APPLICATION OF AMSU-BASED PRODUCTS TO SUPPORT NOAA'S MISSION GOALS

Ralph Ferraro [1]
Sheldon Kusselson[2]
Stan Kidder[3]
Limin Zhao[2]
Huan Meng[1]

[1]NOAA/NESDIS
College Park, Maryland

[2]NOAA/NESDIS
Camp Springs, Maryland

[3]Colorado State University
Fort Collins, Colorado

Abstract

Passive microwave observations and derived products from the National Oceanic and Atmospheric Administration (NOAA) Polar-orbiting Operational Environmental Satellite (POES) Advanced Microwave Sounding Unit (AMSU) are now widely used in an assortment of meteorological analysis and forecasting applications. These hydrological and imagery products, which first became operational in January 2000, build upon the success of a similar product suite from the Department of Defense (DoD) Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I). This paper highlights the AMSU rainfall, total precipitable water (TPW) and snowfall rate products with examples from various applications at NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) and National Weather Service (NWS). Discussion of the future polar-orbiting operational satellites and products are presented at the conclusion of the paper.

Corresponding Author: Ralph Ferraro
University of Maryland Research Park (M-Square), 5825 University Research Court, Suite 4001, College Park, MD 20740-3823
Email: Ralph.R.Ferraro@noaa.gov

1. Introduction

During the 1970's and 1980's, most weather forecasters and satellite analysts utilized measurements taken at visible (VIS) and infrared (IR) portions of the spectrum, primarily from instruments on geostationary satellites (e.g., Geostationary Operational Environmental Satellites (GOES) series). During that time period, loops of GOES imagery became the cornerstone of meteorological analysis and nowcasting and are still used today. During the 1990's, another operational satellite sensor became popular by complementing and supplementing the more traditional GOES VIS and IR data; passive microwave (MW) observations taken by the Special Sensor Microwave Imager (SSM/I), which is flown aboard the Department of Defense (DoD) Defense Meteorological Satellite Program (DMSP) polar-orbiting satellite series. This sensor provides forecasters with information when clouds obscure VIS and IR measurements. Because the SSM/I has seven independent measurements, simultaneous retrievals can be performed to obtain information on several meteorological parameters, including rain rate, water vapor, and snow cover (Ferraro et al. 1999). In addition, the retrievals are made using objective algorithms thereby requiring very little human intervention or the use of ancillary data. Recently, the SSM/I sensor has been replaced by the SSMI/S (Special Sensor Microwave Imager/Sounder) that will continue to operate for at least the next decade.

Passive microwave sensors are now standard payloads on polar-orbiting operational satellites throughout the world. For example, the National Oceanic and Atmospheric Administration's (NOAA) Polar-orbiting Operational Environmental Satellites (POES) have carried the Advanced Microwave Sounding Unit (AMSU) sensor since 1998. The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Meteorological Operational (MetOp) satellite (first launched in 2006) carries an AMSU and Microwave Humidity Sounder (MHS). Japan's Advanced Earth Observing Satellite (ADEOS) carried the Advanced Microwave Scanning Radiometer (AMSR) (the future Global Change Observation Mission (GCOM) will also carry an AMSR). Additionally, several research satellites carry passive microwave sensors that are utilized in operational analyses and forecasts, and these include: the National Aeronautics and Space Administration's (NASA) TRMM (Tropical Rainfall Measuring Mission); Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) on NASA's Earth Observing System (EOS) Aqua mission; and the WindSat instrument on the DoD Coriolis satellite mission.

A decade ago a paper by Ferraro et al. (1999) was published in the *National Weather Digest* as a way of introducing the "new" microwave products from SSM/I. The purpose of this paper is to describe the current suite of NOAA/NESDIS (National Environmental Satellite, Data, and Information Service) operational products generated from the AMSU. Section 2 presents an overview of the AMSU products; section 3 presents case studies highlighting the applications of these data and emerging products; and section 4 presents a summary and discussion on new products and applications, as well as future satellite missions.

2. Overview of AMSU Products

The AMSU products are generated through an operational NOAA/NESDIS system known as the Microwave Surface and Precipitation Products System (MSPPS)[1] (Ferraro et al. 2005a). At the time of this writing, operational MSPPS products are generated for the NOAA-15, -16, -17, -18, -19 and MetOp-A satellites.

Table 1 provides an overview of the POES/MetOp AMSU constellation. Table 2 provides some basic information on the AMSU sensors, which consist of two primary modules; AMSU-A, which consists of two radiometers (AMSU-A1 and A2) and AMSU-B. Note that beginning with NOAA-

Satellite	Launch Date	Period of Record	Current Status	Overpass Time (6/09)
NOAA-15	5/13/98	5/98 - present	AM Secondary	1655 (A)
NOAA-16	9/21/00	9/00 – present	PM Secondary	1712 (A)
NOAA-17	6/24/02	6/02 – present	AM Backup	2143 (A)
NOAA-18	5/20/05	5/05 – present	PM Backup	1339 (A)
MetOp-A	10/19/06	10/06 - present	AM Primary	0930 (D)
NOAA-19	2/06/09	2/09 - present	PM Primary	1355 (A)

Table 1. Attributes of the NOAA POES/EUMETSAT MetOp constellation. Overpass time denotes the Equatorial crossing Local Time Ascending (A)/Descending (D) Node.

[1]http://www.star.nesdis.noaa.gov/corp/scsb/mspps/ and http://www.osdpd.noaa.gov/ml/mspps

18 (and continuing with MetOp-A), AMSU-B has been replaced with MHS which is a very similar instrument.

The current and near-future polar-orbiting operational satellite constellation will feature an early AM primary satellite at 0530 Equatorial crossing Local Time Descending Node (LTDN) (DMSP/DOD), mid-AM primary satellite at 0930 LTDN (MetOp/EUMETSAT), and PM primary satellite at 1330 Equatorial crossing Local Time Ascending Node (LTAN) (POES/NOAA)[2]. Thus, in current configuration (as of July 2009), the DMSP (carrying SSMI/S) is the early AM primary (DMSP F-17), MetOp is the mid-AM primary (MetOp-A), and POES is the PM primary (NOAA-19). With this configuration, global observations are made approximately every four hours. NOAA and EUMETSAT established the Initial Joint Polar Orbiting Operational Satellite System (IJPS) in 1999, and it became functional with the launch of MetOp-A in 2006 and will continue into the foreseeable future. With the advent of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) beginning in 2011 with the NPOESS Preparatory Project (NPP) and in 2014 with NPOESS-C1, advanced microwave sensors, such as the Advanced Technology Microwave Sounder (ATMS) and the Microwave Imager/Sounder (MIS), will replace the AMSU/MHS and SSMI/S on the early AM and PM satellites.

A set of nine operational products are provided through MSPPS, as summarized in Table 3. