposition.* Summary of any actions or recommendations related to the Targeted Observable. As described in Chapter 3, due to resource constraints, not all Targeted Observables were allocated to identified flight opportunities. Observing system priorities are summarized in Table 3.3.

TABLE C.1 Targeted Observables

		Science/Applications Priorities by Panel[a]			
Targeted Observable	Science and Applications Summary		MI	VI	I
TO-1 Aerosol and Cloud Radiative Properties	· Aerosol/particulate matter optical depth, particle size, speciation · Cloud optical depth and cloud hydrometeor size for top 1-2 optical depths	H	**1c**		
		W	**1a, 2a, 5a**		6a, 9a, 10a
		E			
		C	**2h**	2g, 5a, 5c, 7a	3d, 4d, 5b, 5d, 7b, 9a
		S	**1a**		
TO-2 Aerosol Vertical Profiles	· Aerosol extinction profiles · Column integrated cloud properties	H			2b
		W	**1a, 2a, 5a**		6a, 9a
		E			
		C	**2a, 2h**	2g, 5a, 5c	5b, 5d, 7b, 8g, 9a
		S	**1a**		
TO-3 Aquatic-Coastal Biogeochemistry	· Distribution, composition, and functioning of aquatic ecosystems and their biogeochemical impacts · Chlorophyll, particulate organic carbon and primary production · Phytoplankton biomass and composition	H			3a, 3b
		W			
		E	**1c, 3a**	1a	2b, 3b, 4a, 4b, 5a, 5b
		C	**2d**		3c, 4d, 5b, 7b
		S			
TO-4 Atmospheric Winds	· 3D wind, in troposphere/PBL · Cloud dynamics · Convection	H		2a, 4a	4b
		W	**1a, 2a, 4a**		9a, 10a
		E			
		C		4a, 5a, 7a, 7c	3f, 4b, 5b, 7b, 7d, 7e, 8i
		S			

Related ESAS 2007 and POR	Identified Need/Gap	Candidate Measurement Approach	ESAS 2017 Disposition
ESAS 2007: ACE ***POR:*** MISR/Terra, MODIS/Terra, MODIS/Aqua, MAIA, VIIRS, MSI/EarthCARE, 3MI/MetOp-SG	POR has no multi-angle polarimeter post-MAIA, and reduced spatial coverage post-MISR	***Similar to:* MISR, MODIS, MAIA** · Multichannel/multiangle/polarization imaging radiometer · Moderate spatial resolution	**DESIGNATED** PROGRAM ELEMENT Joint implementation with TO-2, maximum development cost $800 million
ESAS 2007: ACE ***POR:*** ATLID/EarthCARE, CALIOP/CALIPSO	POR has no backscatter lidar post-EarthCARE	***Similar to:* CALIOP/CALIPSO, ATLID/EarthCARE** · Lidar extinction profiles from backscatter or high spectral resolution lidar · Horizontal resolution ~100 m-1 km; vertical resolution similar or better than CALIPSO	**DESIGNATED** PROGRAM ELEMENT Joint implementation with TO-1, maximum development cost $800 million
ESAS 2007: ACE, GEO-CAPE ***POR:*** MODIS/Aqua, MODIS/Terra, PACE, VIIRS	POR does not provide high temporal resolution	***Similar to:* GEO-CAPE** · Imaging radiometer · Hyperspectral with spatial resolution 1 km and 1-2 day revisit for open ocean · Multispectral regional imaging with <200 m spatial resolution and <1 day revisit for coastal and inland waters	**UNALLOCATED** Consider any related submissions to Venture solicitations, R&A efforts
ESAS 2007: 3D-Winds ***POR:*** Aladin/Aeolus, QuikSCAT, CYGNSS, AMVs from GOES, METEOSAT, MTSAT, MetOp, VIIRS, MODIS	POR lacks 3D horizontal vector winds in the PBL/lower troposphere	***Similar to:* Aladin/Aeolus** · Lidar, radar, scatterometer, or passive radiometry-based feature tracking methods for the PBL and troposphere · Sampling with 3-20 km horizontal, 0.2-1 km vertical, 1-3 h temporal resolution and 1 m/s horizontal, 0.5-1 m/s vertical accuracy	**INCUBATION** PROGRAM ELEMENT *Also eligible for competition in Earth System Explorer program element*

continued

TABLE C.1 (Continued)

		Science/Applications Priorities by Panel[a]			
Targeted Observable	Science and Applications Summary		MI	VI	I
TO-5 Clouds, Convection, and Precipitation	· Cloud coverage and optical properties · Solid and liquid precipitation rate · Liquid and ice water path · Convection and cloud dynamics · Diurnal cycle of clouds and precipitation	H	**1a, 1b, 1c**		3b, 4b
		W	**1a, 2a, 4a**	3a	9a, 10a
		E	**3a**		
		C	**2a, 2h**	2g	3f, 5d, 7e, 8h
		S		1c	4b
TO-6 Greenhouse Gases	· Global/regional CO_2 land fluxes and their trends · Global/regional methane emissions and their trends · Quantification of point sources	H			
		W			8a
		E	**2a, 3a**		4a, 5a, 5b, 5c
		C	**2d**	3a, 4a	3b, 3c, 3e, 3g, 4d, 7b
		S			
TO-7 Ice Elevation	· Land ice: surface elevation change (for determining ice sheet and glacier mass balance) · Sea ice: freeboard height (for determining sea-ice thickness and its changes over time)	H			4b
		W		3a	
		E			
		C	**1c**	8a, 8b, 8c	8h
		S	**3a**		
TO-8 Magnetic Field	· Magnetic field changes	H			
		W			
		E			
		C			
		S		5a	5b

Related ESAS 2007 and POR	Identified Need/Gap	Candidate Measurement Approach	ESAS 2017 Disposition
ESAS 2007: ACE ***POR:*** CPR/EarthCARE, GPM, CloudSat, MODIS, VIIRS, SSMI, TROPICS	POR does not address diurnal cycle and does not cover precipitation after EarthCARE, GPM and SSMI, or snowfall, convection, and cloud dynamics after EarthCARE	***Similar to:* CloudSat, CPR/ EarthCARE** · Dual-frequency radar and multifrequency microwave radiometer · Sampling with ~1-4 km horizontal and ~250 m vertical resolution and ~0.2 mm/hr precipitation (rain) accuracy Doppler for dynamics/ convection (~1 m/s) · Spatial resolution ~4-10 km for global precipitation and snowfall; ~1mm/hr snowfall accuracy	**DESIGNATED** PROGRAM ELEMENT Maximum development cost $800 million; considerable synergistic value in TO-5 being coordinated in time with TO-1 and TO-2
ESAS 2007: GEO-CAPE, ASCENDS ***POR:*** OCO-2, OCO-3, GeoCARB, TEMPO, FLEX	POR does not include global coverage after OCO-2 and lacks information on vertical distribution	***Similar to:* OCO-2, OCO-3, GeoCARB, TEMPO** · SWIR and TIR sounders to measure CO$_2$, CH$_4$, and CO · Precision of 0.5-1 ppm CO$_2$, 10-20 ppb CH$_4$, and 10-30 ppb CO with spatial resolution to support point source detection	**EARTH SYSTEM EXPLORER** PROGRAM ELEMENT Recommended for competition
ESAS 2007: ICESat-2 ***POR:*** ICESat-2, ESA/CryoSat-2 (2010-present)	POR does not include coverage post-ICESat-2 unless CryoSat-3 is approved	***Similar to:* ICESat-2, ESA/ CryoSat-2** · Laser or radar altimeter · Spatial sampling 5 km (0.25 km near ice-sheet margins) with ~0.1 m vertical accuracy	**EARTH SYSTEM EXPLORER** PROGRAM ELEMENT Recommended for competition as part of multifunction lidar; if CryoSat-3 not approved then highest priority function for multi-function lidar
ESAS 2007: none ***POR:*** ESA/Swarm	POR does not include coverage after Swarm	***Similar to:* SWARM** · Global magnetic field measurements · Precision of 0.1 nT and 1 nT absolute accuracy	**UNALLOCATED** Consider any related submissions to Venture solicitations, R&A efforts

continued

TABLE C.1 (Continued)

		Science/Applications Priorities by Panel[a]			
Targeted Observable	Science and Applications Summary		MI	VI	I
TO-9 Mass Change	· Groundwater and water storage mass change · Land-ice mass change · Ocean mass change · Glacial isostatic adjustment · Earthquake mass movement	H	**1a, 2c**		3b, 4c
		W			
		E			
		C	**1a, 1b, 1c**	1d	7d, 7e
		S	**1b, 3a, 4a**	5a	6b
TO-10 Ocean Ecosystem Structure	· Stocks of planktonic biomass · Primary productivity estimates · Mixed layer depth · Changes in particle biomass, particle size, spectral light attenuation differences	H			
		W		3a	
		E	**1b, 3a**		3b, 4b, 5a, 5b
		C	**2d**	8d	3d
		S			
TO-11 Ocean Surface Winds and Currents	· Ocean vector wind and wind-stress curl · Surface currents · Sea-ice drift and sea-ice extent · Ocean/atmosphere momentum exchange	H			4b
		W	**1a, 2a**	3a	
		E			
		C		4a, 5a, 6a, 7a, 8d	3d, 4b, 7b, 7d, 7e, 8i
		S			
TO-12 Ozone and Trace Gases	· Vertical profiles of ozone, water vapor, CO, NO_2, methane, and N_2O · Long-term trends in ozone layer · Factors controlling ozone in UT/LS · Mechanisms of stratosphere-troposphere exchange	H			
		W	**2a, 4a, 5a**		6a, 7a, 8a
		E			
		C		2g	3f, 3g, 6c, 9a
		S			

Related ESAS 2007 and POR	Identified Need/Gap	Candidate Measurement Approach	ESAS 2017 Disposition
ESAS 2007: GRACE-II ***POR:*** GRACE, GRACE-FO	POR does not include coverage after GRACE-FO	***Similar to:* GRACE** · Measurement of gravity anomaly with spatial resolution of 200 km at the equator (goal of 50 km or less)	**DESIGNATED** PROGRAM ELEMENT Maximum development cost $300 million; ensure continuity after GRACE-FO
ESAS 2007: ACE, DESDynI ***POR:*** CALIOP/CALIPSO, ATLID/EarthCARE	POR does not include coverage after EarthCARE	***Similar to:* CALIOP/CALIPSO, HSRL-2 airborne instrument** · Multifrequency imaging lidar · Global sampling with 1 km footprint and 2 m vertical resolution to 3 optical depths · Priority coverage of sub-polar and polar oceans in spring and fall	**UNALLOCATED** Consider opportunistic use of data from recommended Aerosols TO-2 to address TO-10; consider any related submissions to Venture solicitations, R&A efforts
ESAS 2007: XOVWM ***POR:*** Metop/ASCAT, SCATSAT, QuikSCAT, METOP-A, METOP-B, CFOSAT	POR does not support measurement of ocean surface currents in conjunction with wind	***Similar to:* QuikSCAT, RapidScat** with additional capabilities to measure ocean currents · Radar scatterometer and Doppler surface currents · Ocean surface wind accuracy of ~1 m/s or ~0.02 N/m^2 at 100 km spatial resolution and 1-2 day temporal resolution · Ocean surface currents with accuracy of ~0.5 m/s at 5 km resolution or ~2 cm/s at 100 km resolution and 1-2 day temporal resolution	**EARTH SYSTEM EXPLORER** PROGRAM ELEMENT Recommended for competition
ESAS 2007: GACM ***POR:*** MLS/Aura, HIRDLS, SAGE-III, ACE-FTS, GOMOS, OMPS/NPP, OMPS/JPSS	POR does not include vertical profiling for species other than ozone and aerosol	***Similar to:* MLS, HIRDLS, SAGE, ACE-FTS** · UV/VIS/IR microwave limb sounding and UV/VIS/IR solar/stellar occultation measurements of ozone, water vapor, CO, NO_2, methane, N_2O · Sub-km vertical resolution in the upper troposphere and lower stratosphere	**EARTH SYSTEM EXPLORER** PROGRAM ELEMENT Recommended for competition

continued

TABLE C.1 (Continued)

		Science/Applications Priorities by Panel[a]			
Targeted Observable	Science and Applications Summary		MI	VI	I
TO-13 Planetary Boundary Layer	- Temperature - Water vapor - PBL height	H		2a	
		W	**1a, 2a**	3a	10a
		E			
		C		2b, 4a, 7a, 7c	7b, 7d, 7e
		S			
TO-14 Radiance Inter-calibration	- Climate sensitivity - Inter-calibration of in-flight radiometers	H			
		W			
		E			
		C	**2a, 2h**	2b, 2c, 5c, 7c	2e, 5d, 7b
		S			
TO-15 Salinity	- Sea surface salinity	H			3a
		W		3a	
		E			2b
		C		6a, 7a	3d, 7d, 7e
		S	**3a**		
TO-16 Snow Depth and Snow Water Equivalent	- Snow depth at high spatial resolution in mountain areas - Snow water equivalent (SWE)	H	**1a, 1c**	4a	2b
		W		3a	
		E			
		C		8c	8f
		S	**4a**		4b, 4c
TO-17 Soil Moisture	- Soil, root zone moisture - Freeze/thaw, active layer monitoring - Evapotranspiration - Gross primary production (GPP)	H	**1a, 2c**	2a	4b, 4c, 4d
		W	**2a**	3a	
		E			1d, 2c
		C		3a, 5a, 6a, 7a	3c, 5b, 7b, 7e, 8f
		S		1c	4b, 6b

Related ESAS 2007 and POR	Identified Need/Gap	Candidate Measurement Approach	ESAS 2017 Disposition
ESAS 2007: PATH ***POR:*** AMSU/Aqua, AIRS/Aqua, CrIS/JPSS, ISAI/MetOp, AMSU/MetOp, COSMIC, MHS/MetOp, CALIPSO, GOES-R, AMSR	POR lacks sufficient horizontal and temporal resolution	***Similar to:* AIRS, AMSU, COSMIC** - Microwave and hyperspectral IR sounders; lidar for PBL height - Sampling with 3-20 km horizontal, 0.2-1 km vertical, 1-4 hr temporal resolution	**INCUBATION** PROGRAM ELEMENT Consider opportunistic use of data from recommended TO-1/2 investment for PBL height
ESAS 2007: CLARREO ***POR:*** CLARREO-PF	POR does not include an intercalibration reference for thermal IR	***Similar to:* CLARREO-PF** - Reflected solar and thermal IR narrow-swath spectrometers - High spectral resolution (0.5-cm in IR, 4 nm in solar) and radiometric accuracy (0.03 K, 1 sigma in IR; 0.15%, 1 sigma in solar)	**UNALLOCATED** Consider any related submissions to Venture solicitations
ESAS 2007: SMAP ***POR:*** Aquarius, SMAP, SMOS	POR does not include coverage after SMAP and SMOS	***Similar to:* Aquarius, SMAP, SMOS** - Multifrequency radar - Spatial and temporal resolution similar to microwave sea-surface temperature (i.e., 25 km spatial resolution with 3-day temporal resolution) - Accuracy of ~0.15 practical salinity units (psu) on monthly time scales and 1-degree spatial scales, or 0.1 psu on 10-degree spatial scales	**UNALLOCATED** Consider any related submissions to Venture solicitations, R&A efforts, technology development initiatives to reduce cost and improve performance
ESAS 2007: SWOT, LIST ***POR:*** GEDI, Jason-2/3, SWOT, Sentinel-6A/B	POR does not provide sufficient spatial resolution and coverage needed to quantify snow processes and storage in mountainous terrain	***Similar to:* SWOT** - Radar (Ka/Ku-band) altimeter or lidar - Spatial resolution of 50 m with snow depth accuracy of 2-20 cm	**EARTH SYSTEM EXPLORER** PROGRAM ELEMENT Recommended for competition
ESAS 2007: SMAP ***POR:*** SMAP, SMOS	POR does not include coverage after SMAP and SMOS	***Similar to:* SMAP, SMOS** - Radar and microwave radiometer - Spatial resolution of 100 m to 1 km (radar) and 20-60 km (radiometer) with a combined active passive product at 1-10 km resolution	**UNALLOCATED** Consider any related submissions to Venture solicitations, R&A efforts, technology development initiatives to reduce cost and improve performance

continued

TABLE C.1 (Continued)

		Science/Applications Priorities by Panel[a]			
Targeted Observable	Science and Applications Summary		MI	VI	I
TO-18 Surface Biology and Geology	· Surface geology and biology · Active geologic processes · Ground and water temperature · GPP · Snow spectral albedo · Functional traits of terrestrial vegetation and inland and near-coastal aquatic ecosystems	H	**1c**	2a, 4a	2b, 3a, 3b, 3c, 4c, 4d
		W		3a	
		E	**1c, 2a, 3a**	1a	1d, 5a, 5b, 5c
		C		3a	3c, 3d, 6b, 7e, 8f
		S	**1a**	1c, 2b	4b, 4c, 7a
TO-19 Surface Deformation and Change	· Surface change monitoring · Ice-sheet dynamics · Antarctic grounding line · Permafrost thaw subsidence	H	**1c, 2c**	4a	4b
		W			
		E			
		C	**1c**		7b, 8f
		S	**1a, 1b, 2a, 3a, 3b, 4a**	1c, 2b, 2c, 5a, 6a	4b, 6b, 6c, 6d, 7a
TO-20 Surface Topography and Vegetation	· Bare surface land topography · Ice topography · Vegetation structure · Shallow water bathymetry	H	**2c**		2b, 3c, 4b, 4d
		W		3a	
		E	**1b**		1e
		C	**1c**		8f
		S	**1a, 1b, 3a, 3b, 4a**	1c, 2b, 2c	1d, 4b, 4c, 6b, 7a
TO-21 Surface Water Height	· Horizontal structure of ocean surface height · Two-dimensional geostrophic velocities · Bathymetry/gravity · Significant wave height · Tsunami height · Inland waters/ecosystems · Tides and dissipation of tidal energy · Sea-ice thickness · River flow and terrestrial water storage · River height variations for transport of material from land to ocean	H	**1c**		
		W		3a	
		E			
		C	**1a, 1b**	1d, 4a, 6a, 7a, 8a, 8b, 8c	4b, 8g, 8i
		S	**3a**		1d

Related ESAS 2007 and POR	Identified Need/Gap	Candidate Measurement Approach	ESAS 2017 Disposition
ESAS 2007: HyspIRI ***POR:*** ASTER/Terra, MODIS, Landsat, AIRS, PACE, Hyperion, ECOSTRESS	POR does not include hyperspectral imagery in the visible or shortwave infrared	***Similar to:* HyspIRI, combination of ASTER, MODIS, Landsat, AIRS; airborne instrument AVIRIS-NG** · Hyperspectral imagery in the visible and shortwave infrared and multi- or hyperspectral imagery in the thermal infrared · Spatial resolution of 30-60 m (VIS-SWIR) and 60 m (TIR) with 14-19 day (SWIR) and 5 day (TIR) temporal resolution	**DESIGNATED** PROGRAM ELEMENT Maximum development cost $650 million
***ESAS 2007*:** DESDynI ***POR*:** NISAR, TanDEM-X	POR does not include coverage after NISAR	***Similar to:* NISAR** · Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction · Spatial coverage similar to NISAR with higher spatial resolution and shorter repeat cycle (subweekly to daily)	**DESIGNATED** PROGRAM ELEMENT Maximum development cost $500 million; provide continuity after NISAR
***ESAS 2007*:** LIST, DESDynI ***POR*:** GEDI, ICESat-2	POR does not provide global sampling with sufficient density	***Similar to:* SRTM and airborne topography lidar** · Radar or lidar · Global sampling at 1-5 m resolution and 0.1 m vertical resolution with seasonal repeat	**INCUBATION** PROGRAM ELEMENT Consider investment in suborbital approaches to meet needs on a regional basis
ESAS 2007: SWOT ***POR:*** SWOT	POR does not include swath altimeter after SWOT	***Similar to:* SWOT** · Swath SAR altimetry · Spatial resolution of ~15 km with ~± 2 cm accuracy and submonthly temporal resolution for oceans · Spatial resolution of ~100 m with anomalies in river flow and elevation accurate to ± 20% and weekly temporal resolution for inland waters	**UNALLOCATED** Consider any related submissions to Venture solicitations, R&A efforts

continued

TABLE C.1 (Continued)

Targeted Observable	Science and Applications Summary	Science/Applications Priorities by Panel[a]			
			MI	VI	I
TO-22 Terrestrial Ecosystem Structure	- Forest 3D canopy height/structure and aboveground biomass - Changes in aboveground carbon stock from processes such as deforestation and forest degradation	H			3c
		W			
		E	**1b, 3a**		1e, 4a, 5a, 5b, 5c
		C	**2d**		3c, 8f
		S			4c

[a] References to panels are abbreviated as follows: Global Hydrological Cycles and Water Resources = "Hydrology" or "H"; Weather and Air Quality: Minutes to Subseasonal = "Weather" or "W"; Marine and Terrestrial Ecosystems and Natural Resource Management = "Ecosystems" or "E"; Climate Variability and Change: Seasonal to Centennial = "Climate" or "C"; and Earth Surface and Interior: Dynamics and Hazards = "Solid Earth" or "S."

Related ESAS 2007 and POR	Identified Need/Gap	Candidate Measurement Approach	ESAS 2017 Disposition
ESAS 2007: ACE, DESDynI ***POR:*** GEDI	POR does not include coverage after GEDI	***Similar to:*** **GEDI, HSRL-2 airborne instrument** · Imaging lidar · Global sampling with 10-25 m footprint at 0.25 m vertical resolution	**EARTH SYSTEM EXPLORER** PROGRAM ELEMENT Recommended for competition as part of a multifunction lidar

D

Request for Information and Responses from the Community

The request for information from the Earth and environmental science and applications community is reprinted below, and a list of responses is provided in Table D.1.

To: *Members of the Earth and Environmental Science and Applications Community*

From: *Waleed Abdalati and Antonio Busalacchi, co-chairs of the 2017-2027 Decadal Survey for Earth Science and Applications from Space ("ESAS 2017")*

Date: *February 18, 2016*

Dear Colleagues:

As you likely know, the Space Studies Board, in collaboration with other units[1] *of the National Academies of Sciences, Engineering, and Medicine has begun ESAS 2017, the 2017-2027 Decadal Survey for Earth Science and Applications from Space. This community-based effort will develop a comprehensive strategy that updates and extends the inaugural decadal survey, which was released in January 2007. Sponsored by NASA (Earth Science Division); NOAA (NESDIS), and USGS (Climate & Land Use Change), the study will generate prioritized recommendations regarding an integrated and sustainable systems approach to the space-based and ancillary observations that are central to the research and operational programs of the study's sponsors. A website has been created to describe the survey and to provide an opportunity for community input throughout the study process: www.nas.edu/esas2017.*

The statement of task, which is posted on the website, directs the survey committee to:

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[1] Within the National Academies, the decadal survey is being led by the Space Studies Board (SSB), which is working in close collaboration—including the sharing of staff—with the Board on Atmospheric Sciences and Climate (BASC), the Board on Earth Sciences and Resources (BESR), the Ocean Studies Board (OSB), the Polar Research Board (PRB), and the Water Science and Technology Board (WSTB). Information about SSB is available at: http://sites.nationalacademies.org/SSB; information about the other Boards is available via links at: http://dels.nas.edu/.

1. *Assess progress in addressing the major scientific and application challenges outlined in the 2007 Earth Science Decadal Survey.*
2. *Develop a prioritized list of top-level science and application objectives to guide space-based Earth observations over a 10-year period commencing approximately at the start of fiscal year 2018 (October 1, 2017).*
3. *Identify gaps and opportunities in the programs of record at NASA, NOAA, and USGS in pursuit of the top-level science and application challenges—including space-based opportunities that provide both sustained and experimental observations.*
4. *Recommend approaches to facilitate the development of a robust, resilient, and appropriately balanced U.S. program of Earth observations from space. In doing so, consider: Science priorities, implementation costs, new technologies and platforms, interagency partnerships, international partners, and the in situ and other complementary programs carried out at NSF, DoE, DoA, DoD.*

The present decadal survey's task statement also asks the survey committee to, "include reconsideration of the scientific priorities associated with the named missions from the 2007 decadal survey." Accordingly, the geophysical variables associated with the measurement objectives of missions prescribed in the 2007 survey (Earth Science and Applications from Space) that have not yet been formally confirmed for implementation will be considered as part of the 2017 survey's prioritization effort.

The scope of the study and the "deliverables" expected by the sponsors are described in the full task statement that is posted on the survey's website. Working with five study panels (described below), the survey committee will establish science and application priorities and measurement needs. The previous decadal survey wrapped its science and application objectives around detailed mission concepts. In a change from the previous survey, recommendations in the 2017 decadal survey will generally refer to Earth science and applications targets (i.e., an objective or a set of objectives that could be pursued and significantly advanced by means of a space-based observation) and the required measurements to address those targets rather than specific mission implementations. However, for recommendations involving potentially large investments, notional mission concepts may be generated for the purposes of independent analysis of cost and risk.

An initial RFI, issued by the standing Committee on Earth Science and Applications from Space in late September 2015, asked for community input on the following questions:

1. *What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?*
2. *Why are these challenge/questions timely to address now especially with respect to readiness?*
3. *Why are space-based observations fundamental to addressing these challenges/questions?*

The more than 200 responses to this RFI are available at the survey website. The responses guided the steering committee's initial discussions on survey organization; in particular, regarding the structure of its supporting study panels. The responses will also continue to inform the work of the committee and will be made available to the soon to be formed 3 study panels. However, by design, the initial RFI did not ask the community for ideas on how to address an identified challenge/question in Earth System Science.

We now invite you to submit ideas for specific science and applications targets (i.e., objectives) that promise to substantially advance understanding in one or more of the following Earth System Science themes:

I. Global Hydrological Cycles and Water Resources
The movement, distribution, and availability of water and how these are changing over time

II. Weather and Air Quality: Minutes to Subseasonal
Atmospheric Dynamics, Thermodynamics, Chemistry, and their interactions at land and ocean interfaces

III. Marine and Terrestrial Ecosystems and Natural Resource Management
Biogeochemical Cycles, Ecosystem Functioning, Biodiversity, and factors that influence health and ecosystem services

IV. Climate Variability and Change: Seasonal to Centennial
Forcings and Feedbacks of the Ocean, Atmosphere, Land, and Cryosphere within the Coupled Climate System

V. Earth Surface and Interior: Dynamics and Hazards
Core, mantle, lithosphere, and surface processes, system interactions, and the hazards they generate

Submitted ideas will be reviewed by one or more of the survey's study panels, which are organized to address the above-mentioned themes. Suggested targets that are crosscutting among these themes are particularly encouraged. ***Submissions should also identify the key geophysical variables/measurements, and the observational requirements, needed to address the science and application targets.***

We anticipate that some of the targets, and their associated measurements, recommended by the Panels will be selected by the Steering Committee for detailed technical and cost analysis of potential implementation architectures. ***To assist those efforts, you are encouraged to provide information on measurement approaches, including technical, performance and maturity/heritage specifications, for relevant current and near-future instrumentation.***

All responses will be considered non-proprietary public information for distribution with attribution. Submitted papers should be no longer than five single-spaced pages in length, excluding figures and tables, and should provide the following information, if possible:

1. *A clear description of the Science and Application target, its importance to the Theme as evidenced in previous reports or community roadmaps, and how, by addressing it, understanding in one or more of the above-mentioned Decadal Survey Themes is advanced.*
2. *An explanation of the utility of the measured geophysical variable(s) to achieving the science and application target.*
3. *The key requirements on the quality (i.e. the performance and coverage specifications) of the measurement(s) needed for achieving the science and application target.*
4. *The likelihood of affordably achieving the required measurement(s) in the decadal timeframe given the heritage and maturity of current and near-future instruments and data algorithms, and the potential for leveraging similar or complementary measurements, especially from international partners.*

In reviewing ideas for science and applications targets, the survey panels and steering committee may use an evaluation methodology similar to that outlined in the recent NRC report Continuity of NASA Earth Observations from Space: A Value Framework (2015). Accordingly, we encourage you to submit your ideas for science and application targets in the context of a potential contribution to a "Quantified Earth Science Objective" (QESO).[2]

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[2] As discussed in *Continuity of NASA Earth Observations from Space*, examples of Quantified Earth Science Objectives—provided by the authoring committee solely to illustrate the methodology—include "Narrow the Intergovernmental Panel on Climate Change

For full consideration, please submit the concept paper by April 30, 2016 via the "RFI #2" submission link that will be posted by March 1, 2016 to the survey website (www.nas.edu/esas2017). Questions about the RFI may be directed to the study director, Art Charo (acharo@nas.edu), or to us: Waleed Abdalati (waleed.abdalati@colorado.edu) and Tony Busalacchi tonyb@essic.umd.edu). You can also contact Dr. Charo by telephone at 202 334-3477, or by fax at 202 334-3701.

Fifth Assessment (IPCC AR5) uncertainty in equilibrium climate sensitivity (ECS) (1.5 to 6°C at 90% confidence) by a factor of 2" and "Determine the change in ocean heat storage within 0.1 W m^{-2} per decade (1σ)." Additional examples and the motivation for this methodology are presented in the report (National Research Council, *Continuity of NASA Earth Observations from Space: A Value Framework*, The National Academies Press, Washington, DC, 2015); see especially Box 3.2 on p. 33.

TABLE D.1 Community Responses to the ESAS 2017 Request for Information

RFI Response Number	Response Title	Summary Description[a]
1	The Moon and Earth Radiation Budget Experiment (MERBE)	Moon and Earth Radiation Budget Experiment (MERBE) data suggest a capability of validating climate predictions immediately upon its free global release after 2015, decades before that possible with planned missions such as CLARREO.
2	MERBE-Sat: Low Cost/Risk Spectral SI Traceability Extension to the Moon and Earth Radiation Budget Experiment (MERBE)	Moon and Earth Radiation Budget Experiment (MERBE) data suggest a capability of validating climate predictions immediately upon its free global release after 2015, decades before that possible with planned missions such as CLARREO. The low cost MERBE-Sat CubeSat will then give further spectral SI traceability to this first climate observing system.
3	New Low Cost & Low Power LIDAR Method of Diurnal and Global Green House Gas monitoring from Space: Application to the ASCENDS Mission	A new method is described of sounding greenhouse gas content from space using LIDAR and continuous wave signals, which are generated by cheap/reliable telecommunication lasers etc. Needing only 5% the power of a pulse system, it is shown in tests to yield better accuracy than such a higher power device (which is still in development for ASCENDS).
4	Low-Frequency, Multi-channel Microwave Radiometry for Cryospheric Monitoring	This white-paper introduces a new concept of low-frequency, multi-channel microwave radiometry that should be one of the tools supporting a variety of geophysical products, including sub-surface temperature and other physical properties of ice sheets, sea ice, permafrost, river and lake ice, and seasonal snow cover.
5	Global Capacity Building Vision for Societal Applications of Earth Observing Systems and Data	A community of Earth scientists who develop applications or solutions, and the stakeholders who need them, provided consensus-based input on key questions and recommendations to achieve a vision for global and resilient societal applications of Earth observations.
6	Measurement Needs for Addressing the Water Challenge from Space	This is a one page slide on what and how NASA should measure water to provide more meaningful measurements (from underground to atmosphere) to enable greater impact for society and sustainability of earth.
7	Key Earth System Science Water Quality Objectives	Good water quality is necessary to support drinking water supplies, aquatic life, as well as recreation. EPA identified the key science challenge as the ability to link anthropogenic stressors to their environmental responses for coastal marine waters and inland water bodies defined as any lake, reservoir, river, and estuary.
8	Key Earth System Science Objectives Related to Climate Change and Air Pollution	This is one of three responses formally provided by the USEPA to the National Research Council Committee on Earth Science and Applications from Space 2017 RFI #2. EPA emphasizes the need to consider atmospheric composition observables as part of an integrated, systems-oriented approach cutting across several of the Earth System Science themes.
9	High Time, Tropospheric Temperature, Tropospheric Moisture	The need is clear for high time resolution, tropospheric temperature and moisture profile measurements over a large area. This is possible from the geostationary orbit (GEO) using an advanced infrared (IR) sensor. The science and application targets for such a sensor would allow improved monitoring and modeling of the atmospheric process.
10	White Paper for the ESAS 2017 Decadal Survey on Hyperspectral 3D Atmospheric Motion Vector Winds and High Spatial Resolution IR Sounding	This white paper summarizes the scientific and application benefits of observations of the 3D wind field together with high spatial resolution observations of the thermodynamic field, describes the requirements framework and the current state of technology for implementation.

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
11	DS RFI#2 response for the Ocean Ecosystem and Ocean-Aerosol Interactions components of the Aerosol, Cloud, and ocean Ecosystem (ACE) Mission	This white paper represents the Aerosol, Cloud, and ocean Ecosystem (ACE) Mission response to the NRC DS RFI#2 regarding the OCEAN ECOSYSTEM and the OCEAN-AEROSOL INTERACTIONS components of the ACE mission. Recommendations in this white paper reflect outcomes of ACE mission work since its announcement as a Tier 2 mission in the 2007 NRC DS report.
12	Continuity of Earth Radiation Budget Observations	We discuss Earth Radiation Budget (ERB) science, community-defined ERB requirements, and the impact and probability of a data gap in the ERB record. We also provide in Appendix A two QESOs for TOA and surface radiation budget.
13	A global ocean science target for the coming decade: Response to the 2017 NRC Decadal Survey Request for Information	This white paper describes an observational framework to significantly reduce uncertainties assoicated with a key ocean science QESO. Uncertainties are quantifed, a value assessment is given in IUQSB categories, and measurement requirements are specified. This white paper was coordinated with the Advanced Planning Commitee for NASAs OBB Program.
14	Application of Satellite Earth Observation Data for Global Societal Benefit: Past, Present &Future	This paper is intended as a general overview of key societal applications that have been enabled globally with the use of EO data. The paper also argues for capacity building that is crucial to building sustainable solutions when using EO data for science-based decision making.
15	Thunderstorms, Lightning and Atmospheric Electricity	Thunderstorms and lightning remain poorly understood, despite being among the most widely recognized and dangerous natural phenomena on Earth. Climate change may cause stronger and more frequent storms, increasing lightning activity. Thunderstorms and lightning are an integral part of the Earth system and fit naturally into Themes 2 and 4.
16	Carbon Architecture	This white paper describes a study conducted by the carbon science community, identifying a unifying carbon science question, the requirements for studying it and the observing system architectures that can meet these requirements.
17	Accurate Inter-Calibration of Spaceborne Reflected Solar Sensors	The accuracy and consistency of measurements across multiple spaceborne instruments are directly connected to understanding of complex systems such as Earth's climate. We address one of the key challenges for Earth observations: improving accuracy of multiple on-orbit sensors in reflected solar via reference inter-calibration approach.
18	Satellite Derived Nearshore Sea Surface Salinity Measurements	Due to the dynamic nature of salinity in nearshore regions, accurate and well resolved observations of salinity are essential to understand and predict a range of physical, chemical and ecological processes.
19	High Spatial, Temporal, and Spectral Resolution Instrument for Modeling/Monitoring Land Cover, Biophysical, and Societal Changes in Urban Environments	There is critical need to adequately model, monitor land cover/land use, biophysical, and societal changes in the urban environment and assess climate change impacts on cities. The Hyperspectral Infrared Imager (HyspIRI) is a Decadal Survey tier 2 sensor that is well developed and can be used to satisfy this need.

continued

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
20	Detecting and tracking ocean heat content and large-scale circulation and transport changes from space	The Earth's oceans are changing: warming throughout the water column, and variations of large-scale circulation and transport systems. We argue for continued and expanded altimetry and gravimetry observations to target these essential climate variables to detect and track changes on intra-annual to decadal time-scales across basin scales.
21	Global Surface Air Pressure Measurements from Space for Greenhouse Gas Volume Mixing Ratio Observations	This is for filling a gap, namely global surface air pressure measurements, in global greenhouse gas mixing ratio observations using O2-band differential absorption barometric radar systems.
22	Characterizing the vertical distribution of aerosols for improving model estimates of aerosol transport, radiative forcing, and air quality	Aerosols are hazardous to human health and remain a major uncertainty in modeling the climate system. Better characterization of aerosol vertical distributions from lidar measurements are required to complement passive aerosol retrievals and improve model estimates of aerosol transport, radiative forcing, and air quality.
23	Determining sea surface air pressure and gradient with precise measurements for reliable longer-term storm track and intensification predictions	Quantified Objective: Determining sea surface air pressure and gradient with precise measurements of 1 mbar and 1 mbar/10 km, respectively, for reliable longer-term storm track and intensification predictions For Earth system Science theme II. Weather and Air Quality: Minutes to Subseasonal.
24	Terrestrial Reference Frame	The terrestrial reference frame (TRF) provides the fundamental framework and metrological basis for Earth observation. But the accuracy and stability of the TRF need to dramatically improve in order to fully realize the measurement potential of current and future Earth observing satellites.
25	A community submission for observing the dynamics of convection for severe weather analysis and forecasting	This paper calls for systematic global observations of time-resolved convective processes (convective air mass flux and water fluxes) in order to improve our understanding of convective processes and to improve their representation in weather models.
26	Air Quality in Tropical and Subtropical Megacities	Because of the degradation of air quality in and around major population centers of developing countries, we put forward the objective of monitoring air quality from space over the population centers of the tropics and subtropics from either a geostationary constellation or a single satellite at the Earth-Sun Lagrange 1 position.
27	A community submission for observing the dynamics of convection for climate modeling and prediction	This paper calls for systematic global observations of time-resolved convective processes (convective air mass flux and water fluxes) in order to improve our understanding of convective processes and to improve their representation in climate models.
28	Glacial Acceleration - Reduction of Uncertainty in Sea-Level-Rise Assessment	Paper motivated by the need to understand glacial acceleration which is a main source of uncertainty in sea-level change assessment. Observables: High-res surface height. Possible Measurement Approach: Swath or multi-beam altimetry in several frequencies. Links of thought: ice -ocean-atmosphere, beyond-ICEsat2, observation suite Themes I, IV, V.
29	Measuring the variability and changes of the global water distribution and balance	We stress the importance of measuring time variable gravity to answer a diverse range of Earth system science questions related to furthering our understanding of the global water cycle.

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
30	Severe Storms	We discuss the need for time-continuous observations of severe convective storms - tropical cyclones, mesoscale convective systems, explosive extratropical cyclones - to improve modeling and prediction. Our focus is on storm-scale thermodynamic and kinematic processes and interactions with the environment at 10 km to 1000's and minutes to weeks.
31	High resolution atmospheric temperature and water vapor observations to improve drought and vector borne disease predictions and weather forecasting	How are local near-surface atmospheric temperature and humidity controlled by fine-scale variations in emissivity and topography? High-resolution hyperspectral infrared observations can provide surface and atmospheric quantities. These drive processes relevant to agricultural, human health monitoring, drought, fire and weather forecasting.
32	Air-Sea Exchange Drivers of Climate Variability, Ocean Circulation and Weather: A Case For Coincident Observations of Ocean Surface Winds and Currents	Contemporaneous, global, collocated observations of ocean surface currents (including ageostrophic components) and surface winds are achievable and poised to provide the next major step in understanding dynamics of the upper ocean and its coupling to the atmosphere, thereby improving and constraining future models of climate variability and change.
33	Mobilizing Philanthropy and Public-Private Partnerships for Earth & Space Science Missions and Research	We encourage ESAS 2017 to include philanthropic funding and public-private partnerships in its programmatic planning and advocacy. A coordinated basic research initiative, similar in scale to the Breakthrough Energy Coalition's recent multi-billion dollar pledge, could have profound impacts on the Earth system science research enterprise.
34	Observational Requirements for Global Land Use and Land Change Studies	Presents the science context, measurement requirements, and instrumentation options for improved monitoring of land use/cover dynamics, and highlights the opportunity for a "30m MODIS" capability to characterize vegetation phenology at the scale of land management.
35	Methane Lidar (MELI): Observing in Challenging, Critical Source Regions	Current methane observations are not sufficient to constrain its global and regional sources or explain atmospheric trends over the last few decades. Active remote sensing measurements of atmospheric methane are needed at high latitudes in all seasons, in the presence of clouds and aerosols to complement observations from existing sensors.
36	Long-Term Low Frequency Microwave Observations for Environmental Applications and Climate Assessment	Continuity of information about the components of the terrestrial water cycle, particularly soil moisture, is important in addressing the question of future water availability. However, there are no known commitments from any space agency to continue L band passive microwave imaging capability beyond the SMOS and SMAP missions.
37	A look into the physical properties of oceans: Response to the 2017 NRC Decadal Survey Request for Information	Temperature and salinity are two of the most important properties defining the state of seawater. An instrument capable of deriving vertical profiles of temperature of the world's ocean quickly and repeatedly would significantly advance our current knowledge of the ocean dynamics.
39	Thermodynamical Structure Within Precipitation	To better understand when and how precipitation evolves from the large scale environmental conditions of evolving weather systems, it is important to track the moist thermodynamic state within precipitating cloud systems over an extended period of time.

continued

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
40	Improved Observation and Characterization of Stratospheric Aerosols	Uncertainties in characterizing stratospheric aerosols limit the accuracy of direct radiative forcing in climate models. Improved spatial and temporal sampling would benefit these models and short-term forecasts following volcanic injections. A focused small satellite observational system can be developed at low cost to provide this information.
41	Low Clouds: Drivers of Climate Sensitivity and Variability	Low clouds determine: (1) Uncertainty in climate sensitivity. (2) Southern Ocean SW biases. (3) The double ITCZ bias. (4) Subseasonal predictability of tropical precipitation. We suggest observations to address these issues: (1) More accurate cloud properties. (2) Links between cloud properties and atmospheric state. (3) Long high quality records.
42	Global 3D Wind Measurements Derived from Hyperspectral Infrared Sounders to Improve Weather Forecasts	Our topic addresses the need to improve weather forecasting by providing a more complete representation of the global tropospheric wind field utilizing affordable and space-proven technology and algorithms.
43	High Revisit Meteorological Observation of the Arctic to Improve Weather Forecasts	Our topic addresses the need to improve weather forecasting in the Arctic by providing high revisit meteorological observations of the Arctic from space.
44	High Revisit Hyperspectral Infrared Measurements to Improve Weather Forecasts	Our topic addresses the need to improve weather forecasting by providing high revisit, high spectral resolution meteorological observations from space.
45	Detecting atmospheric temperature, humidity, and cloud property changes using an average-then-retrieve approach	We describe a retrieval method suitable for trend and change detections using spectral radiances observed from satellites. Properties to be retrieved include temperature and water vapor mixing ratio vertical profiles, surface skin temperature, cloud fraction, optical thickness, cloud height, and particle size.
46	Dynamic Coupling of Earthquakes and Tsunamis to Ionosphere	The ionosphere-based sensing of natural hazards such as earthquakes and tsunamis is remarkably useful because the combination of ground-based and spaceborne sensing allows scientists to characterize earthquake-tsunami coupling processes and better understand tsunami generation and their earthquake sources.
47	Carbon and Climate: Quantifying CO_2 Sources and Sinks from Space With Low Bias and High Space-Time Representation	A lidar-based CO_2 space mission to quantify the current global distribution of CO_2 terrestrial and oceanic sources and sinks with sufficient accuracy and spatiotemporal resolution and coverage to attribute them to specific biogeochemical processes.
48	Continuity of Air-Sea Climate Variables	We propose continuing the 3 decades of air-sea climate variables measured by satellite microwave sensors. These variables are through-clouds sea-surface temperature, ocean vector winds and stress, total water vapor and cloud water, and precipitation. The proposed sensor also measures sea-ice extent/concentration/age and snow cover over land.
49	Lidar-Optical Fusion for High-resolution Measurements of Ice and Vegetation Change	This proposal outlines measurement requirements for cryosphere and ecosystem science objectives using a combination of lidar and optical measurements from a single space-based observatory.
50	Evapotranspiration: A Critical Variable Linking Ecosystem Functioning, Carbon and Climate Feedbacks, Agricultural Management, and Water Resources	This White Paper describes Evapotranspiration (ET) in the context of the Decadal Survey RFI #2—science & application targets, utility of the measured geophysical variable, quality requirements, and affordability.

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
52	Quantifying aerosol-cloud interaction processes with high spatiotemporal resolution measurements from space	We recommend a strategy for making significant progress in quantifying aerosol-cloud interactions and their environmental effects. It focuses on cloud and aerosol regimes with an integrated observing system, including high spatiotemporal resolution observations from space complemented by arrays of ground-based networks and airborne measurements.
54	Benefits of lower troposphere, low-bias, high-density CO_2 measurements for determination of sources and sinks of CO_2	Science target is evaluation of CO_2 sources and sinks using space-based pulsed 2-micron CO_2 lidar measurements to improve understanding of carbon-cycle processes in critical regions. This has a direct benefit within Climate Variability and Change: Seasonal to Centennial and Marine and Terrestrial Ecosystems and Natural Resource Management themes.
55	Integrating a Doppler Wind Lidar into a network of wind observing systems: capitalizing on synergisms with a high precision, cloud penetrating lidar	NWP has an ongoing unmet need for 3D winds. A logical pathfinder mission would investigate off-nadir cloud effects and requires high accuracy and resolution. Coherent lidar offers synergisms with other wind measurements, maturity for space, and potential international collaborations to reduce NASA's cost.
56	Monitoring Coastal and Wetland Biodiversity from Space	Actionable knowledge to guide the sustainable use of resources from wetlands, coastal and marine aquatic habitats, and ice-edge environments around the world, and to promote resilient coastal communities, requires ocean-color quality spectral data of several hundred select targets around the world every 3 days or less, at 30 m spatial resolution.
57	Monitoring ice sheets and sea ice: The need for satellite altimetry data in the coming decades.	Here we describe a set of science goals for understanding changes in ice sheets and sea ice, and describe a set of measurements that will meet these goals. We propose that laser altimetry measurements provide the best chance to meet these goals and conclude that the heritage of NASA technology will make this mission reliable and affordable.
58	Connecting Plate Boundary Processes to Earthquake Faults using Geodetic and Topographic Imaging	Large earthquakes cause extensive loss of life and property. Remote sensing provides measurements of transient and long-term crustal deformation, which are needed to improve our understanding of earthquake processes. This white paper recommends topographic imaging in the necessary context of geodetic crustal deformation measurements.
59	Passive spaceborne measurements of height-resolved atmospheric winds	Atmospheric winds are critical to weather and climate. To provide height-assigned global wind vectors with the required accuracy and coverage, a constellation of tandem platforms carrying compact multiangle imagers is envisioned. The passive concept uses flight-proven hardware and data processing methods, providing high affordability and heritage.
60	The Boundary Layer Gap over Land and Importance of Improved Retrieval from Space	The PBL remains a major gap in our observational suite and is therefore a limiting factor in Earth System Science and weather and climate understanding and prediction. This paper discusses the potential ways forward in terms of PBL thermodynamic profile, PBL height, and entrainment flux retrieval from space.
62	Infrared Radiance Intercalibration for Climate Quality Products and Benchmarking	Many infrared satellite radiance and derived products can be greatly improved through intercalibration with observations from a potential mission/sensor aimed at providing radiance products with unprecedented accuracy, verified using on-orbit international standards.

continued

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
63	Space-based Measurements to Quantify Anthropogenic CO_2 and CH_4 Emissions	This paper outlines the justification and strategy for measurements to quantify anthropogenic CO_2 and CH_4 emissions from urban areas or large point sources. Multiple GEO X_{CO2} and X_{CH4} missions are needed as the foundation of a constellation, which would include already planned LEO missions from NASA and other agencies.
64	Anthropogenic and lithospheric process interactions	Anthropogenic processes from water, petroleum, and geothermal production cause important interaction with the solid Earth and impact human infrastructure. Global observations of mass and fluid volume changes are needed to understand these process interactions. We recommend gravity, surface motion, and subsurface reservoir imaging measurements.
65	Water beneath the land surface: The holy grail of hydrologic science	This RFI response addresses "subsurface water storage" in the context of Theme I: Global Hydrological Cycles and Water Resources. A continuing global record of changing subsurface water storage is necessary for better understanding of hydrologic extreme events, monitoring of global water resources, and evaluation of global land-surface models.
66	Science and Application Targets Addressed with the 2007 Decadal Survey HyspIRI Mission Current Baseline	New and important science and application targets, in this time of rapid environmental change, that are addressed with the evolved 2007 Decadal Survey HyspIRI mission concept with combined global 16 day revisit imaging spectroscopy and 4 day revisit thermal multispectral measurements.
67	Quantifying Mass Change Components of Land Ice and Sea Ice	The cryospheric community advocates for a multi-sensor mission that includes a Lidar capable of precise topographic and bathymetric mapping and a wide-bandwidth dual-frequency radar to reduced uncertainties in future ice mass loss and sea level rise.
68	Inland Waters	Measurement needs for inland waters.
69	Coral Reefs: Living on the Edge	Coral reefs are a vital resource, but they are threatened by humans at both local and global scales. In-water methods have allowed study of very little reef area. Satellite remote sensing is the only possible method to gather the necessary data on reef condition at regional to global scales. Space-borne imaging spectroscopy is a feasible course.
70	A Thermodynamic Paradigm For Using Satellite Based Geophysical Measurements For Public Health Applications	This whitepaper describes the rationale satellite based geophysical measurements for three public health applications; vector borne diseases, impact of urbanization and harmful algal blooms (HABS) and addresses area III.
72	Global Wind Profiles will Advance Cross-Cutting Earth Science	Observing system simulation experiments have shown conclusively that the addition of space-based global wind profiles to the current observing network will improve weather forecasting and advance science across multiple Earth System Science themes. A space-based Doppler wind lidar able to provide the needed observations is doable and affordable.
73	Groundwater Recharge and Evapotranspiration: Fluxes at the Interface of Water, Energy, Biogeochemical and Human Systems	This white paper presents the case for developing new measurement capabilities for characterizing global recharge and evapotranspiration—two fluxes that are simultaneously key components of the water cycle and poorly monitored.

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
74	Establishing a global benchmark of the current climate from space	We advocate for establishing a global benchmark of the current climate from space using highly accurate measurements of spectrally resolved Earth emitted brightness temperature (<0.1 K k=3), verified frequently with an SI standard on-orbit. Commitment to an IR Pathfinder closely followed by a full CLARREO mission will have large societal value.
75	Monitoring and measuring disaster resiliency of social and built environments in the coastal zone using remote sensing observations	Spaceborne observations provide synoptic and time-critical situational awareness to responders and decision makers during a disaster, and long-term assessment and evaluation of changes and impacts resulting disasters. A key target for hazard assessment is quantifying growth and vulnerability of infrastructure and megacities to multiple hazards.
76	Geophysical and Anthropogenic Drivers of Coastal Subsidence and Land Loss	We discuss determination of subsidence rates in wetlands and agricultural lands sufficient to differentiate the heterogeneous mix of geologic and anthropogenic driving mechanisms. We evaluate requirements for accuracy, coverage, and frequency of remote sensing observations necessary to make a significant improvement on the global scale.
77	Global Precipitation Observations to Advance Water/Energy Cycle, Climate, Model, and Disaster Science	Provide a 30-year record of high-quality daily and sub-daily precipitation for water/energy cycle closure, global change detection, climate and numerical weather forecast model evaluations, and flood and landslide analysis.
78	Linkages of salinity with ocean circulation, water cycle, and climate variability	This white paper addresses the enhancement of capability for space-based measurements of global sea surface salinity (SSS) and sea ice thickness to study the linkages of ocean circulation with the water cycle and climate variability, as well as to facilitate biogeochemistry research.
79	Multidisciplinary Earth System Science: An Approach to Enhance Value from Passive Microwave Earth Observing Satellite Sensors	Strategic planning, support, and sharing of limited-resource satellite data both for those currently in orbit and future missions, particularly conically scanning passive microwave sensors, applicable across all relevant scientific disciplines.
80	The critical need for continued measurements of the upper troposphere and stratosphere to improve predictive capability for climate and air quality	We review outstanding science questions for Earth's upper troposphere and stratosphere and discuss critical needs for high vertical resolution measurements to address them. We emphasize the anticipated "gap" in such measurements in the coming decade, highlighted in international assessments, and note new capabilities enabled by NASA investments.
81	Quantifying Truly Global Aerosol Direct Radiative Effects	Observational global estimates of the aerosol direct radiative effect are still unknown to within a reasonable degree of certainty. This white paper discusses how a future space-based high spectral resolution lidar (HSRL) would nearly eliminate bias that exist in current estimates.
82	Topography, Vegetation Structure, Water Surface and Snow Depth Mapping for Multi-disciplinary Earth Science and Applications Objectives	Knowledge of the vertical structure of the Earth's surface and its change is of critical importance for a diverse array of science and applications objectives. This white paper focuses on global mapping of ground surface topography, vegetation height and structure, inland water surface height and snow depth with high resolution and accuracy.

continued

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
83	The ACE Lidar-Polarimeter Concept to Reduce Uncertainties in Direct Aerosol Radiative Forcing With Applications to Air Quality & Atmospheric Dynamics	We describe the NASA ACE measurement concepts that: 1) enable the reduction of uncertainties in aerosol radiative forcing, 2) directly address air-quality and human health, and 3) help quantify the impact of absorbing aerosols on atmospheric dynamics and thermodynamics and the effects on monsoonal circulations and the global hydrological cycle.
84	Ice Dynamics from Space	This paper is about understanding and quantifying glacier and Ice Sheet dynamics for improved sea level projections.
85	Measuring the Earth's Surface Mineral Dust Source Composition for Radiative Forcing and Related Earth System Impacts	Mineral dust impacts direct & indirect forcing, tropospheric chemistry, ecosystem fertilization, human health & safety. Global source composition is poorly constrained by <5000 mineral analyses. Global spectroscopic measurement of surface mineralogy closes this gap to advance understanding & Earth system modelling of current & future impacts.
87	Remote Sensing of Sea Surface Salinity with enhanced capabilities in Coastal Zone and Cold Water	We propose a sea surface salinity mission to 1/ provide continuity of global SSS monitoring and 2/ improve measurements closer to land and ice, and in cold waters. The mission will enhance the capabilities to monitor the processes of the littoral zone and the changes due to the melting of ice sheets and other changes in high latitude climate.
88	The ACE Measurement Concept for Reducing Uncertainties in Climate Sensitivity and Understanding Cloud-Aerosol Interactions	Knowledge of the climate sensitivity of the earth has ranged between roughly 1.5 and 6 Kelvins for two decades. The source of this uncertainty has been traced to simulations of marine boundary layer clouds. We discuss a measurement suite concept that aims to significantly reduce the spread in climate sensitivity uncertainty.
89	Reducing Uncertainty in Climate Sensitivity by Constraining SW Cloud Feedback Uncertainty	Reducing uncertainty in equilibrium climate sensitivity by a factor of 2 by reducing trend uncertainty in cloud properties can be accomplished with SI-traceable calibration sensors in orbit.
90	Global Measurement of Non-Photosynthetic Vegetation	We propose global seasonal measurement of non-photosynthetic vegetation (NPV) cover. NPV measurements are needed to quantify vegetation response to climate variability and a wide range of ecosystem disturbance, crop residue and susceptibility to erosion, and forage conditions. The technology required for global NPV mapping is currently available.
91	Global Terrestrial Ecosystem Functioning and Biogeochemical Processes	A global imaging spectroscopy mission will provide unique and urgent quantitative measurements of vegetation functional traits and biochemistry that are not currently available. Narrowband VSWIR measurements will close major gaps in our understanding of biogeochemical cycles and improve representation of vegetation in Earth system process models.
92	Maintaining and Improving Upper Air Temperature Records	The white paper demonstrates the importance of a mission to directly measure the diurnal cycle of the upper air temperature, and proposes an inexpensive mission based on precessing microsatellites to make the required measurements in concert with existing operational satellites.
93	Characterizing evapotranspiration, ecosystem productivity and water stress to address global food and water security	To achieve further understanding of the impact of stress on ecosystem productivity and water availability, simultaneous measurements across the electromagnetic spectrum are needed. Remotely-sensed evapotranspiration can provide land surface models with observations of evaporative stress to improve simulations on climate, carbon and water cycling.

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
94	Redeveloping the Lunar Reflectance as a High-accuracy Absolute Reference for On-orbit Radiometric Calibration	This paper describes the refinements needed to enable using the Moon as an SI-traceable absolute radiometric reference for on-orbit calibration of reflected solar band sensors. With advances in measurements of the lunar reflectance from space, lunar calibration can provide the accuracy and consistency needed to detect climate change signatures.
95	Change in Continental Water, Solid Earth's Elastic Response, and Impact on Sea Level	To determine changes in the availability of freshwater resources due to mankind's activity, we advocate gravimetric measurements of mass change and accurate and high-resolution measurements of displacements of solid Earth's surface in elastic and porous response to water change.
96	Systematic Aircraft Measurements to Characterizing Aerosol Air Masses	Systematic aircraft in situ measurements in a modest operational program can add value to the existing and future satellite aerosol data record, by resolving key limitations in their application to climate and air quality issues.
97	Quantifying the Magnitude and Uncertainty in Feedbacks between Arctic Clouds and the Arctic Climate System	Quantifying the magnitude and uncertainty of Arctic cloud-climate feedbacks will reduce uncertainty in Arctic climate . Continuation of the collocated satellite lidar-radar record with technological advancements and a coordinated, synergistic use of satellites, ground sites, and focused field campaigns are needed to address our science target.
98	Constraining Atmospheric Ice Processes with Coincident Measurements of Ice Mass and Cloud Vertical Motion	Advancing capabilities for observing and predicting the coupled hydrological cycle and energy balance responses to environmental forcings through coordinated multi-frequency Doppler radar and sub-millimeter radiometer measurements of ice mass, vertical motion, and precipitation.
99	Quantum Gravity Gradiometer and the Next Generation Gravity Mission	The focus of this white paper is to propose a Quantum Gravity Gradiometer based on atomic interferometry as the technological observational path to making significant time variable gravity measurement improvements in the coming decade.
100	Water Vapor and Lapse Rate Feedbacks - Reducing Uncertainty With New Measurements	We describe the need for reduction in uncertainty in knowledge of the absolute magnitudes of water vapor and lapse rate feedbacks. This knowledge is essential to reduce the uncertainty in climate sensitivity. New, accurate, SI-traceable temperature and moisture vertical profiles and measurements of top-of-atmosphere infrared spectra are required.
101	Measuring critical changes in ice and snow thicknesses in time and space	Paper describes the following geophysical parameters and argues for the importance of measuring them from space to complement sub-orbital observations: Ice sheet thickness and bed topography Ice sheet basal conditions Ice sheet internal layers Ice sheet snow accumulation Ice shelf thickness changes/marine ice extent and thickness Sea ice snow thickness.
102	Comprehensive Imagery for Water Resource Management	Our paper addresses the need to support the full characterization and understanding of regional to local water supply and demand within the context of global water availability, utilizing affordable and space-proven technology and algorithms.
103	High frequency measurements of coastal regions to improve predictive understanding of coastal oceans, protect ecosystems, & enhance economic activit	Understanding coastal dynamics requires frequent high-quality coastal ocean color observations, which can only be obtained from a sensor in geostationary orbit. Such observations would, for the first time, capture coastal dynamics from space and obtain actionable knowledge for protecting ecosystems and the sustainable management of resources.

continued

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
104	Addressing Major Earth Science Challenges in Cloud and Precipitation Process Modeling	Water is necessary for life on Earth, thus knowing where, when and how clouds form, and whether they precipitate or not, is vital for all civilization. We must observe the underlying cloud processes globally and locally that produce precipitation to inform and improve the next generation of climate and numerical weather prediction models.
105	Permafrost Active Layer Dynamics represent a Critical Climate Feedback requiring Space-based Measurements	This white paper addresses the key question of "What are the spatial distributions and temporal dynamics of permafrost soils and what are their feedbacks to/from the regional and global climate?" The topic is of principal relevance to the panel for "IV. Climate Variability and Change: Seasonal to Centennial." It is also relevant to panels I & III.
106	The Long-term Challenge of Detecting Unambiguous Trends in Stratospheric Temperature	Quantified Earth Science Objective: Measure the global, annual temperature trend in stratospheric layers to better than 0.1 K/decade at the 95% confidence level in the lower (30 km), middle (40 km), and upper (45 km) stratosphere with layer thicknesses of 10 to 15 km.
107	Enabling measurement of groundwater distribution and dynamics in arid regions using subsurface radar imaging	Simultaneous spatial and temporal large-scale systematic remote-sensing of arid and semi-arid groundwater is needed at sufficiently high frequency and resolution to map the distributions of groundwater and fresh water flow, and to observe the water cycle process driving the recharge and discharge of young aquifers in these regions.
108	Investigating the coupled stratosphere-troposphere system with an advanced infrared limb sounder	This RFI describes an IR limb sounder that addresses climate-chemistry-radiation-dynamics science themes & questions from the mid-troposphere through the stratosphere. The instrument, based upon Aura HIRDLS, would be low cost, & make high vertical resolution, global profiles of temperature and a large number of chemical species on a daily basis.
109	Rate Processes and Fluxes of Marine Biogeochemical Cycles, Ecosystem Functioning, and Natural Resources	High temporal frequency (sub-diurnal) ocean color measurements to derive open ocean and coastal ocean primary production, carbon stocks, export production and phytoplankton community composition are needed to better constrain the magnitude and uncertainties in marine ecosystem climate change responses and feedbacks and improve application models.
110	Earth Surface Geochemistry and Mineralogy: Processes, Hazards, Soils, and Resources	New spectroscopic measurements of the Earth's exposed surface to derive mineralogy are required to address key science and application targets. These measurements will advance understanding of fundamental geological processes, natural and anthropogenic hazards, soil geochemistry and evolution, and the location of energy and mineral resources.
111	Space-based Global Assessment of Aerosol Impacts on Human Health Associated with Specific Pollution Sources in a Changing World	Understanding the global distribution of specific airborne particulates and the associations between specific particle types and health impacts is critical because different types of particles originate from a variety of sources, and intervention and emission control strategies need to be prioritized to maximize protection of human health.
112	Enabling global measurement of the distribution and dynamics of deep groundwater and magma systems via resonance radar imaging	Global sensing of the distribution and dynamics of deep groundwater and magma systems from space via resonant electromagnetic scattering of waves, instead of high frequency pulses as used in sounding radars today which operate based on geometrical optics scattering of a wideband signal and which cannot penetrate deep in lossy mediums.

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
113	Understanding the Mechanics of Faults and Fault Systems	Faults have many responses to stress, from slow creep to rapid earthquake ruptures. Measurement of 3D surface motion over fault systems around the Earth will enable understanding of spatial and temporal properties of faults and surrounding rocks, critical for forecasting their behavior, including location and probability of future earthquakes.
114	Biodiversity	Biodiversity is changing rapidly across the globe. There is an urgent need for an integrated global observing system designed to quantify biodiversity on Earth and detect change through time to better understand the pace and consequences of this changes, and how to manage it.
115	The role of fire in the Earth System	We describe the role of fire in the earth system from indirect and direct effects of greenhouse gases and aerosols to changes in the land surface. In this RFI we identify the fire community's needs to both advance understanding of the role of fire in the Earth system and that are relevant to fire applications science.
116	Wetlands: a key component of the water cycle and driver of methane emission	The excessive uncertainty in methane emissions (ME) from wetlands limits acceptable climate change projections. The hypothesis is that wetlands play a major role in ME, and their dominant pathways are yet to be determined. The rapid rate of wetland collapse demands urgent attention, both for ME and for the impact to water cycle assessments.
117	Constraining Climate Sensitivity Using Satellite Humidity Observations	This white paper explains why the Earth Science community must invest on improving current state-of-the-art water vapor measurements and describes the science requirements needed. It suggests possible ways to achieve this task by current and future space-based platforms. Measuring the fine spatial structures of water vapor is key to reducing ECS.
118	The Importance of Kilometer-Scale Soil Moisture Observations to Terrestrial Hydrology	We focus on the scientific benefits of kilometer-scale soil moisture observations, which are important to understanding the soil moisture-precipitation feedback, a fundamental land surface-atmosphere interaction. Ground-reflected Global Navigation Satellite System signals received from satellite may be able to provide the needed observations.
119	Long-term Observations of Tropopause Parameters for Climate Change Detection and Model Assessments	Long-term temperature observations with high vertical resolution, accuracy, and stability are sorely needed to address key climate objectives relating to future changes in large-scale circulation and stratospheric water vapor concentration. The science objectives can be met affordably with a sufficient number of GNSS-RO receivers in space.
120	Ozone Impacts on Crop and Ecosystem Health	Tropospheric ozone reduces crop production, alters forest productivity and carbon storage, and may drive changes in plant species distributions and biodiversity. This white paper describes the need for measurements that will substantially improve our quantification and understanding of ozone damage to crops and ecosystems at large scales.
121	Narrowing Uncertainty in Climate Sensitivity	Equilibrium Climate Sensitivity (ECS) remains the largest uncertainty in estimating future economic impacts of climate change. This uncertainty is driven by uncertainty in cloud feedback. More rapid reduction of ECS uncertainty requires improved accuracy of decadal change of shortwave cloud radiative forcing. New approaches are described.

continued

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
124	A rigorous and efficient ground truth strategy to evaluate satellite greenhouse gas measurements using commercial aircraft	Accurate vertical profile measurements of CO_2, CH_4, and H_2O from commercial aircraft would provide uniquely valuable and cost-effective ground truth data for current and new space-based greenhouse gas missions using a wide variety of approaches. We propose new infrastructure to firmly establish long-term continuity of greenhouse gas measurements.
125	Assessing Transient Threats and Disasters in the Coastal Zone with Airborne Portable Sensors	Assessing threats and hazards in the coastal zone requires high temporal, spatial, and spectral resolution imagery from portable airborne sensors. A fleet of well-equipped drones that could be deployed to respond to immediate threats and hazards along the U.S. coastal zone with imaging spectrometers, fluorescence and bathymetric lidars.
126	Improved retrievals of cloud condensation nuclei (CCN) number concentration over the ocean to reduce indirect forcing uncertainties in climate models	We propose that satellite retrieval of CCN number concentrations within a factor of two of the measured values are required to constrain anthropogenic aerosol indirect effect in climate models. Such high accuracy in CCN retrievals can be achieved by the most capable High Spectral Resolution Lidar that is envisioned for the NASA ACE mission
127	Constraining Upper Bounds On Global Sea Level Rise Over The Next Century	This white paper attempts to provide an affordable, prioritized, list of cross-cutting geophysical measurements that are most important for constraining the upper bound of sea level rise projections.
128	The Pressing Need for Reactive Nitrogen Measurements for Space	A geostationary satellite mission for North America over the next decade providing information on the temporal variability of reactive nitrogen is critical for addressing ecosystems, food security, air quality, and climate management needs.
129	Reducing Current Uncertainties in Cloud-Climate Feedbacks with Space Lidar	Nearly a decade of observation by satellite-borne active sensors have transformed our understanding of the vertical distribution of condensate and are central to advancing understanding of the atmospheric energy budget, the coupling of clouds to circulation and the response of clouds to warming (i.e., cloud feedbacks).
130	USGS RFI Response for the ESAS 2017 Decadal Survey for Earth Science and Applications from Space	USGS RFI response for water topic area based on 2015 USGS value tree information elicitation.
131	USGS RFI Response for the ESAS 2017 Decadal Survey for Earth Science and Applications from Space	USGS RFI response for ecosystems topic area based on 2015 USGS value tree information elicitation.
132	USGS RFI Response for the ESAS 2017 Decadal Survey for Earth Science and Applications from Space	USGS RFI response for geology and hazards topic area based on 2015 USGS value tree information elicitation.
133	Understanding Snow Cover and its Role in Providing Water for Life and a Habitable Climate	The seasonal blanket of snow that covers land, sea ice, and glaciers drives global climate and is the main source of freshwater run-off for billions of people. Here we describe a multi-sensor approach to obtaining higher resolution and more accurate distributed fields of snow water equivalent for water management, modeling and climate studies.
134	Atmospheric Boundary Layer Thermodynamic Structure: Blending Infrared and Radar Observations	To solve key weather and climate ABL challenges, there is an urgent need for more accurate observations of ABL water vapor and temperature structure. This can be achieved in the next 10 years by investing in an optimal combination of (i) higher resolution IR sounding in clear sky with (ii) water vapor radar profiling within clouds.

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
135	Toward a Next-Generation Global Observing System for Air Quality	Air pollution is responsible for ~3.7 million premature deaths worldwide. This white paper describes the measurements needed to reduce the end-to-end uncertainty of the global air quality monitoring and prediction system, from emissions attribution, to transformation in the atmosphere, to exposure and climate forcing.
136	Understanding glaciers and ice sheets response to changes in atmosphere and ocean conditions	Desired geophysical observations for improving understanding of glacier and ice sheet processes relevant to improving projections of sea level change. The three key variables identified are repeat measurements of surface velocity, gravity and elevation.
137	Cross-cutting Applications of Vertically Resolved Optical Properties to Reduce Uncertainties in Atmosphere and Ocean Earth System Processes	Several submission to RFIs #1 and #2 call for vertically resolved atmospheric and/or oceanic measurements of particulate backscatter, extinction, depolarization, and speciation. This paper identifies measurement requirements common to several submissions and explains the range of lidar capabilities required for these cross-cutting applications.
138	Understanding the controls on cryospheric albedo, energy balance, and melting in a changing world	The distribution and quantification of forcings controlling accelerated melting of snow and ice are poorly known. We must measure with optical spectroscopy the grain size and radiative forcing by impurities with the accuracy and precision of which we understand the distribution of present GHG warming.
140	Predicting Changes in the Behavior of Erupting Volcanoes, and Reducing the Uncertainties Associated with their Impact on Society and the Environment	Satellite observations allow us to characterize the complexity of terrestrial volcanism on global scales. Improvements in the spatial, spectral, and temporal resolution of space-borne instruments will enable improved forecasts of when eruptions begin and end, and how volcanic hazards impact lives at global, regional, and local scales.
141	Dynamics of Canopy to Root-zone Water Content Predicting Forest Ecosystem Vulnerability to Water Stress	Forest ecosystems are vulnerable to water stress that are projected to intensify in future climates. Here, we propose frequent global measurements of water status in soil and vegetation as an imperative observational strategy for the coming decade to predict and to mitigate the vulnerability of terrestrial ecosystem to climatic stress.
142	The Ocean Surface Boundary Layer: Remote Profiling To Improve Air-Sea Exchange Quantification And Forecasting Of Climate, Weather & Ecology	Recent advances in LiDAR technology make feasible remote Ocean Surface Boundary Layer (OSBL) turbulence, temperature, and salinity profiling capabilities. Proposed observations will lead to significant progress in multiple areas of research. Development of an airborne campaign can be achieved in the 2017-2027 time frame.
143	Understanding Clouds & Their Interactions with Aerosols: Bridging Gaps with Airborne Programs, Next-Gen Satellite Sensors & Novel Retrieval Algorithms	Representations of clouds and their interactions with aerosols in GCMs are major sources of uncertainty in predicting climate change. To address this stubborn issue, we need to map aerosol-cloud systems in 3D using well-designed sensors, space-based & airborne, and whole new class of algorithms to process their signals into key physical quantities.
144	Temporally-Resolved Observations of Cloud Processes and Precipitation	We address temporally resolved observations of cloud processes that lead to precipitation. Improvement of parameterization in global climate models is essential to improve understanding of climate variability and change. Temporal sampling of convective precipitation with 5 minutes resolution can be achieved with a 5-nanosatellite constellation.
145	Understanding anthropogenic methane and carbon dioxide point source emissions	We propose a tiered observational strategy focused on methane and carbon dioxide point source fluxes at fine-space time scales sufficient to detect, quantify and attribute them to address key earth system science questions and provide timely information to decision makers.

continued

TABLE D.1 Continued

RFI Response Number	Response Title	Summary Description[a]
146	Global Observations of Coastal and Inland Aquatic Habitats	The proposed Quantified Earth Science Objective (QESO) is to inventory and assess coastal and inland aquatic habitats, which are extremely important and are very vulnerable to global anthropogenic pressures and climatic change. Multiple orbiting and airborne platforms may be needed to get complete picture of how these vital resources are changing.
147	Remote sensing of marine debris to study dynamics, balances and trends	Marine debris has become one of the most urgent global environmental problems. We argue that only remote sensing can provide a global and uniform observing system to deal with the problem. Most of the necessary technologies already exist but their parameters and output formats need to be adjusted to provide the useful data on marine debris.
148	The Role of Global Lightning Detection in Earth System Science	Continued and improved satellite observations of global lightning are needed to monitor weather and climate-forced changes in regional to global-scale deep convective cloud properties, associated impacts on atmospheric composition, and as a means to detect and monitor changes in extreme storms and wildland fire ignitions.
149	Carbon Emissions from Biomass Burning	Measurement needs for calculating carbon emissions from biomass burning.
150	Enabling a global perspective for deterministic modeling of volcanic unrest	The biggest challenge to volcano science is understanding how magma systems evolve before volcanoes erupt. Remote sensing of precursor emissions to bound physics-based predictive models is dramatically more effective when atmospheric water is accounted for. We recommend hyperspectral thermal infrared measurements to lift the water veil.
151	3D Vegetation Structure and Dynamics	In this white paper we propose to measure fine-scale 3D forest structure and its rate of changes over time using radar technology to (1) understand future trajectories of atmospheric carbon dioxide, (2) elucidate how climate is evolving and affecting Earth's biodiversity, and (3) assess how Earth's forests are changing due to human activities.

[a] Each person submitting a response to the request for information was required to provide a summary description. These descriptions are provided here unedited.

E

Statement of Task

The National Research Council will appoint an ad hoc committee and supporting panels to carry out a decadal survey in Earth Science and Applications from Space. The study will generate recommendations from the environmental monitoring and Earth science and applications communities for an integrated and sustainable approach to the conduct of the U.S. government's civilian space-based Earth-system science programs.

The survey's prioritization of research activities will be based on the committee's consideration of identified science priorities; broad national operational observation priorities as identified in U.S. government policy, law, and international agreements (for example, the 2014 National Plan for Civil Earth Observation) and the relevant appropriation and authorization acts governing NASA, NOAA, and USGS; cost and technical readiness; the likely emergence of new technologies; the role of supporting activities such as in situ measurements; computational infrastructure for modeling, data assimilation, and data management; and opportunities to leverage related activities including consideration of interagency cooperation and international collaboration. The survey committee will work with NASA, NOAA, and USGS to understand agency expectations of future budget allocations and design its recommendations based on budget scenarios relative to those expectations. The committee may also consider scenarios that account for higher or lower than anticipated allocations.

During this study, the committee's primary cross-cutting tasks will be:

1. Assess progress in addressing the major scientific and application challenges outlined in the 2007 Earth Science Decadal Survey.
2. Develop a prioritized list of top-level science and application objectives to guide space-based Earth observations over a 10-year period commencing approximately at the start of fiscal year 2018 (October 1, 2017).
3. Identify gaps and opportunities in the programs of record at NASA, NOAA, and USGS in pursuit of the top-level science and application challenges—including space-based opportunities that provide both sustained and experimental observations.

4. Recommend approaches to facilitate the development of a robust, resilient, and appropriately balanced U.S. program of Earth observations from space.
5. In addition the committee will conduct the following agency-specific tasks:
6. Recommend NASA research activities to advance Earth system science and applications by means of a set of prioritized strategic "science targets" for the space-based observation opportunities in the decade 2018-2027. (A science target in this instance comprises a set of science objectives that could be pursued and significantly advanced by means of a space-based observation.) The prioritization process will begin with the committee identifying the critical measurement capabilities associated with the science target. For each science target, the committee will then identify a set of objectives and measurement requirements/capabilities for space-based data acquisitions. If appropriate and usually only for recommendations associated with major investments, the committee will (via a Cost and Technical Evaluation "CATE" process) assemble notional proof-of-concept missions with the recommended capabilities in order to better understand the top-level scientific performance and technical risk options associated with mission development and execution. In addition:
    a. The committee will carry out its prioritization with a view towards minimizing mission development and acquisition costs and maximizing the role of competition in implementing flight recommendations.
    b. For each science target, the committee will establish the context, criteria, and justifications for its recommended prioritization, and identify scientific and/or programmatic developments of sufficient significance that they would warrant reexamination of the committee's recommendation.
    c. The prioritization process will include reconsideration of the scientific priorities associated with the named missions from 2007 Earth Science and Applications from Space Decadal Survey.
    d. In considering budget scenarios for NASA, the committee may consider scenarios that account for higher or lower than anticipated allocations. For NASA, the committee's recommendations will also include guidance on how to rebalance programs upon failure of one or more of the criteria/assumptions underpinning a mission recommendation.
    e. The committee may also identify potential interagency and international synergies; proposed augmentations to planned international missions; and adjustments to U.S. missions planned, but not yet implemented.
    f. The committee may comment on technology investments; new areas of research emphasis; or suborbital, ground, or in situ activities.

    For NASA, the committee will pay particular attention to prioritizing and recommending balances among the full suite of Earth system science research, technology development, flight mission development and operation, and applications/capacity building development conducted in the Earth Science Division (ESD) of the Science Mission Directorate. In particular, while making clear its assumptions regarding the overall scope of the NASA ESD program relative to the contributions of the mission agencies NOAA and USGS, the committee will make recommendations on:

    a. The target budgetary balance between Flight and Non-Flight aspects of the ESD portfolio;
    b. In the Non-Flight portion of the program, the target balance between R&A, Applied Science, and Technology elements;
    c. In the Flight element, the target budgetary balance between systematic/directed, and competed/cost/schedule-constrained mission programs;
    d. In the Flight element and considering overall resource constraints, the target budgetary balance between general mission-enabling investments (such as common spacecraft development, highly disaggregated constellations, etc.) and traditional focused single-mission developments;

   e. In the Flight and Technology elements, the degree that NASA investment decisions could be informed by NOAA and USGS operational satellite measurement objectives,;
   f. Expanding or modifying the present 3-strand Venture-Class competed program, including examining whether ESD should initiate additional or different Venture Class strands, possibly with different cost caps;
   g. Decision principles for balancing new measurements against time series extensions of existing data sets; and
   h. Any changes in scope(s) of the non-flight R&A, Applied Sciences, and Technology Development elements.

8. For NOAA and the USGS, which have a critical requirement for continuity of observations and delivery of services and information to the public and commercial sectors, the decadal survey committee's recommendations will be framed around national needs, including, but not limited to research priorities. The committee's recommendations for NOAA and the USGS will, as far as practicable, align with anticipated budgets at the relevant portion(s) of the agencies, with any deviations from those budgets clearly presented. Recommendations may be organized around 1) how new technology may enhance current operations, and 2) what new science is needed to expand current operations, either to enable new capabilities or to include new areas of interest. In making these recommendations, the committee will consider the need to bridge current operations and support a viable path forward for the uninterrupted delivery of public services through these generational changes. In particular, the committee:
   a. Will, with the expectation that the capabilities of non-traditional providers of Earth observations continue to increase in scope and quality, suggest approaches for evaluating these new capabilities and integrating them, where appropriate, into NOAA and USGS strategic plans. The committee will also consider how such capabilities might alter NOAA's and USGS's flight mission and sensor priorities in the next decade and beyond.
   b. Will consider which scientific advances are needed to add to NOAA's future predictive capabilities. This includes taking into account the overlap and interdependencies between water, weather and climate, and encouraging the development of extended, and diversified forecasts. The committee will similarly consider advances needed to meet the needs of USGS science priorities and data users, for example advising on advances that can support both the natural resource management community and the climate research community.
   c. May offer recommendations concerning "research to operations" (or "innovation for continuity and service improvements across agencies"). For example, the committee may identify areas where NASA technology investments may lead to more efficient or effective NOAA and USGS missions by raising the Technology Readiness Level (TRL) of enabling technologies.
   d. Will consider the agencies' ability to replicate existing technologies to improve and sustain operational delivery of public services, and also to produce consistent and reliable science and applications data products across different generations of measurement technology, as new measurement innovations are introduced.

F

Committee Member and Panel Biographies

COMMITTEE ON THE DECADAL SURVEY FOR EARTH SCIENCE AND APPLICATIONS FROM SPACE

WALEED ABDALATI, *Co-Chair*, is director of the Cooperative Institute for Research in Environmental Sciences (CIRES), a joint institute of the National Oceanic and Atmospheric Administration (NOAA) and the University of Colorado, Boulder (CU Boulder). Dr. Abdalati is also a professor in the CU Boulder Geography Department. Dr. Abdalati's research focuses on the use of satellites and aircraft to understand how and why Earth's ice cover, particularly glaciers and ice sheets, is changing and what those changes mean for life on Earth. In 2011 and 2012, while on leave from the university, Dr. Abdalati served as National Aeronautics and Space Administration (NASA) chief scientist, advising the NASA administrator on science programs and strategic planning. Before that Dr. Abdalati directed the Earth Science and Observation Center at CU Boulder, where he led the NASA Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) Science Definition Team during its earliest stages of development. He has worked as a research scientist and branch head at NASA GSFC, managed the agency's Cryospheric Sciences Program, and spent time in private industry as an aerospace engineer. Dr. Abdalati has won numerous professional awards from the White House, NASA, National Science Foundation (NSF), and others. He has also been involved in several additional National Academies of Sciences, Engineering, and Medicine activities, including America's Climate Choices, the Committee on Geoengineering, and the Polar Research Board. Dr. Abdalati earned a B.S. from Syracuse University and an M.S. and a Ph.D. from CU Boulder.

WILLIAM B. GAIL, *Co-Chair*, is co-founder and chief technology officer of Global Weather Corporation, a provider of precision forecasts for weather-sensitive business sectors, and is a past president of the American Meteorological Society (AMS). Dr. Gail was previously a director in the Startup Business Group at Microsoft, vice president of mapping products at Vexcel Corporation, and director of Earth science programs at Ball Aerospace. Dr. Gail received his undergraduate degree in physics and his Ph.D. in electrical engineering from Stanford University, where his research focused on the physics of Earth's magnetosphere. During this period he spent a year as a cosmic ray field scientist at the South Pole Station. Dr. Gail is a fellow of the AMS and a lifetime associate of the National Academy of Sciences (NAS). He is the co-chair of the National Academies 2017 Earth Sciences Decadal Survey, serves on the National Academies Board on Atmospheric Sciences and Climate, and has participated on many prior National Academies committees, including the 2012 review of the National Weather Service (NWS) and the 2007 Earth sciences and applications from space decadal survey (ESAS 2007). He is a member of the U.S. Commerce Data Advisory Council and serves or has served on a variety of other editorial, corporate, and organizational boards. His book *Climate Conundrums: What the Climate Debate Reveals About Us* was released in 2014, and his opinion pieces have been published in the *New York Times*, *USA Today*, and elsewhere.

STEVEN J. BATTEL is the president of Battel Engineering, Inc. Mr. Battel has 38 years of experience as a consultant, an engineer, and a manager in multiple aerospace and scientific disciplines. His areas of specialization include program management, systems engineering, precision electronics design, scientific instrument design, spacecraft avionics, power systems technology development, technology assessment, and technology costing methods. He is a recognized expert on low-noise instrumentation, space power systems, and space high voltage systems, especially for high-voltage systems intended for operation in the Mars environment. He is a fellow of the American Institute of Aeronautics and Astronautics (AIAA), a member of the National Academy of Engineering (NAE), and a member of the NASA Engineering and Safety Council for both the Power and Avionics teams. He has also served as a Red Team or an Independent Review Team member for more than 70 NASA and NOAA missions, including multiple past and present Earth observing missions. He earned his B.S. in electrical engineering from the University of Michigan.

STACEY W. BOLAND is a systems engineer at the Jet Propulsion Laboratory (JPL), and is the project systems engineer for the International Space Station (ISS)-RapidScat and the Multi-Angle Imager for Aerosols (MAIA) Earth Venture Instrument. Previously, Dr. Boland served as the observatory system engineer for the Orbiting Carbon Observatory-2 (OCO-2) Earth System Science Pathfinder (ESSP) mission and as a member of the Project Systems Engineering team for the OCO. She is also a cross-disciplinary generalist specializing in Earth mission concept development, mission architecture development for advanced (future) Earth observing mission concepts, and systems engineering. Dr. Boland was awarded the NASA Exceptional Achievement Medal in 2009 and 2015. Dr. Boland received her B.S. in physics from the University of Texas, Dallas, and her M.S. and Ph.D. in mechanical engineering from California Institute of Technology (Caltech).

ROBERT D. BRAUN is a professor and dean of the College of Engineering and Applied Science at CU Boulder. Previously, Dr. Braun was the David and Andrew Lewis Professor of Space Technology at the Georgia Institute of Technology (Georgia Tech) in the Daniel Guggenheim School of Aerospace Engineering. He has worked extensively in the areas of entry system design, planetary atmospheric flight, and space mission architecture development and has contributed to the design, development, testing, and operation of several space flight systems. In 2010 and 2011 Dr. Braun served as the first NASA chief technologist in more than a decade. In this capacity he was the senior agency executive responsible for technology and innovation policy and programs. Earlier in his career Dr. Braun served on the technical staff of NASA Langley Research Center. He is a member of the NAE, a fellow of the AIAA, the editor-in-chief of the *AIAA Journal of Spacecraft and Rockets*, and the author or co-author of over 300 technical publications in the fields of planetary exploration, atmospheric entry, multidisciplinary design optimization, and systems engineering. Dr. Braun has a B.S. in aerospace engineering from the Pennsylvania State University, an M.S. in astronautics from George Washington University, and a Ph.D. in aeronautics and astronautics from Stanford University.

SHUYI S. CHEN is a professor of meteorology at the University of Washington. Previously, Dr. Chen was a professor at the Rosenstiel School of Marine and Atmospheric Sciences of the University of Miami. Her research interests include satellite and airborne observations of tropical atmosphere and ocean with a focus on precipitation and air-sea fluxes from weather to subseasonal time scales, development of coupled atmosphere-wave-ocean-land models, and prediction of extreme weather including hurricanes and winter storms and the Madden-Julian Oscillation (MJO). Dr. Chen received the NASA Group Achievement Award for tropical cloud systems and processes and is a member of the NASA Ocean Vector Wind and Precipitation Measurement Missions science teams. She was an editor of the AMS journal *Weather and Forecasting*. Dr. Chen is a fellow of the AMS. She received her Ph.D. in meteorology from Pennsylvania State University.

WILLIAM E. DIETRICH is a professor of Earth and planetary sciences at the University of California, Berkeley. Dr. Dietrich's research focuses on the processes that underlie the evolution of landscapes. His research group and collaborators are developing geomorphic transport laws for soil production, weathering and transport, and river and debris flow incision into bedrock. They are exploring the processes that control the sorting of sediment on riverbeds; the transport of sediment in steep, coarse bedded channels; the routing of sediment through river networks; the influence of sediment supply on river morphodynamics; the entrainment of sediment to form debris flows; and the dispersion and deposition of sediment across floodplains. New computational approaches are being tested to predict the size and location of shallow landslides. He is collaborating in an intensive field investigation to identify, quantify, and model the processes that will control the co-evolution of climate, vegetation, and water availability in Northern California forested landscapes. He is part of the Mars Science Laboratory Mission to Mars and is collaborating on related field studies of the soil development and landscape evolution in the hyperarid Atacama Desert in Chile. Dr. Dietrich co-founded the National Center for Airborne Laser Mapping. As part of the National Center for Earth-Surface Dynamics, he is co-developing a digital terrain model for predicting salmon populations from digital terrain data. Other collaborative studies are under way to link ecologic and geomorphic processes. Dr. Dietrich is a member of the NAS. He earned his Ph.D. in geology from the University of Washington.

SCOTT C. DONEY is the Joe D. and Helen J. Kington Professor in Environmental Change in the Department of Environmental Sciences at the University of Virginia. Previously, Dr. Doney was a senior scientist and department chair at the Woods Hole Oceanographic Institution (WHOI), and prior to that he was a postdoctoral fellow and then a scientist at the National Center for Atmospheric Research (NCAR). His science interests span oceanography, climate, and biogeochemistry and applying computational methods (data analysis, numerical modeling, and satellite remote sensing) to understand how the global carbon cycle and ocean ecology respond to natural and human-driven climate change. Dr. Doney was awarded the James B. Macelwane Medal from the American Geophysical Union (AGU) and the A. G. Huntsman Award from the Royal Society of Canada. He is an Aldo Leopold Leadership Fellow, the WHOI W. Van Alan Clark Sr. Chair, and a fellow of the American Association for the Advancement of Science (AAAS). He received a B.A. in chemistry from University of California, San Diego (UCSD), and a Ph.D. in chemical oceanography from the Massachusetts Institute of Technology (MIT)/WHOI Joint Program in Oceanography.

CHRISTOPHER B. FIELD is the founding director of the Department of Global Ecology at the Carnegie Institution for Science. Dr. Field is also the Melvin and Joan Lane Professor for Interdisciplinary Environmental Studies at Stanford University. His research focuses on climate change, ranging from work on improving climate models, to prospects for renewable energy systems, to community organizations that can minimize the risk of a tragedy of the commons. Dr. Field was co-chair of Working Group II of the Intergovernmental

Panel on Climate Change (IPCC), where he led the effort on the IPCC Special Report *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* and the Working Group II contribution to the IPCC Fifth Assessment Report *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. He is a recipient of the Heinz Award, the Max Planck Research Award, the BBVA Foundation Frontiers of Knowledge Award, and the Roger Revelle Medal. Dr. Field is a member of the NAS and a fellow of the AAAS, the American Academy of Arts and Sciences, the Ecological Society of America, and the AGU. He received his Ph.D. in biology from Stanford University.

HELEN A. FRICKER holds the John Dove Isaacs Chair and is a professor of geophysics in the Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics at Scripps Institution of Oceanography, UCSD. Professor Fricker uses a combination of satellite radar and laser altimetry and other remote-sensing data to understand ice-sheet processes. Professor Fricker is widely recognized for her discovery of active subglacial lakes, and she has shown that these lakes form dynamic hydrologic systems, where one lake can drain into another in a short period of time. She is also known for her innovative research into Antarctic ice-shelf mass budget processes such as iceberg calving and basal melting and freezing. Professor Fricker received her B.Sc., with first-class honors, in mathematics and physics from University College London and her Ph.D. in glaciology from the University of Tasmania. She received the Royal Tasmania Society Doctoral Award for her Ph.D. and the Tinker-Muse Prize for Science and Policy in Antarctica from the Scientific Committee on Antarctic Research (SCAR) in 2010, and was elected a fellow of the AGU in 2017. She received the NASA Group Achievement Award for her role in the ICESat Mission Development Team, and was a member of the ICESat Science Team. She is on the ICESat-2 Science Definition Team.

SARAH T. GILLE is a professor at Scripps Institution of Oceanography, which is part of UCSD. Previously, Dr. Gille was an assistant professor at the University of California, Irvine. She is a physical oceanographer, and her research interests include Southern Ocean processes and diurnal variability. She is a fellow of the AGU and a member of the AMS. She earned a Ph.D. from the MIT/WHOI Joint Program in Oceanography.

DENNIS L. HARTMANN is professor of atmospheric sciences at the University of Washington. Dr. Hartmann also served as department chair and interim dean of the College of the Environment at the University of Washington. Dr. Hartmann's research interests include dynamics of the atmosphere, atmosphere-ocean interaction, and climate change. His primary areas of expertise are atmospheric dynamics, radiation and remote sensing, and mathematical and statistical techniques for data analysis. He is a member of the NAS and a fellow of the AMS, the AGU, and the AAAS. He was awarded the NASA Distinguished Public Service Medal and the Carl Gustav Rossby Research Medal of the AMS. He served as a coordinating lead author for the Fifth Assessment report *The Physical Science Basis of Climate Change* for the IPCC, 2014. Dr. Hartmann received his Ph.D. in geophysical fluid dynamics from Princeton University.

DANIEL J. JACOB is the Vasco McCoy Family Professor of Atmospheric Chemistry and Environmental Engineering at Harvard University. Dr. Jacob came to Harvard as a postdoctorate in 1985 and joined the faculty in 1987. Dr. Jacob has been a leader in the development of global three-dimensional (3D) models of atmospheric composition, has served as mission scientist on eight NASA aircraft missions, and is a member of several satellite science teams. He presently leads the NASA Air Quality Applied Sciences Team, the Atmospheric Science Working Group for the NASA Geostationary Coastal and Air Pollution Events (GEO-CAPE) satellite mission, and the steering committee for the GEOS-Chem global chemical transport model. Among his professional honors are the Haagen-Smit Prize, the NASA Distinguished Public Service Medal, the AGU Macelwane Medal, and the Packard Fellowship for Science and Engineering. Dr. Jacob has published over 350 papers and trained over 60 Ph.D. students and postdoctoratess over the course of his career. He received his B.S. in chemical engineering from the Ecole Supérieure de Physique et Chimie de Paris and his Ph.D. in environmental engineering from Caltech. He has served on many National Academies committees, including the Committee on a National Strategy for Advancing Climate Modeling, and chaired the Committee on Radiative Forcing Effects on Climate.

ANTHONY C. JANETOS is the Frederick S. Pardee Professor of Earth and Environment and the director of the Pardee Center for the Study of the Longer-Range Future at Boston University. Dr. Janetos has previously served as the director of the Joint Global Change Research Institute of the Pacific Northwest National Laboratory (PNNL) and University of Maryland, as vice president for research at the Heinz Center and World Resources Institute, and as a program manager in NASA and the Environmental Protection Agency (EPA). Dr. Janetos is primarily interested in land cover and land use change, climate impacts, and adaptation to climate change. He is a fellow of the AAAS and the Ecological Society of America. He has an A.B. in biology from Harvard University and an M.A. and a Ph.D. in biology from Princeton University.

EVERETTE JOSEPH is the director of the University of Albany, State University of New York (SUNY), Atmospheric Sciences Research Center (ASRC). Dr. Joseph is also SUNY Empire Innovations Professor in Atmospheric Sciences. Before coming to the University of Albany, he served as director of the Howard University Program in Atmospheric Sciences (HUPAS), director of the Howard University Beltsville Center for Climate System Observations, and deputy director of the NOAA Center for Atmospheric Science at Howard University. Dr. Joseph has co-led the development of the New York State Mesonet, a $25 million project for development of an early warning system to aid state emergency managers and the public in mitigating the effects of hazardous weather. He has also led an international team of scientists from the United States and Taiwan that was awarded a Program for International Research and Education grant from NSF and the Ministry of Science and Technology in Taiwan to study weather extremes and decision making, and he helped lead the development of a major field observation program with university, government, and industry partners designed to improve the ability of satellites to monitor the atmosphere from space and the skill of atmospheric models to better forecast weather, climate, and air quality. Dr. Joseph received his Ph.D. in physics from the University of Albany, SUNY.

JOYCE E. PENNER is the Ralph J. Cicerone Distinguished University Professor of Atmospheric Science and associate chair of the Department of Atmospheric, Oceanic, and Space Sciences at the University of Michigan. Dr. Penner's research focuses on improving climate models through the addition of interactive chemistry and the description of aerosols and their direct and indirect effects on the radiation balance in climate models. She is also interested in urban, regional, and global tropospheric chemistry and budgets; cloud and aerosol interactions and cloud microphysics; climate and climate change; and model development and interpretation. Dr. Penner has been a member of numerous advisory committees related to atmospheric chemistry, global change, and Earth science, including the United Nations IPCC, and, consequently, a co-winner of the 2007 Nobel Peace Prize. She was the coordinating lead author for IPCC (2001) Chapter 5 on aerosols and was a lead author for the IPCC (2007) report and a review editor for the IPCC (2014) report. Dr. Penner also serves on the Committee on Space Research (COSPAR) Earth science roadmap committee. Dr. Penner received a B.A. in applied mathematics from the University of California, Santa Barbara, and an M.S. and a Ph.D. in applied mathematics from Harvard University.

SOROOSH SOROOSHIAN is a distinguished professor at the University of California, Irvine. His area of expertise is hydrometeorology, water resources systems, climate studies, and application of remote sensing to Earth science problems with special focus on the hydrologic cycle and water resources issues of arid and semiarid zones. Previously, Dr. Sorooshian was a Regents Professor at the University of Arizona for 20 years and was the founding director of the $35-million-funded NSF Science and Technology Centers (STC) Sustainability of Semi-Arid Hydrology and Riparian Areas (SAHRA). He is a member of the NAS and of the International Academy of Astronautics (IAA) and the World Academy of Sciences. He has served on numerous advisory committees, including those of ASA, NOAA, DOE, the U.S. Department of Agriculture (USDA), NSF, the EPA, and UNESCO. Dr. Sorooshian is a fellow of the AAAS and serves as a member-at-large, Section on Atmospheric and Hydrospheric Sciences; the AGU and serves as a member of the board of directors; the AMS; the International Water Resources Association (IWRA); member of the Joint Scientific Committee (JSC) of the World Climate Research Programme (WCRP); past chair of the Science Steering Group (SSG) of Global Energy and Water Cycle Experiment (GEWEX) of the WCRP; U.S. member of the Hydrology Commission for the World Meteorological Association (WMO); emeritus member of UCAR Board of Trustees and NOAA Science Advisory Board; past president of the AGU Hydrology Section; member of five editorial boards and former editor of AGU Water Resources Research. His numerous honors include the Chinese Academy of Sciences Einstein Professorship, 2014; AGU Robert E. Horton Medalist, 2013; and Eagleson lectureship, Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI), 2012. He received a Ph.D. from the University of California, Los Angeles.

GRAEME L. STEPHENS is the director of climate sciences at JPL. Dr. Stephens is also a distinguished professor emeritus at Colorado State University (CSU), Fort Collins, after spending 26 years there and serving as director of a NOAA cooperative center at CSU. As director of climate sciences, Dr. Stephens focuses on finding better ways to exploit existing Earth observation data and to marry this better with Earth system models. This has led to a development of modeling partnerships between JPL and major Earth system model groups. Dr. Stephens currently serves as co-chair of the Global Energy and Water Cycle Experiment Science Steering Group (GEWEX SSG), a panel that oversees the water cycle science activities of the WCRP. His areas of research include research on interactions between solar and infrared radiation and the terrestrial atmosphere, and in use of remote sensing for understanding of the energy budget of Earth and how it relates to the planet's hydrological cycle. Awards and recognition include the AMS Houghton and Jule Charney Awards, the IAMAS IRC Gold Medal for career contributions to radiation sciences, the Jule Charney Lecturer at the AGU and recipient of the NASA Rotary Stellar Award, and the NASA Exceptional Public Service Medal and also election to the NAE. Dr. Stephens is a fellow of AMS and AGU and the AAAS. He earned his Ph.D. in meteorology from the University of Melbourne.

BYRON D. TAPLEY is research professor in aerospace engineering at the University of Texas, Austin. Dr. Tapley previously held the Clare Cockrell Williams Centennial Chair in engineering and was director of the Center for Space Research. His research interests include orbit mechanics, precision orbit determination, nonlinear parameter estimation, satellite data analysis, and the uses of methods from these areas to study the Earth and planetary system. Currently, Dr. Tapley is the mission principal investigator (PI) for the Gravity Recovery and Climate Experiment (GRACE) mission, which is the first NASA ESSP mission. A recent focus of his research has been directed to applying the GRACE measurements to determine accurate models for Earth's gravity field and using these measurements for studies of climate-driven mass exchange between Earth's dynamic system components. He is a member of the NAE and a fellow member of the AIAA, the AGU, and the AAAS. Among the awards he has received are the NASA Medal for Exceptional Scientific Achievement, the NASA Exceptional Public Service Medal, the AAS Brouwer Award, the AIAA Mechanics and Control of Flight Award, and the AGU Charles A. Whitten Medal. Dr. Tapley has been a PI for nine NASA and international missions. He is a registered professional engineer in the State of Texas. He earned a

Ph.D. in engineering mechanics, an M.S. in engineering mechanics, and a B.S. in mechanical engineering from the University of Texas, Austin.

W. STANLEY WILSON retired as senior scientist with NOAA/National Environmental Satellite Data and Information Service (NESDIS) in 2011 after managing ocean programs for four decades, first at the Office of Naval Research, then at NASA headquarters, and finally at NOAA. At NASA Dr. Wilson initiated the French partnership to implement the Ocean Topography Experiment (TOPEX)/Poseidon in 1992; its global sea-level record continues today with the Jason series. Working through the former Joint Oceanographic Institutions, he led development of "Oceanography from Space: A Research Strategy for the Decade 1985-1995," which was fully realized with the launch of GRACE in 2002. As NOAA deputy chief scientist he organized a dozen-country coalition in support of Argo, the 3000+ profiling floats now routinely monitoring the upper ocean globally. At NESDIS he led the advocacy for Jason-3 and Jason-CS. Dr. Wilson received the AGU Ocean Sciences Award in 1984 for his central role in the establishment of ocean remote sensing as a proven technology in ocean sciences. His other awards include the U.S. Navy Superior Civilian Service Award, NASA Exceptional Scientific Achievement Medal, Compass Distinguished Achievement Award, Remote Sensing Society Award, French Space Agency Medal, two NASA Group Achievement Awards, Department of Commerce Gold Medal Group Award, Oceanology International Lifetime Achievement Award, and fellow of the Oceanography Society. Dr. Wilson received a Ph.D. in physical oceanography from Johns Hopkins University in 1972.

PANEL ON GLOBAL HYDROLOGICAL CYCLES AND WATER RESOURCES

ANA P. BARROS, *Co-Chair*, is the James L. Meriam Professor of civil and environmental engineering in the Edmund T. Pratt Jr. School of Engineering at Duke University. Dr. Barros's primary research interests include hydrology, hydrometeorology, and environmental physics, with a focus on water-cycle processes in the coupled land-atmosphere-biosphere system. Before joining Duke University, Dr. Barros was on the engineering faculty at Pennsylvania State University and Harvard University. She is a fellow of the AGU and a fellow of the AMS. She was also a member of the U.S. National Committee for the International Hydrology Program of UNESCO. Dr. Barros served on the National Academies Space Studies Board, and on several committees of the Water Science and Technology Board and the Board of Atmospheric Sciences and Climate, including the Climate Research Committee. She received her Ph.D. in civil and environmental engineering from the University of Washington.

JEFF DOZIER, *Co-Chair*, is a distinguished professor at the Bren School of Environmental Science and Management at the University of California, Santa Barbara. Dr. Dozier founded the Bren School and served as its first dean for six years. His research interests are in the fields of snow hydrology, Earth system science, remote sensing, and information systems. He has led interdisciplinary studies in two areas: one addresses hydrologic science, environmental engineering, and social science in the water environment; the other involves the integration of environmental science and remote sensing with computer science and technology. He was a PI on the Landsat-4 and -5 programs, when the satellites carrying the first Landsat Thematic Mapper instruments were launched. He served as the senior project scientist for NASA's Earth Observing System (EOS) when the configuration for the system was established. Dr. Dozier is a fellow of the AGU and the AAAS, an honorary professor of the Chinese Academy of Sciences, a recipient of both the NASA/Department of the Interior William T. Pecora Award and the NASA Public Service Medal, the winner of the Jim Gray Award from Microsoft for his achievements in data-intensive science, and the John Nye Lecturer for AGU. He also helped Disney Animation Studios on the film *Frozen*, which won the 2014

Oscar for Best Animated Feature. He has previously served on 13 National Academies committees, most recently the Planning Committee on Training Students to Extract Value from Big Data: A Workshop; the Committee on the Implementation of a Sustained Land Imaging Program, as chair; and the Committee on Indicators for Understanding Global Climate Change. He received a Ph.D. in geography from the University of Michigan in 1973.

NEWSHA AJAMI is a director of Urban Water Policy at Stanford University. Dr. Ajami is a hydrologist specializing in sustainable water resource management, flood and water supply forecasting, and advancing uncertainty assessment techniques impacting hydrological predictions. Her research throughout the years has been interdisciplinary and impact driven, focusing on the improvement of the science-policy-stakeholder interface by incorporating social and economic measures, and through relevant and effective communication. Dr. Ajami has published many highly cited peer-reviewed papers in predominant journals and was the recipient of 2010 William R. Gianelli Water Leaders scholarship, 2005 NSF funding for AMS Science and Policy Colloquium, and ICSC-World Laboratory Hydrologic Science and Water Resources Fellowship from 2000-2003. She received her Ph.D. in civil and environmental engineering from University of California, Irvine.

JOHN D. BOLTEN is a physical research scientist at the NASA GSFC Hydrological Sciences Lab. Dr. Bolten also serves as the associate program manager of Water Resources for the NASA Applied Sciences Program. He has served as the NASA GRACE Mission Applications deputy representative for Water and Coastal Resources; chair of the AGU Hydrology Remote Sensing Technical Committee; and co-lead on the Committee on Earth Observing Satellites (CEOS), Flood Disaster Pilot Risk Management; and is an active Soil Moisture Active-Passive (SMAP) Applications Working Group and Calibration and Validation Working Group member. Previously, Dr. Bolten served as a research physical scientist at the USDA Hydrology and Remote Sensing Lab. His research focuses on the application of satellite-based remote sensing and land-surface hydrological modeling for improved ecological and water resource management. He received a Ph.D. in geology with an emphasis on hydrology and remote sensing from the University of South Carolina.

DARA ENTEKHABI is the Bacardi and Stockholm Water Foundations Professor at MIT in the Department of Civil and Environmental Engineering with a joint appointment in the Department of Earth, Atmospheric, and Planetary Sciences. His research interests are coupled surface, subsurface, and atmospheric hydrologic systems and terrestrial remote sensing. Dr. Entekhabi has served on the National Academies Committee on Hydrologic Science, the Water Science and Technology Board, and the Committee to Assess the National Weather Service Advanced Hydrologic Prediction Service Initiative program. He also served on the Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future. He is a fellow of the AMS, the AGU, and the Institute of Electrical and Electronics Engineers (IEEE). He is a member of the NAE. He received a Ph.D. in civil engineering from MIT in 1990.

GRAHAM E. FOGG is a professor of hydrogeology at the University of California, Davis (UC Davis) in the Department of Land, Air, and Water Resources. Dr. Fogg's research interests include groundwater contaminant transport; groundwater basin characterization and management, geologic and geostatistical characterization of subsurface heterogeneity for improved pollutant transport modeling, numerical modeling of groundwater flow and contaminant transport, the role of molecular diffusion in contaminant transport and remediation, long-term sustainability of regional groundwater quality, and vulnerability of aquifers to non-point-source groundwater contaminants. He was the 2002 Birdsall-Dreiss Distinguished Lecturer and the 2011 O. E. Meinzer Award winner, both awarded by the Geological Society of America

Hydrogeology Division. Dr. Fogg co-developed the graduate program in hydrologic sciences at UC Davis using the 1991 National Research Council report *Opportunities in the Hydrologic Sciences* as a reference. Dr. Fogg received his Ph.D. in geology from the University of Texas, Austin. He has previously served on the 2012 National Academies Committee on Challenges and Opportunities in the Hydrologic Sciences.

EFI FOUFOULA-GEORGIOU is Distinguished Professor in the Department of Civil and Environmental Engineering at the Henry Samueli School of Engineering, University of California, Irvine. From 1989-2016 Dr. Foufoula-Georgiou was on the faculty at the University of Minnesota as a McKnight Distinguished Professor in the Department of Civil, Environmental and Geo-Engineering, the Joseph T. and Rose S. Ling Chair in Environmental Engineering, and a founding fellow of the Institute on the Environment. She has served as director of the NSF STC, National Center for Earth-Surface Dynamics. Her area of research includes hydrology and geomorphology, with special interest in scaling theories, pattern formation, multiscale dynamics, and space-time modeling of precipitation and landforms. Dr. Foufoula-Georgiou is a fellow of the AGU, the AMS, and the AAAS and is an elected member of the European Academy of Sciences. She is the recipient of the Hydrologic Sciences award of AGU, the Dalton Medal of the European Geophysical Union (EGU), the Hydrologic Sciences Medal of AMS, and the Robert E. Horton lecture award of AMS. Dr. Foufoula-Georgiou has served as chair-elect of the board of directors of the Consortium of Universities for the Advancement of Hydrologic Science, trustee of the University Corporation for Atmospheric Research (UCAR), president of the Hydrology section of AGU, and member of national and internationals advisory boards, including the Water Science and Technology Board, Advisory Council for the NSF Geosciences Directorate, NASA Earth Sciences Directorate, and European Union advisory panels. She has served on several National Academies committees, including the Committee on Earth Sciences and Applications from Space, Challenges and Opportunities in the Hydrologic Sciences, and the Committee on Progress and Priorities of U.S. Weather Research and Research-to-Operations. She received a diploma in civil engineering from the National Technical University of Athens and a Ph.D. in environmental engineering from the University of Florida.

DAVID C. GOODRICH received a B.S. in civil and environmental engineering from the University of Wisconsin, Madison, in 1980 and was awarded a Churchill Scholarship for a year of graduate study at Cambridge University. He returned to the University of Wisconsin, Madison, for his M.S. in civil and environmental engineering in 1982, and received a Ph.D. from the Department of Hydrology and Water Resources (HWR) at the University of Arizona in 1990 and was named an adjunct assistant professor with HWR the same year. Dr. Goodrich's early work experience includes positions with the U.S. Geological Survey (USGS) in Wisconsin and Alaska and consulting with Autometric in Washington, DC. Since 1988 he has been employed as a research hydraulic engineer with the Southwest Watershed Research Center of the USDA Agricultural Research Service in Tucson, Arizona. Areas of research during his career have been directed to scaling issues in watershed rainfall-runoff response, identification of dominant hydrologic processes over a range of basin scales, climatic change impacts on semiarid hydrologic response, incorporation of remotely sensed data into hydrologic models, the functioning of semiarid riparian systems, nonmarket valuation of ecosystem services, flash-flood forecasting, and rapid post-fire watershed assessments. Dr. Goodrich co-led the interdisciplinary multiagency Semi-Arid Land-Surface-Atmosphere (SALSA) Research Program. He was an executive member of the NSF Sustainability of Semi-Arid Hydrology and Riparian Areas (SAHRA) STC and has worked closely since 2000 with elected officials and decision makers in the San Pedro Basin. Dr. Goodrich is a fellow of the AGU and received the Arid Lands Hydraulic Engineering Award from the American Society of Civil Engineers (ASCE) for original contributions in hydraulics and hydrology in arid or semiarid climates. He has not previously served on a National Academies committee.

TERRI S. HOGUE is department head and professor in the Department of Civil and Environmental Engineering at Colorado School of Mines. Dr. Hogue is also the director of the Center for a Sustainable Water-Energy Education Science and Technology (WE^{2}ST). Her research focuses on urban and ecosystem dynamics, including wildfire impacts, urban water use and stormwater capture, remote sensing of hydrologic parameters, hydrologic response to climate change, and water sustainability related to oil and gas production in the western United States. Prior to her present position, Dr. Hogue was on the faculty at the University of California, Los Angeles. Dr. Hogue was awarded the NSF Early Career Award and was a speaker at a "Hazards on the Hill" Event for the U.S. Senate. Dr. Hogue is a member of the National Academies Board of Atmospheric Sciences and Climate and recently served as secretary of the Hydrology Section of the AGU. She received a Ph.D. in hydrology and water resources from the University of Arizona, Tucson.

JEFFREY S. KARGEL is a senior associate research scientist and adjunct professor at the University of Arizona, Tucson, in the Department of Hydrology and Water Resources. Dr. Kargel is involved in several projects related to the natural hazards and response of glaciers to climate change in the Himalaya. This work involves both satellite remote sensing and field-based research, which in recent years has focused on glacier lakes and landslides in Nepal. Dr. Kargel also maintains a strong research activity in planetary science, particular the hydrogeology and glaciology of Mars, and ice processes and low-temperature chemistry of icy moons. Dr. Kargel led the international glacier remote sensing consortium Global Land Ice Measurements from Space (GLIMS), for which he continues involvement as a core team member after he resigned the role of director. Previously, Dr. Kargel worked at USGS in Flagstaff, Arizona. He earned a Ph.D. in planetary science from the University of Arizona, Tucson.

CHRISTIAN D. KUMMEROW is professor of atmospheric science at CSU, where he also serves as director of the Cooperative Institute for Research in the Atmosphere (CIRA). His research interests include remote sensing, the global water cycle and its uncertainties—how uncertainties relate to physical aspects of the atmosphere, and thus the fundamental processes underlying precipitation and the water cycle. Prior to joining Colorado State, Dr. Kummerow worked at NASA GSFC serving as the project scientist for the Tropical Rainfall Measuring Mission (TRMM) and as study scientist for the then-emerging Global Precipitation Mission (GPM). Dr. Kummerow is currently on the Advanced Microwave Scanning Radiometer Science Team as well as the team lead for GPM's passive microwave algorithm team. In addition to CIRA director, he has been a chair and member of the GEWEX Data and Assessments Panel, and serves on the NASA Earth Science Advisory Committee. He was awarded the NASA Goddard Exceptional Achievement Award and Maryland's Distinguished Young Scientist Award. He received a Ph.D. in atmospheric physics from the University of Minnesota, Minneapolis. Dr. Kummerow has previously served on the National Academies Panel on Water Resources and the Global Hydrologic Cycle.

VENKAT LAKSHMI is a Carolina Trustee Professor at the University of South Carolina in the School of Earth Ocean and Environment. Dr. Lakshmi served as the Cox Visiting Professor of Earth Sciences at Stanford University in 2006-2007 and 2015-2016. His research interests are in the areas of hydrometeorology and hydroclimatology, land-atmospheric-ecological interactions through modeling, and remote sensing. Prior to his current position he worked at NASA GSFC as a research scientist in the Laboratory for the Atmospheres. Dr. Lakshmi has over 70 peer-reviewed articles and 250 presentations. He has served as the thesis advisor for about 20 graduate students. He has served as editor EOS and associate editor of *Water Resources Research*, *Journal of Hydrologic Engineering*, and *Journal of Geophysical Research*. He is currently serving as associate editor of *Journal of Hydrology* and communications editor of *Vadose Zone Journal*. He is the founding editor-in-chief of *Remote Sensing in Earth System Science* (Springer publication). He has served on the board of directors of the Consortium of Universities for the Advancement of Hydrological Sciences, the AGU, and Hydrological Executive Council, and has been the co-chair for the Hydrology Section for the fall meeting. Dr. Lakshmi has served as a member of the executive council for the AGU heads and chairs of geosciences. He received a Ph.D. in civil and environmental engineering from Princeton University. He has not previously served on a National Academies committee.

EDWIN WELLES is executive director of and a hydrologist at Deltares-USA, a U.S. affiliate of the Dutch national water resources research institute of the same name. At Deltares Dr. Welles has led research and implementation of water resources forecasting techniques in support of flood forecasting, water supply, and reservoir management. His particular focus has been on ensemble methodologies and integrating those methods into systems used for agency operations. In addition he is leading research into coastal resilience planning methods for both water surplus and scarcity with a focus on the methods to assess the long- and short-term economic impacts of proposed hydraulic mitigation strategies. Prior to his current position he was a hydrologist and a branch chief at NWS.

ERIC F. WOOD is the Susan Dod Brown Professor of Civil and Environmental Engineering at Princeton University, where he has taught since 1976. His research area is in hydroclimatology with an emphasis on the modeling and analysis of the global water and energy cycles through land-surface modeling, satellite remote sensing, and data analysis. His foci include the monitoring and forecasting of drought, hydrologic impacts from climate change, and seasonal hydrological forecasting. Dr. Wood is on the editorial board of *Hydrological Processes*. He is a member of the NAE. He was a member of the Climate Research Committee and the Panel on Climate Change Feedbacks and is a former member of the Water Science and Technology Board, Board on Atmospheric Science and Climate's Global Energy, and Water Cycle Experiment Panel. Dr. Wood received an Sc.D. in civil engineering from MIT.

PANEL ON WEATHER AND AIR QUALITY: MINUTES TO SUBSEASONAL

STEVEN A. ACKERMAN, *Co-Chair*, is a professor of atmospheric and ocean sciences and director of the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin, Madison. Dr. Ackerman also serves as associate vice chancellor for research physical sciences. Dr. Ackerman's current research focuses on satellite remote sensing and has produced several new methodologies for interpreting satellite observations, which has led to improved understanding of the radiative properties of clouds, a critical factor in weather and climate. He was elected a fellow of the AMS and a fellow of the Wisconsin Academy of Science, Arts, and Letters. He is the recipient of numerous awards, including the NASA Exceptional Public Service Medal and the AMS Teaching Excellence Award. He received a Ph.D. in atmospheric science from CSU. Dr. Ackerman has served on the National Academies Committee for Earth Science and Applications from Space and the Committee on a Framework for Analyzing the Needs for Continuity of NASA-Sustained Remote Sensing Observations of Earth from Space.

NANCY L. BAKER, *Co-Chair*, is a meteorologist and head of the data assimilation section in the Marine Meteorology Division at the Naval Research Laboratory. Dr. Baker has more than 30 years of experience with the U.S. Navy in atmospheric data assimilation, observation impact assessment, observation quality control, and numerical weather prediction (NWP). She has expertise in advanced data assimilation methods such as 3D-Var, 4D-Var, and hybrid ensemble/variational 4D-Var, and has had a leading role in the development and transition of those systems to the Navy for operational implementation. Satellite data assimilation has been one of her primary areas for the past 20 years. Dr. Baker currently serves as the associate director for the Navy to the Joint Center for Satellite Data Assimilation, and previously served as the Navy technical liaison. She led a Navy-sponsored study to assess the dependency on foreign satellites for environmental characterization. She is currently PI for a Navy-sponsored project designed to assess the impact of the upcoming NASA Cyclone Global Navigation Satellite System-Earth Venture Mission (CYGNSS [GNSS-R]) mission on tropical NWP and tropical cyclone track, intensity, and structure forecasts. Her dissertation research developed the observation adjoint sensitivity theory, which subsequently led to the groundbreaking development of the Forecast Sensitivity Observation Impact (FSOI) with Dr. Rolf Langland. Dr. Baker earned a Ph.D. in meteorology from the Naval Postgraduate School. She served as a member of the National Academies Committee on the Future of Rainfall Measuring Missions.

PHILIP E. ARDANUY is the chief science officer of INNOVIM. Dr. Ardanuy's research considers the non-stationary influences of a changing climate on the water security, energy security, and food security aspects of national and economic security—and the implications for observing, data management, and stewardship system architectures and technological maturation. His expertise, developed over 35 years working with NASA and NOAA, spans the development of complex remote sensing flight systems and their cyberinfrastructures, end-user services, and societal applications to support operational Earth observation missions and research priorities. Dr. Ardanuy's experience covers the environmental information and intelligence value stream—from algorithm theoretical basis and remote sensing; through architecture and systems engineering, data acquisition and product generation, reprocessing and archiving; to modeling, visualization, and decision support delivering environmental intelligence for multiple Global Earth Observing System of Systems (GEOSS) societal benefit areas. Previously, Dr. Ardanuy served as chief scientist and Earth science solution architect for Raytheon Intelligence and Information Systems, where he led the science team for the design of the advanced Visible Infrared Imaging Radiometer Suite (VIIRS), now in orbit on Suomi-NPP and JPSS-1. At Raytheon he was honored as Raytheon Engineering Fellow in 2007 and as Raytheon Principal Engineering Fellow in 2010, and received the Raytheon Peer Award in 2004. Dr. Ardanuy was honored as a fellow of the AMS in 2011 and elected to the AMS Council in 2015. He served a 6-year term as a member of the NOAA Environmental Information Services Working Group (EISWG), and currently serves on the NASA Applied Sciences Advisory Committee (ASAC). He previously served on the Applications Panel of ESAS 2007, the midterm update, and numerous National Academies ad hoc study panels. Dr. Ardanuy was elected to the Nimbus-7 Earth Radiation Budget Science Team for on-orbit calibration and characterization leadership in 1985. He earned a Ph.D. in meteorology from Florida State University.

ELIZABETH A. BARNES is an assistant professor at CSU in the Department of Atmospheric Sciences. Dr. Barnes's research focuses on large-scale atmospheric dynamics, with specific interests including internal climate variability, climate change, climate statistics, eddy-mean flow dynamics, jet-stream variability, tropospheric transport, cross-tropopause exchange, and air quality. She is currently the lead of the NOAA Modeling, Analysis, Predictions, and Projections Subseasonal-to-Seasonal (MAPP S2S) Prediction Task Force. Previously, Dr. Barnes was a NOAA Climate and Global Change postdoctoral fellow at the Lamont-Doherty Earth Observatory of Columbia University. She is a recipient of the 2014 AGU James R. Holton Junior Scientist Award. She earned a Ph.D. in atmospheric science from the University of Washington.

STANLEY G. BENJAMIN is senior scientist for advanced modeling systems at the NOAA Earth System Research Laboratory. Dr. Benjamin has led projects on the development of advanced regional and global atmospheric prediction models and data assimilation. He led a storm-model-development group awarded the Department of Commerce Gold Medal in 2015. In addition to basic model and assimilation development, he has focused on model applications to global circulation, hydrology, transportation, renewable (wind and solar) energy, severe weather, winter storms, and air quality. Dr. Benjamin earned a Ph.D. in meteorology from Pennsylvania State University.

MARK A. BOURASSA is a professor of meteorology at Florida State University in the Department of Earth, Ocean, and Atmospheric Sciences. Dr. Bourassa is also the associate director of the Center for Ocean-Atmospheric Prediction Studies. His areas of expertise are remote sensing, air/sea interaction, boundary-layer physics, and the climate observing system. He has been a member of many NASA science teams and NOAA's team of ocean observations. He has been the team leader for NASA's Ocean Vector Winds Science Team for the last eight years, during which time this team received the William T. Pecora Award. He has served as co-chair of a U.S. Climate Variability and Predictability Program Panel on high-latitude surface fluxes, and is a recent co-chair of a Global Climate Observing System Panel. Dr. Bourassa earned a Ph.D. in atmospheric science from Purdue University.

BRYAN N. DUNCAN is a research physical scientist at NASA GSFC in the Atmospheric Chemistry and Dynamics Laboratory. Dr. Duncan is the project scientist of NASA's Aura satellite mission, which has air quality as one of its core science objectives. He has published a number of studies that use satellite data for air quality applications and that show how atmospheric columns (measured by the satellite) relate to quantities that the air quality community knows, such as "nose-level" concentrations. He is a selected member of NASA's Health and Air Quality Applied Sciences Team (HAQAST), which works to facilitate the use of satellite data by the health and air quality communities. Dr. Duncan was also involved in NASA's DISCOVER-AQ campaign. In addition to air quality, his research interests include computer modeling of the transport and chemistry of methane and other trace gases. Previously, Dr. Duncan was a postdoctoral fellow at Harvard University and the Swiss Institute of Technology, and a senior research scientist at the University of Maryland, Baltimore County. He earned a Ph.D. in the Earth and Atmospheric Sciences Department of the Georgia Tech.

CHARLES E. KOLB is the president and chief executive officer of Aerodyne Research, Inc. (ARI). He has extensive experience in atmospheric and environmental chemistry, combustion chemistry, and the chemistry and physics of rocket and aircraft exhaust plumes. He has authored or co-authored over 230 peer-reviewed journal articles and book chapters on these and related topics, including gas-phase and heterogeneous (gas-surface) chemical kinetics, quantitative trace gas spectroscopy, and computer simulations of chemically reacting systems. He initiated ARI's efforts to develop advanced laser spectroscopy and mass spectrometry sensors for atmospheric trace gases and aerosol particles, which are widely used to measure ambient concentrations and emission/deposition fluxes of atmospheric pollutants. He received the 1997 Award for Creative Advances in Environmental Science and Technology from the American Chemical Society (ACS). Dr. Kolb has also been elected a fellow of the ACS, the American Physical Society, the Optical Society of America, the AGU, and the AAAS. He has served as the atmospheric sciences editor of the journal *Geophysical Research Letters*, and as a member of the editorial advisory boards of the *International Journal of Chemical Kinetics* and *Environmental Science and Technology*. He was recognized as a national associate of the National Academies in 2003 and elected a member of the NAE in 2013. He has served on numerous boards and committees of the National Academies, including the boards on Atmospheric Sciences and Climate (1990-1993 and 1997-2000) and Chemical Science and Technology (2008-2014), and was chair of the Committee on Atmospheric Chemistry (1990-1993) and the Committee on the Significance of International Transport of Air Pollutants (2008-2009). He earned a B.S. in chemistry from MIT and an M.A. and a Ph.D. in physical chemistry from Princeton University.

YING-HWA KUO is the director of UCAR Community Programs (UCP) at UCAR. UCAR consists of seven community-based programs in education and training, science support services, and data services, including the Constellation Observing System for Meteorology (COSMIC) program. COSMIC is a joint U.S.-Taiwan mission, which demonstrated the use of GPS radio occultation technique in operational weather forecasting, climate monitoring, and space weather prediction. Dr. Kuo led the COSMIC program from its inception. His team is currently working with NOAA, the U.S. Air Force, and Taiwan's NSPO on the development of the follow-on COSMIC-2 mission, which will be launched in the spring of 2017. His scientific interests include GPS atmospheric remote sensing and its research applications and analysis and prediction of hurricanes, extratropical cyclones, mesoscale convective systems, and heavy rainfall events. Dr. Kuo also serves as the director of the Developmental Testbed Center, which is jointly funded by NOAA, the U.S. Air Force, NCAR, and NSF, with the primary mission to facilitate the transition of research in numerical weather prediction into operations. Previously, Dr. Kuo was the head of the Mesoscale Prediction Group at NCAR, responsible for the development and applications of mesoscale weather prediction models. He is a fellow of the AMS. He earned a Ph.D. in meteorology from Pennsylvania State University. He has previously served on the National Academies Committee on Utilization of Environmental Satellite Data: A Vision for 2010 and Beyond.

W. PAUL MENZEL is a senior scientist at the University of Wisconsin, Madison, in the Space Science Engineering Center (SSEC). Dr. Menzel's current research is focused on studying cloud and moisture properties derived from 35 years of High-resolution Infrared Radiation Sounder (HIRS) data and extending that record with Cross-track Infrared Sounder (CrIS) and Infrared Atmospheric Sounding Interferometer (IASI) data. Previously, Dr. Menzel was the Verner Suomi Distinguished Professor in the Department of Atmospheric and Oceanic Sciences at the University of Wisconsin, Madison; earlier, he served in several roles at NOAA/NESDIS. First, he was the leader of the Advanced Satellite Products Project, where he was responsible for the development, testing, and evaluation of procedures for deriving new atmospheric products from spaceborne observations, and also their transfer from the research laboratory to the operational weather forecaster. Thereafter, he was the chief scientist of the Office of Research and Applications of NOAA/NESDIS, responsible for providing guidance on science issues and initiating major science programs for the office director. Dr. Menzel has been a PI of the Moderate-Resolution Imaging Spectroradiometer (MODIS) Science Team for over 20 years, where he has had primary responsibility for algorithms to derive cloud-top properties, atmospheric profiles, and column water vapor using infrared bands on MODIS. Dr. Menzel received a Ph.D. in theoretical solid-state physics at the University of Wisconsin, Madison.

MARIA A. PIRONE is the senior manager of business development for Environmental Solutions at Harris Corporation. At Harris, Ms. Pirone has led business development offering information technology solutions for satellite ground processing, and weather and climate challenges within the federal government and internationally. Her expertise is in information technology that provides useful information from aggregated disparate data to benefit specific markets and individual users. During her 40-year career she has held senior management positions in both the marketing and the technical development of weather and climate products and services. At Weather Services International (WSI; now The Weather Company), Ms. Pirone managed the technical development and later product management of a family of weather radar products based on the first widely used national radar mosaic. She also developed strategic plans for new services, the most memorable included delivering weather in the cockpit for pilot use. Most recently at Atmospheric and Environmental Research (AER), she led the commercialization of key research including seasonal forecasts, space weather, and ensembles processed into statistically based, probabilistic forecast products for weather and energy traders. Ms. Pirone received an M.B.A. in finance from Suffolk University in Boston. She has previously served as a member of the National Academies Committee on Partnerships in Weather and Climate Services.

ARMISTEAD G. RUSSELL is the Howard T. Tellepsen Chair and Regents' Professor at the Georgia Tech in the School of Civil and Environmental Engineering. Dr. Russell's primary research is aimed at better understanding the dynamics of air pollutants at urban and regional scales and assessing their impacts on health and the environment to develop approaches to design strategies to effectively improve air quality. Prior to coming to Georgia Tech he was a professor of mechanical engineering at Carnegie Mellon University. He is a fellow of the AAAS and the American Society of Mechanical Engineers (ASME). He earned a Ph.D. in mechanical engineering from Caltech. He has previously served on the National Academies Committee on the Review of the Draft Interagency Report on the Impacts of Climate Change on Human Health in the United States, Board on Environmental Studies and Toxicology, the Committee on the Assessment of the Department of Veterans Affairs Airborne Hazards, and Open Burn Pit Registry and the Planning Committee for Black Carbon Issues.

JULIE O. THOMAS is a co-PI and program manager for the Coastal Data Information Program (CDIP). Ms. Thomas is also senior advisor (previously executive director) of the Southern California Coastal Ocean Observing System (SCCOOS). Based at the Scripps Institution of Oceanography, Ms. Thomas has been focused on real-time data transfers, particularly for physical oceanographic parameters such as waves, winds, and currents. In collaboration with the National Data Buoy Center, CDIP disseminated wave data to NWS and to the general public. Ms. Thomas was involved with early efforts to standardize wave data formats and to develop metadata, quality control, and archive procedures. In this role, with her focus on wave data, she maintained standards for an "end to end" system, collecting and disseminating high-resolution data. Her work promotes the primary operational interface with the scientific user community and technical partners and provides direction for the curation and management of the data holdings. Ms. Thomas is an advocate for the development of ocean observing systems at regional, state, and national levels, promoting interagency collaboration, data interoperability, and data standards. Ms. Thomas earned an M.A. in French literature from San Diego State University.

DUANE E. WALISER is chief scientist of the Earth Science and Technology Directorate at JPL. Dr. Waliser's principal research interests lie in weather-climate prediction and predictability, with emphasis on the tropics, Earth system processes, and Earth's water cycle. His recent research focus involves utilizing new and emerging satellite data sets to study weather and climate as well as advance model simulation and forecast capabilities, particularly for long-range weather and short-term climate applications. Previously, he was on the faculty in the School of Marine and Atmospheric Sciences at the State University of New York, Stony Brook. Dr. Waliser is also a visiting associate in the Geological and Planetary Sciences Division at Caltech and an adjunct professor in the Atmospheric and Oceanic Sciences Department at University of California, Los Angeles (UCLA). He is presently a member of the WCRP- World Weather Research Program Subseasonal-to-Seasonal (WCRP-WWRP S2S) Steering Group, co-chair of the WCRP Data Advisory Council obs4MIPs Task Team, and previous co-chair of the WCRP-WWRP/The Observing System Research and Predictability Experiment (THORPEX) Year of Tropical Convection (YOTC) Activity, U.S. Climate Variability and Predictability (CLIVAR) Madden-Julian Oscillation (MJO) Working Group, and WCRP-WWRP MJO Task Team. He has previously served on the National Academies Committee on Assessment of Intraseasonal to Interannual Climate Prediction and Predictability and the Committee on Developing a U.S. Research Agenda to Advance Subseasonal to Seasonal Forecasting.

XUBIN ZENG is the Agnese N. Haury Chair in Environment, professor of atmospheric sciences, director of the Climate Dynamics and Hydrometeorology Center, and co-chair of the Strategic Planning and Budget Advisory Committee at the University of Arizona. Through over 160 peer-reviewed papers, Dr. Zeng's research has focused on land-atmosphere-ocean interface processes, weather and climate modeling, hydrometeorology, remote sensing, and nonlinear dynamics. His model parameterizations and global value-added observation-based data sets have been widely used in weather and climate models. Dr. Zeng's work acts as a bridge linking measurement technology, in situ and satellite data, and modeling communities. He is a fellow of the AMS and served on its council and executive committee. He received the Special Creativity Award from NSF. He is also an Arizona Leadership Institute Fellow and Galileo Circle Fellow. Dr. Zeng earned a Ph.D. in atmospheric science from CSU. He currently co-chairs the international GEWEX Atmospheric System Study Panel. He has previously served on the National Academies Board on Atmospheric Sciences and Climate, co-chaired the Committee on Urban Meteorology: Scoping the Problem, Defining the Needs (A Workshop), and served on two other committees related to weather and big data.

PANEL ON MARINE AND TERRESTRIAL ECOSYSTEMS AND NATURAL RESOURCE MANAGEMENT

COMPTON J. TUCKER, *Co-Chair*, is a senior scientist at NASA GSFC. Dr. Tucker's research interests focus on the terrestrial Earth system through the use of satellite remote sensing and include primary production, land cover mapping, land degradation, food security, tropical deforestation and habitat fragmentation, ecologically coupled disease outbreaks, glacier extent, and geophysical surveys for archaeology. Prior to working at NASA/GSFC, Dr. Tucker worked with the Grassland Biome at CSU, and came to NASA as an NAS postdoctoral fellow. He is also an adjunct professor at the University of Maryland and is a consulting scholar at the University of Pennsylvania's Museum of Archaeology and Anthropology. He is a fellow of the AGU and the AAAS and has been awarded several medals and honors, including NASA's Exceptional Scientific Achievement Medal, the Pecora Award from USGS, the National Air and Space Museum Trophy, the Henry Shaw Medal from the Missouri Botanical Garden, the Galathea Medal from the Royal Danish Geographical Society, the Vega Medal from the Swedish Society of Anthropology and Geography, and most recently received Presidential Rank for Meritorious Senior Professional Service. Tucker received his B.S. in biology, M.S. in forestry, and Ph.D. in forestry, from CSU, was the NASA representative to the U.S. Global Change Research Program from 2005 to 2010, and has prior National Academies experience serving as a member on the Committee on a Framework for Analyzing the Needs for Continuity of NASA-Sustained Remote Sensing Observations of Earth from Space.

JAMES A. YODER, *Co-Chair*, retired in 2017 from his position as the vice president for academic programs and dean at WHOI, having served in this position since moving to WHOI in 2005. Dr. Yoder was a professor at the Graduate School of Oceanography, University of Rhode Island (1989-2005), where he conducted research involving satellite and aircraft measurements to study ocean processes, taught graduate courses, and advised M.S. and Ph.D. students. He also served 5 years as associate dean in charge of the graduate program in oceanography and 1.5 years as interim dean of the school. Dr. Yoder has held temporary positions in the federal government, most recently as director of NSF's Division of Ocean Sciences (2001-2004). During his time at NSF, Dr. Yoder chaired the National Ocean Partnership Program (NOPP) Interagency Working Group (IWG). He has served on many national and international committees and panels. He was a member of the National Academies Decadal Survey of Ocean Sciences (DSOS, 2013-2015); was a former member (2009-2013) of the Ocean Studies Board (OSB); and chaired (2011-2012) the OSB Committee on Assessing Requirements for Sustained Ocean Color Research and Operations. Dr. Yoder currently serves on the advisory board for the NOAA-funded Environmental Cooperative Science Center (ECSC) led by Florida A&M University and is a former member and chair of the International Ocean Colour Coordinating Group (IOCCG). IOCCG seeks cooperation among the international space agencies for satellite measurements of ocean color radiometry and its application for understanding regional to global ocean patterns in the productivity of the seas. He was elected a fellow of the Oceanography Society in 2012.

GREGORY P. ASNER is a staff scientist in the Department of Global Ecology of the Carnegie Institution for Science and a professor in the Department of Earth System Science at Stanford University. Dr. Asner is an ecologist recognized for his work on biospheric processes, land use, and climate change at regional to global scales. Dr. Asner maintains a research program in Earth spectroscopy and laser-based imaging with airborne and orbital remote sensing instrumentation. He has served in numerous national and international posts including the NASA Senior Review Committee, U.S. Carbon Cycle Science Steering Group, U.N. Diversitas Program, NASA-Brazil LBA Steering Committee, and as a senior fellow for the U.S. State Department. He is a recipient of the Presidential Early Career Award for Scientists and Engineers, NASA Early Career and Group Achievement awards, and an Outstanding Contributions Award from the Association of American Geographers. In 2013 Dr. Asner was elected to the NAS. He graduated with a bachelor's degree in engineering from CU Boulder, in 1991, followed by service as an officer in the U.S. Navy. He earned a master's degree in geography and a doctorate degree in biology from the University of Colorado in 1997.

FRANCISCO CHAVEZ is a biological oceanographer interested in how climate variability and change regulate ocean ecosystems on local and basin scales. Dr. Chavez was born and raised in Peru and has a B.S. from Humboldt State University and a Ph.D. from Duke University. He is a founding member of the Monterey Bay Aquarium Research Institute (MBARI), where he has pioneered time series research and the development of new instruments and systems to make this type of research sustainable. Dr. Chavez has authored over 200 peer-reviewed papers, with 10 in *Nature* and *Science*. He is past member of the NSF Geosciences Advisory Committee, has been involved in the development of the U.S. Integrated Ocean Observing System (IOOS), is a member of the governing board of the Central and Northern California Coastal Ocean Observing System (CeNCOOS) and the Science Advisory Team for the California Ocean Protection Council. Dr. Chavez is a fellow of the AAAS, honored for distinguished research on the impact of climate variability on oceanic ecosystems and global carbon cycling. Dr. Chavez is also a fellow of the AGU, honored for advancing fundamental knowledge of the physical-biological coupling between Pacific Decadal Oscillations (PDOs), productivity, and fisheries. He was awarded a Doctor Honoris Causa by the Universidad Pedro Ruiz Gallo in Peru in recognition of his distinguished scientific career and for contributing to elevate academic and cultural levels of university communities in particular and society in general. Dr. Chavez is the 2014 recipient of the Ed Ricketts Memorial Award.

INEZ Y. FUNG is a professor of atmospheric sciences at the University of California, Berkeley. Dr. Fung studies the interactions between climate change and biogeochemical cycles, particularly the processes that maintain and alter the composition of the atmosphere. Her research emphasis is on using atmospheric transport models and coupled carbon-climate models to examine how CO_2 sources and sinks are changing. She is also a member of the science team for NASA's OCO-2. Dr. Fung is a recipient of the AGU Roger Revelle Medal and NASA Exceptional Scientific Achievement Medal and appears in a NAS biography series for middle-school readers, *Women's Adventures in Science*. She is a fellow of the AMS and the AGU, as well as a member of the NAS, the American Academy of Arts and Sciences, and the American Philosophical Society. She received an S.B. in applied mathematics and a Sc.D. in meteorology from MIT.

SCOTT GOETZ joined Northern Arizona University as a professor in the School of Informatics, Computing, and Cyber Systems in 2016, and also affiliates with the Center for Ecosystem Science and Society. Formerly, Dr. Goetz was a senior scientist and deputy director of the Woods Hole Research Center. He has conducted remote sensing research for environmental science applications over the past 30 years, having both organized and served on numerous working groups for the IPCC, UN-REDD, U.S. Global Change Research Program, the NAS, as well as NASA and NSF programs on arctic and carbon cycle science, climate change, and terrestrial ecology. Dr. Goetz is the science lead of the NASA Arctic Boreal Vulnerability Experiment and deputy PI of the NASA Global Ecosystem Dynamics Investigation (GEDI). He has published over 150 refereed publications, which have been cited over 12,000 times and picked up by a wide range of major news media outlets. He earned a Ph.D. from the University of Maryland, and has been awarded a Fulbright Research Scholarship (in Toulouse, France) and received NASA team awards for interdisciplinary science. He is an executive board member of *Environmental Research Letters*, served for 10 years as an associate editor of *Remote Sensing of Environment*, and has participated in numerous educational and professional service activities, including graduate student committees at various institutions. Dr. Goetz served as a member of a National Resource Council committee on Opportunities to Use Remote Sensing in Understanding Permafrost and Related Ecological Characteristics (2013) and Frontiers in Understanding Climate Change and Polar Ecosystems (2010).

PATRICK N. HALPIN is an associate professor of marine geospatial ecology and director of the Geospatial Ecology Program at the Nicholas School of the Environment, Duke University Marine Laboratory. Dr. Halpin's research focuses on marine geospatial analysis, ecological applications of geographic information systems and remote sensing, and marine conservation and ecosystem-based management. Dr. Halpin leads the Marine Geospatial Ecology Lab at Duke University and sits on a number of international scientific and conservation program steering committees. Dr. Halpin currently sits on the executive committee for the UNESCO/IOC Ocean Biogeographic Information System, and steering committee for the GEO-BON Marine Working Group 5. He received a Ph.D. in environmental sciences from the University of Virginia.

ERIC HOCHBERG is an associate scientist at the Bermuda Institute of Ocean Sciences. Dr. Hochberg's research interests center on coral reefs. His primary focus is remote sensing for application to ecosystem studies and conservation at local, regional, and global scales. This is the basic goal of NASA's Earth Venture Suborbital-2 mission, Coral Reef Airborne Laboratory (CORAL), of which Dr. Hochberg is the PI. Dr. Hochberg is also interested in bridging our understanding of organism-, community-, and ecosystem-scale biogeochemical responses to stressors, especially those related to climate change. Prior to moving to Bermuda Dr. Hochberg was on the faculty of the National Coral Reef Institute at Nova Southeastern University. Before that he served on the research faculty at the Hawaii Institute of Marine Biology. He earned a Ph.D. in oceanography from the University of Hawaii.

CHRISTIAN J. JOHANNSEN is a professor emeritus of agronomy and director emeritus of the Laboratory for Applications of Remote Sensing (LARS), Purdue University. Dr. Johannsen directed the LARS research and academic programs of remote sensing, Geographic Information Systems (GIS), and GPS, involving over 35 faculty and 75 graduate students in data acquisition, information processing, and resource applications. His personal research has related to remote sensing, GIS and GPS applications to precision agriculture, soil pattern influences on reflectance, spatial-spectral-temporal resolution impacts, and land degradation. From 1988-1996 he served as director of the Natural Resources Research Institute (renamed Environmental Sciences and Engineering Institute in 1994), which provided the leadership in directing research and educational activities to environmental and natural resources concerns. Dr. Johannsen also directed the

Purdue Agricultural Data Network (1985-1987) with a staff of 15 people in developing techniques, programs, approaches and training for university research and extension faculty and staff within the School of Agriculture in computer automation of data and information. At the University of Missouri (1972-1985), his extension and research program was recognized for emphasis in soil survey, soil conservation, remote sensing applications, resource database development, strip mine reclamation, and municipal waste utilization using spatial technologies. Between 1998 and 2001 Dr. Johannsen also served on the Space Studies Board of the National Academies.

RAPHAEL M. KUDELA is Lynn Professor of Ocean Health in the Ocean Sciences Department at the University of California, Santa Cruz. Dr. Kudela has conducted research on aquatic ecology (emphasis on marine systems, but also including land/sea interface and freshwater systems) for nearly two decades. His research focuses on the factors and processes linking phytoplankton productivity to higher trophic levels, including the ecology, mitigation, and prediction of harmful algal bloom events, changes in global productivity and fisheries, and linkages to human use of aquatic systems. His research utilizes the combination of three tools, remotely sensed data from moorings and satellites in combination with biological models; novel bio-optical methods assaying phytoplankton physiology; and the refinement of stable and radio-tracer isotopes. Dr. Kudela currently serves as chair of the Global Ecology and Oceanography of Harmful Algal Blooms Program (IOC/SCOR), is co-chair of the U.S. National Harmful Algal Bloom Committee, and is a member of theNSF Ocean Observing Systems Review Committee and UNOLS Scientific Committee for Oceanographic Aircraft Research (SCOAR). He previously served on the NSF Coastal Ocean Processes (CoOP) steering committee. Within the ocean observing framework Dr. Kudela serves on the executive committee for the Central and Northern California Ocean Observing System (CeNCOOS) and is the chair of the California Harmful Algal Bloom Monitoring and Alert Program (Cal-HABMAP). He earned a Ph.D. in biology from the University of Southern California.

GREGORY W. McCARTY is a research soil scientist at the USDA ARS Hydrology and Remote Sensing Laboratory in Beltsville, Maryland. Dr. McCarty investigates biogeochemical processes affecting transformation of nitrogen and carbon in agricultural crop fields and adjacent ecosystems such as riparian buffer wetlands. He is a recognized authority on assessing the fate of soil carbon in agricultural landscapes. For example, his research involving an experimental agricultural catchment highlighted the important role of soil deposition in wetlands on carbon dynamics within the ecosystem. His detailed study of soil redistribution patterns on Iowa cropland has also documented the importance of erosion on overall carbon storage within agricultural catchments. Dr. McCarty currently leads the Choptank River Watershed Project on the Eastern Shore of Maryland, which is part of the USDA Long-term Agroecosystem Research network. With this project conservation practices are being assessed at the watershed scale by use of a combination remote sensing and modeling. Dr. McCarty has authored over 150 peer-reviewed journal publications, 15 book chapters, 44 proceedings; has mentored 14 graduate students and 4 postdoctoral scientists; and has hosted 5 visiting scientists.

LINDA O. MEARNS is director of the Weather and Climate Impacts Assessment Science Program (WCIASP) and head of the Regional Integrated Sciences Collective (RISC) within the Institute for Mathematics Applied to Geosciences (IMAGe), and senior scientist at NCAR. Dr. Mearns is also co-chair of the North American CORDEX program. She has performed research and published mainly in the areas of climate change scenario formation, quantifying uncertainties, and climate change impacts on agro-ecosystems. She has particularly worked extensively with regional climate models. She served as director of the Institute for the Study of Society and Environment (ISSE) for 3 years ending in 2008 and was director of the North

American Regional Climate Change Assessment Program. Dr. Mearns was made a fellow of the AMS in 2006 and received the American Association of Geographers Excellence in Scholarship Award in 2016. She holds a Ph.D. in geography/climatology from UCLA. She has been a member of the National Resource Council Climate Research Committee (CRC) and the National Academies Human Dimensions of Global Change (HDGC) Committee, Panel on Adaptation of the America's Climate Choices Program, and Panel on Advancing Climate Modeling.

LESLEY E. OTT is a research meteorologist who leads carbon cycle modeling efforts in NASA's Global Modeling and Assimilation Office. Dr. Ott's research focuses on understanding carbon flux on a global scale through the combined use of land, ocean, and atmospheric models and satellite observations. She is particularly interested in reconciling bottom-up and top-down flux estimates, improving the characterization of uncertainty in model-based flux estimates, and using models to define requirements for atmospheric composition observations. Dr. Ott is currently a member of NASA's Carbon Monitoring System and OCO-2 science teams. She was previously a NASA postdoctoral program fellow and assistant state climatologist for the State of Maryland. Dr. Ott received a B.Sc. in physical sciences, an M.Sc. in meteorology, and a Ph.D. in atmospheric and oceanic science, all from the University of Maryland, College Park.

MARY JANE PERRY is a professor emerita at the University of Maine and an affiliate professor of oceanography at the University of Washington. Dr. Perry received a Ph.D. from the Scripps Institution of Oceanography in 1974 and a B.A. from the College of New Rochelle. Dr. Perry is a seagoing oceanographer whose research interests include a variety of direct and inverse methods to determine phytoplankton abundance using optical and remote-sensing techniques. She is particularly interested in using autonomous vehicles for long-term studies of ocean phytoplankton and carbon. Dr. Perry was a rotator for two years in biological oceanography at NSF and served on numerous NSF advisory committees. She co-chaired the Autonomous and Lagrangian Platforms and Sensors (ALPS) workshop and report in 2003. Dr. Perry has prior National Academies experience as a member of the Committee on Oceanography in 2025: A Workshop, as a member of the Committee on Molecular Marine Biology, and as a member of the steering committee for the Sixth Symposium on Tactical Oceanography. She served on the NASA Export Processes in the Ocean from Remote Sensing (EXPORTS) Science Writing and Definition Teams and is a member of the EXPORTS project. She is a fellow of the Oceanography Society.

DAVID A. SIEGEL is an interdisciplinary marine scientist at the University of California, Santa Barbara. Professor Siegel's research focuses on aquatic ecosystems and their functioning using the tools of an applied physicist—namely, radiative transfer and fluid mechanics. He has worked extensively in marine bio-optics and satellite ocean color remote sensing as well as assessing the roles of ocean circulation from basin to micro-scales in problems ranging from microbial diversity, biogeochemical cycling, kelp spatial population dynamics, and nearshore fisheries management. Professor Siegel received a B.A. in chemistry and a B.S. in engineering sciences from UCSD, and M.S. and Ph.D. degrees in geological sciences from the University of Southern California. In 1989 he was a postdoctoral fellow at WHOI. Since 1990 he has been on the faculty at the University of California, Santa Barbara, and is presently a professor in the Department of Geography, director of the Earth Research Institute, and chair of the Interdepartmental Graduate Program in Marine Science. In 2010-2011 Professor Siegel served on the National Academies Committee on Sustained Satellite Ocean Color Observations and is presently the chair of the Export Processes in the Ocean from Remote Sensing (EXPORTS) Science Definition Team for NASA. Since 2009 he has been a member of the Earth Sciences Subcommittee of the NASA Advisory Committee. Professor Siegel is a fellow of both the AGU and the AAAS.

DAVID L. SKOLE is professor of global change science at Michigan State University (MSU). Dr. Skole has more than 25 years of experience with research on the global carbon cycle and climate change. Dr. Skole leads the Carbon to Markets Program, a project of MSU that focuses on combining value chains from carbon credits in the carbon financial markets and agro-forestry products for small holders in developing countries. He was instrumental in constructing the first numerical carbon accounting model and has been spearheading the integration of satellite-based remote sensing into carbon accounting models. He is now active in the emerging carbon financial markets and REDD+ programs and in applications of his research to carbon sequestration projects in developing countries. Dr. Skole is chair of the NSF Advisory Committee on Environmental Research and Education. He was previously implementation chair of the UN Program on Global Observations of Land Cover, which is coordinating a monitoring program for land use change worldwide. He has a Ph.D. in natural resources from the University of New Hampshire. His past National Academies service includes the Geographical Sciences Committee, the Panel on Earth Science Applications and Societal Needs, the Panel on Social and Behavioral Science Research Priorities for Environmental Decision Making, the Committee on Ecological Impacts of Road Density, the Committee for Review of the U.S. Climate Change Science Program Strategic Plan, and the Committee on the Geographic Foundation for Agenda 21.

SUSAN L. USTIN is a distinguished professor of environmental resource science in the Department of Land, Air, and Water Resources at UC Davis and serves as vice chair. Dr. Ustin is the associate director of the John Muir Institute at UC Davis. Dr. Ustin received an honorary doctorate from the University of Zurich in 2010 and in 2017 was elected fellow of the AGU. Dr. Ustin also serves on the scientific advisory committee to Battelle for the National Ecological Observatory Network. She has 35 years' experience in multidisciplinary research focused on developing applications of remote sensing data, in particular in the use of imaging spectroscopy for quantitative assessment of plant traits and soil properties. She has been a PI and science team member of several NASA sensor programs for Earth observation and has been a member of the Moderate-Resolution Imaging Spectroradiometer (MODIS) science team and the Hyperspectral Infrared Imager (HyspIRI) preparatory mission. Dr. Ustin received a Ph.D. in botany from UC Davis in 1983, in the area of plant physiological ecology, and a B.S. and an M.A. in biological sciences from the California State University, Hayward. She has previously served as a member on four National Academies committees, the Committee on Scientific Accomplishments of Earth Observations from Space, Ecosystems Panel, Committee on Earth Studies, and the Task Group on Assessment of NASA Plans for Post-2000 Earth Observing Missions and the Committee on Assessing Crop Yield.

CARA WILSON is a research scientist with the Environmental Research Division (ERD) of NOAA's Southwest Fisheries Science Center in Monterey, California, and is the PI of the West Coast node of NOAA's CoastWatch program, which is housed at ERD. At NOAA Dr. Wilson teaches an annual course aimed at providing scientists who are not regular users of satellite data with the knowledge and tools they need to incorporate satellite data into their research and management projects. Her research interests are in using satellite data to examine biophysical coupling in the surface ocean, with a particular focus on determining the biological and physical causes of the large chlorophyll blooms that often develop in late summer in the oligotrophic Pacific near 30 degrees N. She earned a Ph.D. in oceanography from the Oregon State University, Corvallis. In 2011 she served on the National Research Council Committee on Assessing Requirements for Sustained Ocean Color Research and Operations. Dr. Wilson is also the current chair of the IOCCG.

PANEL ON CLIMATE VARIABILITY AND CHANGE: SEASONAL TO CENTENNIAL

CAROL ANNE CLAYSON, *Co-Chair*, is the former director of the Ocean and Climate Change Institute. Dr. Clayson is also a senior scientist in the Department of Physical Oceanography at WHOI. Dr. Clayson has been tenured faculty at Florida State University and Purdue University, and was also the former director of the Geophysical Fluid Dynamics Institute. Her research covers the areas of air and sea interaction, satellite remote sensing, and ocean modeling. She is the recipient of a NSF CAREER Award and the Office of Naval Research Young Investigator Award. She received a Presidential Early Career Award for Scientists and Engineers from President Bill Clinton. Dr. Clayson received a Ph.D. in aerospace engineering sciences from CU Boulder. Previously, Dr. Clayson served as a member of the National Academies Board on Atmospheric Sciences and Climate, including the Committee on the Future of Rainfall Measuring Missions and the Committee to Review the NASA Earth Science Enterprise Strategic Plan.

VENKATACHALAM RAMASWAMY, *Co-Chair*, is director of NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), and a lecturer with the rank of professor in the Atmospheric and Oceanic Sciences Program at Princeton University. Dr. Ramaswamy's primary interests include numerical modeling of the global climate system, advancing the understanding of atmospheric physics and related processes, and investigating the climatic changes due to natural and human-influenced factors. He directs one of the core climate modeling centers in the United States with the mission to develop and apply numerical models for understanding global and regional climate, and conduct research on predictability/predictions and projections of climate. His honors include the following: fellow, AMS, AGU, and AAAS; AMS Houghton and Walter Orr Roberts Lecturer; WMO Norbert-Gerbier International for best scientific paper (three-time recipient); Presidential Rank; and distinguished lecturer, Bert Bolin, Stockholm University, and Joseph Priestley, Chemical Heritage Foundation. Dr. Ramaswamy has been a lead author or review editor on the IPCC WGI Climate Change Science Assessment Reports from 1992 to 2013, and was a member of the IPCC team that was a co-recipient of the 2007 Nobel Peace Prize. Dr. Ramaswamy earned a Ph. D. in atmospheric sciences from the State University of New York, Albany. He has previously served on the National Academies Panel on Informing Effective Decisions and Actions Related to Climate Change as well as the Panel on Aerosol Radiative Forcing and Climate Change.

ARLYN E. ANDREWS is a chemist at the NOAA Earth System Research Laboratory in Boulder, Colorado. Previously, Dr. Andrews worked at NASA GSFC, where she contributed to the initial development of concepts for active and passive CO_2 satellite sensors. Dr. Andrews has measured carbon dioxide from the surface to the stratosphere on a variety of airborne platforms, including NASA's ER-2 aircraft—a modified U-2 spy plane—and high-altitude balloons. She is currently responsible for a network of sites measuring carbon dioxide, methane, and related gases from broadcast towers, and she leads NOAA's Carbon Tracker-Lagrange regional modeling framework for estimating emissions of carbon dioxide and methane and biological uptake of carbon dioxide by terrestrial ecosystems. Dr. Andrews served as a member of the Carbon Cycle Science Steering Group for the U.S. Carbon Cycle Science Program. She earned a Ph.D. in Earth and planetary science from Harvard University.

ENRIQUE CURCHITSER is a professor of oceanography and climate in the Department of Environmental Sciences at Rutgers University. Dr. Curchitser's main research interests include ocean circulation and its role in the climate system, dynamics of boundary currents and shelf circulation, physical-biological interactions, development of coupled Earth system models, and multiscale climate dynamics and numerical modeling. His group at Rutgers University, the Earth System Modeling Lab, assembles an interdisciplinary team of scientists and students that makes use of numerical models to address a range of climate-related problems. Specific projects include the role of upwelling systems in climate and ecosystem dynamics, downscaling of climate models to coastal systems, and exploring the links between coupled eco- and human-systems and climate. Dr. Curchitser is the State Department-appointed academic delegate to the North Pacific Marine Science organization and chair of the CLIVAR research focus on Eastern Boundary Upwelling Systems as well as a member of the Ocean Model Development Panel (OMDP).

LEE-LUENG FU is a senior research scientist at JPL, where he is also a fellow. Dr. Fu has been the project scientist for JPL's satellite altimetry missions for oceanographic and geodetic studies since 1988, including TOPEX/Poseidon, Jason-1, and Jason-2. He is currently the project scientist for the U.S./France joint Surface Water and Ocean Topography (SWOT) mission, which is being developed as the next generation altimetry mission for measuring water elevation on Earth. Dr. Fu's research has been focused on the variability of sea level in relation to ocean circulation and climate. He received a B.S. in physics from National Taiwan University and a Ph.D. in oceanography from MIT and WHOI. He is a member of the NAE and a fellow of the AGU and the AMS. Recently, he was awarded the COSPAR International Cooperation Medal for his leadership in the development and continuation of satellite altimetry missions. He has served on the National Academies Committee on Earth Science and Applications from Space (through 2016) and the Committee on a Framework for Analyzing the Needs for Continuity of NASA-Sustained Remote Sensing Observations of the Earth from Space (through 2015).

GUIDO GROSSE is a professor of permafrost in the Earth system at the University of Potsdam and the Alfred Wegener Institute (AWI) in the Periglacial Research Department in the Helmholtz Centre for Polar and Marine Research in Potsdam, Germany. At AWI Dr. Grosse is leading the European Research Council (ERC) Project PETA-CARB, where a broad range of remote sensing observations are coupled with soil carbon stock estimates to better understand carbon pools and dynamics in Arctic permafrost regions. He is also the lead for two work packages in the European Space Agency (ESA) GlobPermafrost project. His research focuses on the study of climate change impacts in Arctic permafrost environments by using high- to medium-resolution remote sensing, geospatial information systems, and extensive field work. Previously, Dr. Grosse was on the faculty of the Geophysical Institute of the University of Alaska Fairbanks, where he was PI and co-investigator in multiple NASA, NSF, and Alaska LCC projects focusing on remote sensing of permafrost landscape dynamics and associated ecosystem, hydrological, and biogeochemical processes. He led the Thermokarst Working Group in the Permafrost Carbon Network (PCN) and the working group on Vulnerability of High Latitude Soil Carbon to Disturbance within the North American Carbon Program (NACP). He participated in more than 35 Arctic field campaigns in Siberia and Alaska. He earned a Ph.D. for geology at Alfred Wegener Institute, Potsdam, and the University of Potsdam.

RANDAL D. KOSTER is a research scientist at the NASA GSFC. Dr. Koster's early work focused on the analysis of global water isotope geochemistry. Most of his tenure at GSFC, however, has been dedicated to two research thrusts: (1) the development of improved treatments of land-surface physics for atmospheric general circulation models, and (2) the analysis of interactions between the land and atmosphere using these models. He has examined many questions regarding land-atmosphere feedback, including the following: Can knowledge of soil moisture conditions at the beginning of a seasonal weather forecast improve the forecast? Can we find evidence in the observational record that variability in land-surface states has an effect on rainfall, air temperature, and other atmospheric variables? Dr. Koster is the 2016 winner of the AMS Hydrological Sciences Medal. He received an Sc.D. from MIT. He served on the National Academies Committee on Assessment of Intraseasonal to Interannual Climate Prediction and Predictability.

SONIA M. KREIDENWEIS is a university distinguished professor and the associate dean for research at the College of Engineering at CSU. At CSU Dr. Kreidenweis has led the initiation and development of the program in atmospheric chemistry, specializing in her own group in the characterization of aerosol physical and optical properties. Her research interests include the study of aerosol-cloud interactions via observations and modeling; methods for the detection, characterization, and parameterization of cloud condensation nuclei and ice nucleating particles; and application of aerosol-water interaction concepts to visibility and climate. Dr. Kreidenweis is a recipient of the Sinclair Award of the American Association for Aerosol Research (AAAR), and is a fellow of the AAAR and of the AMS. She earned a Ph.D. in chemical engineering from Caltech. She served as a member of the National Academies Committee on International Transport of Air Pollution, the Committee on Opportunities to Improve the Representation of Clouds and Aerosols in Climate Models with National Collection Systems, and the Committee on Atmospheric Chemistry.

EMILIO F. MORAN is John A. Hannah Distinguished Professor at Michigan State University at the Center for Global Change and Earth Observations. Dr. Moran was previously distinguished professor and the James H. Rudy Professor of Anthropology at Indiana University. He is the author of 10 books, 15 edited volumes, and more than 190 journal articles and book chapters. He is formally trained in anthropology, geography, ecology, soil science, and satellite remote sensing. His work for the past 20 years has been focused on linking the social and natural sciences, addressing questions on land use and land cover change, and population and environment. Dr. Moran's research has been supported by NSF, National Institutes of Health (NIH), NOAA, and NASA. His three latest books, *Environmental Social Science* (Wiley/Blackwell, 2010), *People and Nature* (Blackwell, 2006), and *Human Adaptability*, 3rd ed. (Westview, 2007), address broad issues of human interaction with the environment. He is a past Guggenheim fellow, a fellow of the Linnean Society of London, a fellow of the American Anthropological Association and the Society for Applied Anthropology, a fellow of the AAAS, and a member of the NAS. He earned a Ph.D. in anthropology from the University of Florida. He served on the National Academies Division Committee for the Behavioral and Social Sciences and Education, the Committee on the Human Dimensions of Global Change, and the Geographical Sciences Committee.

CORA E. RANDALL is a professor at the CU Boulder in the Department of Atmospheric and Oceanic Sciences, and a faculty member of the CU Laboratory for Atmospheric and Space Physics. Dr. Randall's main area of expertise is remote sensing of Earth's middle atmosphere, with particular emphasis on the polar regions. She investigates processes related to stratospheric ozone depletion, polar mesospheric clouds, and atmospheric coupling through solar and magnetospheric energetic particle precipitation. She teaches courses in chemistry, climate, radiative transfer, and remote sensing. Dr. Randall is a current or prior member of numerous international satellite science teams, and is PI on the Cloud Imaging and Particle Size (CIPS) experiment on the NASA Aeronomy of Ice in the Mesosphere (AIM) satellite mission. She has won a number of awards in recognition of her scientific contributions, and is an elected fellow of the AGU and AAAS. She earned a Ph.D. in chemistry from the University of California, Santa Cruz. She has not previously served on a National Academies committee.

PHILIP J. RASCH is the chief scientist and laboratory fellow at the Pacific Northwest National Laboratory (PNNL). Prior to working for PNNL Dr. Rasch held several positions throughout NCAR. His main focus has been on understanding the connections between clouds, chemistry, and climate of the Earth system. Work in this broad area has required basic contributions in numerical methods for atmospheric models, as well as contributions in the representation of cloud and aerosol processes, and processes that control the transport, production, and loss of trace constituents in the atmosphere. Dr. Rasch is interested in climate change and the water cycle, as well as the role of aerosols on the climate system. He has also worked and published regularly on the controversial subject of climate engineering (geoengineering). Dr. Rasch was a chair of the International Global Atmospheric Chemistry Program of the IGBP. He led activities for the WCRP/IGBP Atmospheric Chemistry and Climate activity. He has served in various editorial positions for international journals and served on advisory panels for NSF, Department of Energy (DOE), NASA, and the AMS. Dr. Rasch has been a contributing author to NASA, the WMO, and the IPCC assessment documents. He earned a Ph.D. in meteorology from Florida State University. He has previously served on the National Academies Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts, and Committee for Review of CCSP Draft Synthesis and Assessment Product 3.2.

ERIC J. RIGNOT is a professor at the University of California, Irvine, in the Department of Earth System Science. Dr. Rignot is also a senior research scientist and joint faculty appointee at JPL. Dr. Rignot has 26 years of experience in glaciology, polar physical oceanography, ice-ocean interaction, synthetic-aperture radar applications for ice-sheet mass balance, low-frequency radar sounding of glaciers, airborne surveying of Greenland and Antarctica, and numerical ice-sheet modeling. Dr. Rignot has received the following awards: NASA Exceptional Scientific Achievement Medal, NASA Outstanding Team Leadership, NASA Group Achievement, JPL Director Award, Nobel Peace Prize in 2007, IPCC AR4 Authors, AGU Fellow, and Thomson Reuters Highly Cited Researcher. He is a member of CLIVAR, NSF SEARCH, NASA's Sea Level Change Team; he is the science lead for the Operation IceBridge mission over land ice and a member of the Science Definition Team for the NASA/Indian Space Research Organization (ISRO) Synthetic Aperture Radar (SAR) mission. He earned a Ph.D. in electrical engineering from UCLA. He served as a member of the National Academies Committee on a Framework for Analyzing the Needs for Continuity of NASA-Sustained Remote Sensing Observations of Earth from Space.

CHRISTOPHER RUF is a professor of atmospheric science and electric engineering at the University of Michigan in the Climate and Space Department. Dr. Ruf is a PI for the NASA Cyclone Global Navigation Satellite System (CYGNSS) Earth Venture Mission, which measures ocean surface wind speed in tropical cyclones with rapid sampling using a constellation of eight microsatellites in low Earth orbit. CYGNSS successfully launched in December 2016. Dr. Ruf's research interests include remote sensing technology and Earth science applications related to climate and weather studies. Previously, Dr. Ruf was on the faculty of the Pennsylvania State University in the Department of Electrical and Computer Engineering and on the technical staff of NASA JPL/Caltech. He earned a Ph.D. in electrical engineering from the University of Massachusetts, Amherst. He served as a member of the National Academies Committee on the Scientific Uses of the Radio Spectrum, Survey Steering Committee for Earth Science and Applications from Space: A Community Assessment and Strategy for the Future: Weather Panel, and the Committee on Radio Frequencies.

ROSS J. SALAWITCH is a professor of atmospheric sciences at the University of Maryland, College Park (UMCP), in the Departments of Atmospheric and Oceanic Science, Chemistry and Biochemistry, and the Earth System Science Interdisciplinary Center. At UMCP Dr. Salawitch leads a research effort focused on stratospheric ozone layer depletion and recovery, air quality, the global carbon cycle, and climate change. All of these efforts involve the use of various computer models and a suite of observations to quantify the effects of human activity on the composition of Earth's atmosphere. Previously, Dr. Salawitch was on the research staff of JPL, Caltech, and also served at various times as visiting research associate and lecturer at Caltech. He is the recipient of the Yoram Kaufman Award for Unselfish Cooperation in Research from the Atmospheric Sciences Section of the AGU and is a fellow of the AAAS. He earned a Ph.D. in applied physics from Harvard University, for research on the cause of the Antarctic ozone hole. He has not previously served on a National Academies committee.

AMY K. SNOVER serves as the director of the Climate Impacts Group and assistant dean of applied research at the University of Washington in the College of the Environment. Dr. Snover is also affiliate associate professor. She works to improve society's resilience to natural and human-caused fluctuations in climate by bridging the gap between science and decision making. Working with a broad range of stakeholders, Dr. Snover helps to develop science-based climate change planning and adaptation guidance, identify research priorities, and advise on strategies for building climate resilience. She has been recognized as a White House Champion of Change for Climate Education and Literacy, was a convening lead author for the Third U.S. National Climate Assessment, and was lead author of the groundbreaking 2007 guidebook, *Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments*, with over 3,000 copies now in use worldwide. Current areas of research include defining successful climate change adaptation, exploring the role of cities in adaptation, and identifying the time of emergence of management-relevant aspects of climate change. Dr. Snover received a Ph.D. in environmental chemistry from the University of Washington.

JULIENNE C. STROEVE is a senior research scientist at the National Snow and Ice Data Center (NSIDC), which is within the CIRES. Dr. Stroeve's polar research interests have focused on the sea-ice cover and include sea-ice predictability, climate change, and associated local and large-scale impacts, particularly in the Arctic. She has conducted several Arctic field campaigns. Dr. Stroeve's work has been featured in numerous magazines, news reports, radio shows, and TV documentaries. She has given keynote addresses around the world on polar issues and has briefed former vice president Al Gore. She has published more than 50 articles in peer-reviewed journals and contributed to several national and international reports on Arctic climate change and polar processes. She received a Ph.D. in geography from the CU Boulder for her work in understanding Greenland climate variability. Dr. Stroeve serves on the NSF Geosciences Advisory Committee. She has served on the National Academies Committee for the Antarctic Sea Ice Variability in the Southern Climate-Ocean System Workshop and has served on the Committee on Designing an Arctic Observing Network.

BRUCE A. WIELICKI is a senior scientist for radiation sciences at NASA Langley Research Center. Dr. Wielicki is currently science team lead of NASA's Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder mission to the International Space Station (ISS), a mission that started in 2016 and is planned for launch in 2020. Dr. Wielicki was a PI on the NASA Cloud-Earth Radiant Energy System (CERES) instruments from 1990 through 2008. He has also been a co-investigator on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), CloudSat, Landsat, and Earth Radiation Budget Experiment (ERBE) NASA missions. His research interests are in climate change, climate sensitivity, cloud feedback, Earth's radiation budget, cloud remote sensing, radiative transfer theory, and testing of climate models. He has published over 110 journal articles with over 5500 citations. Dr. Wielicki has received two Presidential Rank awards and four NASA medals, including the Distinguished Service Medal, which is NASA's highest award. He is a fellow of the AMS and has received the AMS Houghton Award. He has served on numerous national and international committees. Dr. Wielicki has served on two National Academies study committees: the 2013 Total Solar Irradiance study for NOAA, and the 2015 Continuity of NASA Earth Observations from Space: A Value Framework.

GARY W. YOHE is the Huffington Foundation Professor of Economics and Environmental Studies at Wesleyan University. Dr. Yohe has been on the faculty at Wesleyan for more than 30 years. He is the author of more than 100 scholarly articles, several books, and many contributions to media coverage of climate issues. Most of his work has focused attention on the mitigation and adaptation/impacts sides of the climate issue. Involved since the early 1990s with the IPCC that received a share of the 2007 Nobel Peace Prize, Dr. Yohe served as a lead author for four chapters in the Third Assessment Report published in 2001 and as convening lead author for the last chapter of the contribution of Working Group II to the Fourth Assessment Report published in 2007. In that assessment he also worked with the Core Writing Team to prepare the overall Synthesis Report. He was a convening lead author for Chapter 18 of the Contribution of Working Group II to the Fifth Assessment Report, "Detection and Attribution," and a lead author for Chapter 1, "Points of Departure." He received a Ph.D. in economics from Yale University. Most recently, he has served on the National Academies Committee to Advise the U.S. Global Change Research Program, the Board on Environmental Change and Society and the Committee on the Human Dimensions of Global Change. Dr. Yohe was also a vice chair of the 2014 National Climate Assessment Development and Advisory Committee for the Obama Administration.

PANEL ON EARTH SURFACE AND INTERIOR: DYNAMICS AND HAZARDS

DOUGLAS W. BURBANK, *Co-Chair*, is a professor at the University of California, Santa Barbara, in the Department of Earth Science. Dr. Burbank's research in tectonic geomorphology synthesizes surface processes, modern and past climate history, sedimentology, stratigraphy, structure, and diverse dating approaches in order to quantify the growth and decay of topography through time. Previously, Dr. Burbank was a professor at the Pennsylvania State University and at the University of Southern California. He has been elected a fellow of the AGU, the AAAS, and the Geological Society of America. Dr. Burbank earned a Ph.D. from Dartmouth College. He is a member of the NAS, but has not previously served on any committees of the National Academies.

DAVID T. SANDWELL, *Co-Chair*, is professor of geophysics at Scripps Institution of Oceanography in the Institute for Geophysics and Planetary Physics. Dr. Sandwell's research activities are focused on mapping large-scale topographic features beneath the ocean using data collected by remote-sensing instruments on satellites orbiting Earth and sonars on research vessels. Dr. Sandwell worked as a research geodesist at the National Geodetic Survey and as a research geophysicist at the University of Texas, Austin, before taking a faculty position at Scripps Institution of Oceanography. He is the president of the AGU Geodesy Section. Dr. Sandwell earned a Ph.D. in geophysics and space physics from the University of California, Los Angeles. He is a member of the NAS and has served on the National Academies Board on Earth Sciences and Resources, the Committee on Seismology and Geodynamics, and the Committee on National Requirements for Precision Geodetic Infrastructure.

ROBIN E. BELL is a senior research scientist at Columbia University in the Lamont-Doherty Earth Observatory. At Columbia University Dr. Bell directs major research programs on the Hudson River and in Antarctica. Dr. Bell has studied the mechanisms of ice-sheet collapse and the chilly environments beneath the Antarctic ice sheet, including Lake Vostok, and she has led seven major aero-geophysical expeditions to Antarctica. She received the Columbia University Department of Geological Sciences Storke Award in 1992. Dr. Bell earned a Ph.D. in geology from Columbia University. She served on the National Academies Committee on the Development of a Strategic Vision and Implementation Plan for the U.S. Antarctic Program, on the Committee on Antarctic and Southern Ocean Service Review, and on the Polar Research Board.

EMILY E. BRODSKY is a professor at the University of California, Santa Cruz. Dr. Brodsky is an earthquake physicist whose research primarily focuses on identifying the processes that trigger earthquakes and constraining the forces and processes that occur inside a fault zone during slip. These studies require tools from a number of fields including seismology, rheology, hydrogeology, and structural geology. Dr. Brodsky is the recipient of the inaugural Charles Richter Early Career Award from the Seismological Society of America and the James Macelwane Medal from the AGU and is an AGU fellow. She was selected as a distinguished lecturer for the NSF Earthscope program, the Geo-Prisms program, and the National Science Board. She has served on the board of directors of the Southern California Earthquake Center (SCEC) and Incorporated Research Institutes for Seismology (IRIS). She has published over 100 peer-reviewed articles and presented over 150 invited lectures or keynote talks in 30 states and 13 countries. Her work has been featured in major press outlets such as the BBC, NPR, *Time Magazine*, *New York Times*, *Nature*, Reuters, *Los Angeles Times*, and *Wall Street Journal*. She was a 2001 Miller Fellow at the University of California, Berkeley. Dr. Brodsky earned a Ph.D. from Caltech. She has served on the National Academies Committee on Seismology and Geodynamics.

DONALD P. CHAMBERS is an associate professor at the University of South Florida in the College of Marine Science. Dr. Chambers specializes in using satellite observations such as radar altimetry and satellite gravimetry to better understand ocean dynamics and sea-level variability. Previously, Dr. Chambers was a research scientist at the Center for Space Research at the University of Texas, Austin. He is a recipient of the AGU Geodesy Section Award. He earned a Ph.D. in aerospace engineering from the University of Texas, Austin. He has not previously served on a National Academies committee.

LUCY M. FLESCH is a professor of geophysics at Purdue University in the Department of Earth, Atmospheric, and Planetary Sciences in the College of Science. At Purdue University Dr. Flesch has addressed fundamental questions in geophysics relating to quantifying forces driving continental deformation, especially far inboard from the plate edge; determination of role of the convecting mantle in driving surface motions; assessing the level of crust/mantle and lithosphere/asthenosphere coupling; and determining the strength of the continental lithosphere. Her research is done through observationally based numerical simulations that integrate data from geology, geodesy, and seismology. Previously, Dr. Flesch was a postdoctoral fellow at the Carnegie Institution of Washington, Department of Terrestrial Magnetism. She was a member of the writing team Dynamics of Continents: Geodynamics Grand Challenges White Paper commissioned by NSF for National Academies use. She earned a Ph.D. in geophysics from Stony Brook University.

GEORGE E. HILLEY is an associate professor at Stanford University in the Department of Geological Sciences. At Stanford University Dr. Hilley leads the Tectonic Geomorphology Laboratory, which uses geologic observations, remote-sensing data, laboratory analyses, and physically based models to understand landscape change along active plate margins. Specifically, he has combined geologic mapping, Interferometric Synthetic Aperture Radar (InSAR) measures of ground deformation, GPS motions, Shuttle Radar Topography Mission (SRTM) topography, high-resolution airborne lidar, cosmogenic radionuclide abundances, and numerical models to understand landscape change over a range of time scales. Previously, Dr. Hilley was an Alexander von Humboldt Fellow at the Universität Potsdam, Germany, and a postdoctoral researcher at the University of California, Berkeley. Dr. Hilley earned a Ph.D. in geology from Arizona State University.

KRISTINE M. LARSON is a professor at CU Boulder in the Department of Aerospace Engineering Sciences. Dr. Larson's research interests are focused on developing new applications for GPS instruments, including measuring seismic displacements, ice-sheet speeds and firn density, soil moisture, vegetation water content, snow depth, volcanic ash, and water levels. She is an AGU fellow, a Huygens Medalist, and the recipient of the Prince Sultan Bin Abdulaziz Creativity Award for Water. Dr. Larson earned a Ph.D. in geophysics from the Scripps Institution of Oceanography at UCSD. She has served as a member on the National Academies Committee on New Research Opportunities in the Earth Sciences at NSF and the Committee on National Requirements for Precision Geodetic Infrastructure.

STEFAN MAUS is a senior scientist at CU Boulder at CIRES. At CIRES Dr. Maus analyzes satellite, airborne, marine, and ground magnetic data to model contributions to the geomagnetic field originating in Earth's core, mantle, crust, oceans, and space. From 2004 to 2014 he supported the Department of Defense, NOAA, Coast Guard, Federal Aviation Administration, NASA, and the general public to provide accurate geomagnetic reference information for navigation and pointing. In particular, he led the development and release of the World Magnetic Model (WMM) and International Geomagnetic Reference Field (IGRF) for the years 2005 and 2010, and developed the Enhanced Magnetic Model (EMM) and the Earth Magnetic Anomaly Grid (EMAG2). Dr. Maus is the project leader of international standard ISO16695-Geomagnetic reference models. He contributed in an official advisory role to the Swarm triple-satellite constellation mission, launched successfully in November 2013. Previously, Dr. Maus was a mission scientist on the Challenging Mini-satellite Payload (CHAMP) team at Helmholtz Center Potsdam. He earned a Ph.D. in geophysics from Osmania University, Hyderabad, and his Habilitation in geophysics from the Technical University, Braunschweig.

MICHAEL S. RAMSEY is a professor at the University of Pittsburgh in the Department of Geology and Environmental Science. At the University of Pittsburgh Dr. Ramsey formed the Image Visualization and Infrared Spectroscopy (IVIS) Laboratory, which is a state-of-the-art image analysis, infrared spectroscopy, and GPS facility. His research interests are quite varied but focus on physical volcanology, the impact of volcanic emissions on the atmosphere, hazard mitigation, planetary surface processes, and eolian dynamics primarily using thermal infrared (TIR) imaging analysis, spectroscopy, and satellite remote sensing. Dr. Ramsey also serves as a science team member on three TIR NASA instruments: the Earth-orbiting Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER), the Mars-orbiting Thermal Emission Imaging System (THEMIS), and the airborne Mineral and Gas Identifier (MAGI). Prior to coming to the University of Pittsburgh he was a postdoctoral researcher and visiting faculty member in the Department of Geology (now the School of Earth and Space Exploration) at Arizona State University. Dr. Ramsey was appointed by the NASA administrator as an inaugural member of the Earth Science Subcommittee from 2006-2009. He earned a Ph.D. in geology from Arizona State University. He has not previously served on a National Academies committee.

JEANNE SAUBER is a geophysicist in the Geodesy and Geodynamics Laboratory at NASA GSFC. At NASA Dr. Sauber has led research using numerical modeling techniques constrained by crustal deformation, gravity change, high-resolution topography, and other data to study the mechanics of subduction zones, to constrain earthquake source processes, and to determine the crust-mantle rheological structure. She has been a science team member on the Shuttle Radar Topography Mission (SRTM), ICESat, GRACE, and GRACE-Follow On (GRACE-FO) satellite missions and a member of the Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) and Lidar Surface Topography (LIST) mission concept study teams. Her contribution to these missions includes leading science studies, calibration and validation of early data products, and mission design. She has served as a *Journal of Geophysical Research—Solid Earth* associate editor and on numerous geodesy advisory committees. Dr. Sauber earned a Ph.D. in geophysics at MIT.

KHALID A. SOOFI is a science fellow at ConocoPhillips. Prior to joining ConocoPhillips Dr. Soofi worked at CRINC (a NASA research group at the University of Kansas) as project engineer, where he designed the FM-CW Radar for various research projects. He was the project lead in designing antenna calibration algorithms for the SeaSat satellite and radar background-clutter model for the U.S. Air Force. Since joining ConocoPhillips Dr. Soofi has worked on a full spectrum of remote sensing projects ranging from geological and geomorphological analysis of images, to image processing for logistics, to mapping and engineering applications, as well as environmental baseline studies. Dr. Soofi earned a Ph.D. in electrical engineering from the University of Kansas.

HOWARD A. ZEBKER is professor and chair at Stanford University in the Department of Geophysics. Dr. Zebker also serves as associate chair of the Department of Electrical Engineering at Stanford University. His research group specializes in interferometric radar remote sensing applications and technique development. Originally a microwave engineer, Dr. Zebker built support equipment for the SeaSat satellite synthetic aperture radar and designed airborne radar systems. He later developed imaging radar polarimetry, a technique for measurement of the radar scattering matrix of a surface. He is best known for the development of radar interferometry, leading to spaceborne and airborne sensors capable of measuring topography to meter scale accuracy and surface deformation to mm scale. More recently, he has been participating in the NASA Cassini Mission to Saturn, concentrating on analysis of data acquired by the radar/radiometer instrument. He is a fellow of the IEEE. Dr. Zebker earned a Ph.D. from Stanford University. He served as a member of the National Academies Committee on the Implementation of a Sustained Land Imaging Program; the Panel on Solid-Earth Hazards, Resources, and Dynamics; and the Advanced Rader Technology Panel.

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Acronyms and Abbreviations

2D	two-dimensional
3D	three-dimensional
3D Winds	Three-Dimensional Tropospheric Winds from Space-based Lidar
3MI	Multi-Viewing Multi-Channel Multi-Polarization
3U	3 Unit
20CR	20th Century Reanalysis
AAAR	American Association for Aerosol Research
AAAS	American Association for the Advancement of Science
ABI	Advanced Baseline Imager
ABS	Advanced Baseline Sounder
ACS	American Chemical Society
ACT-America	Atmospheric Carbon and Transport-America
ADM	Atmospheric Dynamics Mission
AERI	Atmospheric Emitted Radiance Interferometer
AGU	American Geophysical Union
AHI	Advanced Himawari Imagers
AIAA	American Institute of Aeronautics and Astronautics
AIM	Aeronomy of Ice in the Mesosphere
AirMOSS	Airborne Microwave Observatory of Subcanopy and Subsurface (EVS-1 Mission)
AIRS	Atmospheric Infrared Sounder
ALOS	Advanced Land Observing Satellite
AMDAR	Aircraft Meteorological Data Relay
AMOC	Atlantic Meridional Overturning Circulation
AMS	American Meteorological Society
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit

AMV	atmospheric motion vector
ANN	artificial neural network
AOD	aerosol optical depth
ASAC	Applied Sciences Advisory Committee
ASCAT	advanced scatterometer
ASCENDS	Active Sensing of CO_2 Emissions over Nights, Days, and Seasons
ASME	American Society of Mechanical Engineers
ASO	Airborne Snow Observatory
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATLAS	Advanced Topographic Laser Altimeter System
ATMS	Advanced Technology Microwave Sounder
A-Train	Afternoon Constellation
AUV	autonomous underwater vehicle
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible and Infrared Imaging Spectrometer
BUV	Backscatter Ultraviolet (instrument on Nimbus-4)
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CATE	Cost Assessment and Technical Evaluation
CATS	Cloud-Aerosol Transport System
CCSP	Climate Change Science Program
CDC	Centers for Diseases Control and Prevention
CDIP	Coastal Data Information Program
CDOM	colored dissolved organic matter
CDWP	California Department of Water Resources
CeNCOOS	Central and Northern California Coastal Ocean Observing System
CEOS	Committee on Earth Observing Satellites
CERES	Clouds and the Earth’s Radiant Energy System
CESAS	Committee on Earth Science and Applications from Space
CGMS	Committee for Meteorological Satellites
CHAMP	Challenging Mini-satellite Payload
CIPS	Cloud Imaging and Particle Size
CIRA	Cooperative Institute for Research in the Atmosphere
CIRAS	CubeSat Infrared Atmospheric Sounder
CIRES	Cooperative Institute for Research in Environmental Sciences
CIRiS	Compact Infrared Radiometer in Space
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CLIVAR	Climate Variability and Predictability
CloudSat	satellite-based cloud experiment
CMA	Chinese Meteorological Administration
CNES	Centre National d’Études Spaciales
CoCoRaHS	Community Collaborative Rain, Hail and Snow Network
CORAL	Coral Reef Airborne Laboratory
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate

COSPAR	Committee on Space Research
COSSEs	Climate Observing System Simulation Experiments
CoSSIR	Conical Scanning Submillimeter-wave Imaging Radiometer
COTS	commercial off-the-shelf
COWVR	Compact Ocean Wind Vector Radiometer
CRADA	Cooperative Research and Development Agreement
CrIS	Cross-track Infrared Sounder
CRM	Cloud Resolving Model
CSA	Canadian Space Agency
CSUMB	California State University, Monterey Bay
CubeRRT	CubeSat Radiometer Radio Frequency Interference Technology Validation
CYGNSS	Cyclone Global Navigation Satellite System-Earth Venture Mission
DAAC	Distributed Active Archive Center
DAS	Data Assimilation Systems
DEMs	digital elevation models
DESDynl	Deformation, Ecosystem Structure, and Dynamics of Ice
DFO	Dartmouth Flood Observatory
DIAL	differential absorption lidar
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
DMSP	Defense Meteorological Satellite Program
DOC	Department of Commerce; also dissolved organic carbon
DOD	Department of Defense
DOE	Department of Energy
DPR	Dual-Frequency Precipitation Radar
DSM	digital surface model
DU	Dobson Units
EarthCARE	Earth Cloud Aerosol and Radiation Explorer
EBV	essential biodiversity variable
ECMWF	European Centre for Medium-Range Weather Forecasts
ECOSTRESS	Ecosystem Spaceborne Thermal Radiometer Experiment on the Space Station
ECS	equilibrium climate sensitivity
EEA	European Environmental Agency
EEI	Earth's Energy Imbalance
EGSIEM	European Gravity Service for Improved Emergency Management
EISWG	Environmental Information Services Working Group
EMSA	European Maritime Safety Agency
EnMAP	Environmental Mapping and Analysis Program
ENSO	El Niño Southern Oscillation
EO-1	Earth Observing Mission-1
EOS	Earth Observing System
EOSDIS	Earth Observing System Data and Information System
EPA	Environmental Protection Agency
EPS-SG	EUMETSAT Polar System-Second Generation
ERC	European Research Council

EROS	Center for Earth Resources Observation and Science
ESA	European Space Agency
ESAS	Earth Science and Applications from Space
ESD	Earth Science Division
ESM	Earth system models
ESO	Earth Science Objective
ESSA	Environmental Science Services Administration
ESSP	Earth System Science Pathfinder
ESTO	Earth Science Technology Office
ET	evapotranspiration
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EU SatCen	EU Satellite Center
EUV	extreme ultraviolet
EV	Earth Venture
EV-I	Earth Venture-Instrument
EV-M	Earth Venture Mission
EV-S	Earth Venture Suborbital
EXPORTS	Export Processes in the Ocean from Remote Sensing
FAT	Fixed Anvil Temperature
FCI	Flexible Combined Imager
FEMA	Federal Emergency Management Agency
FLEX	Fluorescence Explorer
FY	fiscal year
GACM	generalized additive model
GCM	global climate model
GCOM-W1, -W2	Global Change Observation Mission-Water
GCOS	Global Climate Observing System
GDACS	Global Disaster Alert and Coordination System
GEDI	Global Ecosystem Dynamics Investigation
GEO	Group on Earth Observations; also geostationary Earth orbit
GEO-CAPE	Geostationary Coastal and Air Pollution Events (mission)
GeoCARB	Geostationary Carbon Cycle Observatory
GEOS-5	Goddard Earth Observation System Version Five
GEOSCCM	Goddard chemistry climate model
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GFMS	Global Flood Monitoring System
GFS	Global Forecast System
GGOS	Global Geodetic Observing System
GHG	greenhouse gas
GHIS	Geostationary High-resolution Interferometer Sounder
GIC	glaciers and ice caps
GIFTS	Geosynchronous Imaging Fourier Transfer System
GIIRS	Geosynchronous Interferometric Infrared Sounder

GIS	Geographic Information Systems
GLAS	Geoscience Laser Altimeter System
GLDAS	Global Land Data Assimilation System
GLISTIN	Glacier and Land Ice Surface Topography Interferometer
GLONASS	Global Navigation Satellite System
GMAO	Global Modeling and Assimilation Office
GMES	Global Monitoring for Environmental Security
GMSL	global mean sea level
GNSS	Global Navigation Satellite System
GNSS RO	Global Navigation Satellite System Radio Occultation
GOCE	European Gravity Field and Steady-State Ocean Circulation Explorer
GOES	Geostationary Operational Environmental Satellite
GOES-R	Geostationary Orbit Environmental Satellite-R Series
GOSAT	Greenhouse Gas Observing Satellite
GPM	Global Precipitation Measurement
GPP	gross primary productivity
GPS	Global Positioning System
GPSRO	Global Positioning System Radio Occultation
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment-Follow On
GSD	ground sample distance
GSFC	Goddard Space Flight Center
GSICS	Global Space-Based Intercalibration System
GTS	Global Telecommunications System
G-WADI	Water and Development Information for Arid Lands—A Global Network
GWP	global warming potential
HAB	harmful algal blooms
HAQAST	Health and Air Quality Applied Sciences Team
HECC	High-end Computing Capability
HES	Hyperspectral Environmental Suite
HHWP	Hetchy Hetchy Water and Power
HICO	Hyperspectral Imager for the Coastal Ocean
HIRDLS	High-resolution Dynamics Limb Sounder
HISUI	Hyperspectral Imager Suite
HMA	High Mountain Asia
HSRL	High Spectral Resolution LiDAR
HyspIRI	Hyperspectral Infrared Imager
IAA	International Academy of Astronauts
IAGOS	In-service Aircraft for a Global Observing System
IASI	Infrared Atmospheric Sounding Interferometer
ICESat	Ice, Cloud, and Land Elevation Satellite
ICESat-1	Ice, Cloud, and Land Elevation Satellite-1
ICESat-2	Ice, Cloud, and Land Elevation Satellite-2
ICI	Ice Cloud Imager

IESA	Integrated Earth System Analysis
IMERG	Integrated Multi-Satellite Retrievals for GPM
InSAR	Interferometric Synthetic Aperture Radar
InVEST	In-Space Validation of Earth Science Technologies
IOCCG	International Ocean Colour Coordinating Group
IOOS	Integrated Ocean Observing System
IPCC	Intergovernmental Panel on Climate Change
IR	infrared
IRS	infrared sounder
ISRO	Indian Space Research Organization
ISS	International Space Station
ITRF	International Terrestrial Reference Frame
IWG	International Working Group
IWG-SEM	International Working Group on Satellite-based Emergency Mapping
IWP	ice water path
Jason-1	Joint Altimetry Satellite Oceanography Network
JAXA	Japan Aerospace Exploration Agency
JCSDA	Joint Center for Satellite Data Assimilation
JMA	Japanese Meteorological Agency
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
JRC	Joint Research Center
LAD	leaf area density
LAI	leaf area index
LEO	low Earth orbit
LHASA	Landslide Hazard Assessment Model for Situational Awareness
lidar	light detection and ranging
LIO	Low-Inclination Orbiter
LIS	Land Information System
LIST	Lidar Surface Topography
LMR	living marine resource
LST	land-surface temperature
MAGI	Mineral and Gas Identifier
MAIA	Multi-Angle Imager for Aerosols (Earth Venture Instrument)
MAPP	Modeling, Analysis, Predictions and Projections
MBARI	Monterey Bay Aquarium Research Institute
MDSC	mineral dust source composition
MEA	Millennium Ecosystem Assessment
MERIS	medium-spectral resolution imaging spectrometer
MERLIN	Methane Remote Sensing Lidar Mission
MERRA	Modern-Era Retrospective Analysis for Research and Applications
MetOp	Meteorological Operational Satellite Program
MHS	Microwave Humidity Sounder

MIDEX	Medium Class Explorer
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MISR	Multi-angle Imaging Spectroradiometer
MJO	Madden-Julian Oscillation
MLS	Microwave Limb Sounder
MODIS	Moderate-Resolution Imaging Spectroradiometer
MOPITT	Measurements of Pollution in the Troposphere
MPAS	Model for Prediction Across Scales
MRI	Magnetic Resonance Imaging
MRLI	Moderate-Resolution Land Imagery
MRV	measurement, reporting, and verification
MTG-3	Meteosat Third Generation
MTPE	Mission to Planet Earth
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCA	National Climate Assessment
NCEI	National Centers for Environmental Information
NDFD	National Forecast Database
NDVI	Normalized Difference Vegetation Index
NED	National Elevation Dataset
NEP	Net Ecosystem Productivity
NESDIS	National Environmental Satellite Data and Information Service
NEWS	NASA Energy and Water System
NFMS	national forest monitoring and measurement system
NGA	National Geospatial-Intelligence Agency
NGGPS	Next-Generation Global Prediction System
NICAM	Nonhydrostatic Icosahedral Atmospheric Model
NIDIS	National Integrated Drought Information System
NIH	National Institutes of Health
NIR	near infrared
NISAR	NASA-ISRO Synthetic Aperture Radar
NLDAS	North American Land Data Assimilation System
NMME	North America Multi-Model Ensemble
NOAA	National Oceanic and Atmospheric Administration
NOPP	National Ocean Partnership Program
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NPP	Net Primary Production
NRC	National Research Council
NSF	National Science Foundation
NWP	numerical weather prediction
NWPS	Nearshore Wave Prediction System
NWS	National Weather Service
OCO	Orbiting Carbon Observatory
OCO-2	Orbiting Carbon Observatory-2

OCO-3	Orbiting Carbon Observatory-3
OCR	Ocean Color Radiometry
ODS	ozone-depleting substance
OIB	Operation IceBridge
OLI	Operational Land Imager
OMB	Office of Management and Budget
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping Profiler Suite
ONR	Office of Naval Research
OSAAP	Office of Systems Architecture and Advanced Planning
OSB	Ocean Studies Board
OSE	Observing System Experiment
OSIP	Operational Satellite Improvement Program
OSSE	Observing System Simulation Experiment
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
PBL (height)	planetary boundary layer
PDO	Pacific Decadal Oscillation
PGC	Polar Geospatial Center
PI	principle investigator
PIA	Path Integrated Attentuation
PM	particulate matter
PNNL	Pacific Northwest National Laboratory
POES	Polar Operational Environmental Satellites
POR	Program of Record
PRISMA	Precursore Iperspettrale della Missione Applicativa
QFF	Quantitative Flood Forecasts
QPE	quantitative precipitation estimates
QPF	Quantitative Precipitation Forecasts
QuickSCAT	Quick Scatterometer
R&A	research and analysis
RapidScat	International Space Station Rapid Scatterometer, or ISS-RapidScat
RBI	Radiation Budget Instrument
RCP	Representative Concentration Pathway
RF	radiative forcing
RFI	request for information
RMS	root mean square
RO	radio occultation
ROSES	Research Opportunities in Space and Earth Sciences
RY	real year
S2D	season-to-decadal
S2S	subseasonal-to-seasonal
SABOR	Ship-Aircraft Bio-optical Research

SAC	Scientific Application Satellite-C
SAR	Synthetic Aperture Radar
SATM	Science and Applications Traceability Matrix
SCA	snow-covered area
SCAR	Scientific Committee on Antarctic Research
Scattsat-1	Scatterometer Satellite-1
SCCOOS	Southern California Coastal Ocean Observing System
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SCLP	Snow and Cold Land Processes
SeaWiFS	Sea-viewing Wide Field of View Sensor
SI	seasonal-interannual variability
SIF	solar-induced chlorophyll fluorescence
SIPN	Sea Ice Prediction Network
SLI	Sustainable Land Imaging
SLR	Satellite Laser Ranging
SMAP	Soil Moisture Active-Passive
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity
SNODAS	Snow Data Assimilation System
S-NPP	Suomi National Polar-Orbiting Partnership
SNR	signal-to-noise ratio
SNWG	Satellite Needs Working Group
SORCE	Solar Radiation and Climate Experiment
SOT	statement of task
SPRWG	Space Platform Requirements Working Group
SRTM	Shuttle Radar Topography Mission
SSEC	Space Science Engineering Center
SSG	Science Steering Group
SSH	sea-surface height
SSMI	Special Sensor Microwave Imager
SSO	semisynchronous orbit
SSS	sea-surface salinity
SST	sea-surface temperature
STAR	Center for Satellite Applications and Research
STC	Science and Technology Centers
SURFRAD	Surface Radiation Budget Network
SWAT	Soil Water Assessment Tool
SWCRE	shortwave cloud radiative effect
SW CRF	shortwave cloud radiative forcing
SWE	snow water equivalent
SWH	significant wave height
SWIR	shortwave infrared
SWOT	Surface Water and Ocean Topography
TanDEM-X	TerraSAR-X Add-on for Digital Elevation Measurement
TC	tropical cyclone

TCAT	Technical Capability Assessment Team
TCCON	Total Carbon Column Observing Network
TCR	transient climate response
TDS	total dissolved solids
TEMPEST	Temporal Experiment for Storms and Tropical Systems
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TES	Tropospheric Emission Spectrometer
THEMIS	Thermal Emission Imaging System
THORPEX	The Observing System Research and Predictability Experiment
TIR	thermal infrared
TIR	Thermal Infrared Radiometer
TIROS	Television Infrared Observation Satellite Program
TIRS	Thermal Infrared Sensor
TMI	TRMM Microwave Imager
TOA	top of atmosphere
TOMS	Total Ozone Mapping Spectrometer
TOPEX	Ocean Topography Experiment
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission
TROPICS	Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats
TSI	Total Solar Irradiance
UAVSAR	Uninhabited Aerial Vehicle Synthetic Aperture Radar
UCAR	University Corporation for Atmospheric Research
USAID	U.S. Agency for International Development
USCRN	U.S. Climate Reference Network
USDA	U.S. Department of Agriculture
USDM	U.S. Drought Monitor
USGCRP	U.S. Global Change Research Program
USGEO	U.S. Group on Earth Observations
USGS	U.S. Geological Survey
UT/LS	upper troposphere and lower stratosphere
UTS	upper troposphere and stratosophere
UV	ultraviolet
VAS	VISSR Atmospheric Sounder
VCL	Vegetation Canopy Lidar
VHF	very high frequency
VIC	Variable Infiltration Capacity
VIIRS	Visible Infrared Imaging Radiometer Suite
VIS	visible
VIS/IR	visible/infrared measurements
VISSR	Visible and Infrared Spin-Scan Radiometer
VLBI	Very Long Baseline Interferometry
VLM	vertical land motion

VNIR	visible/near infrared
VOC	volatile organic chemical
VOI	value of information
VPD	vapor pressure deficit
VSWIR	visible to shortwave infrared
WCRP	World Climate Research Programme
WE^{2}ST	Center for a Sustainable Water-Energy Education Science and Technology
WHOI	Woods Hole Oceanographic Institution
WMO	World Meteorological Organization
WSF	Weather System Follow-on
WWRP	World Weather Research Program
XOVWM	Extended Ocean Vector Winds Mission
YOTC	Year of Tropical Convection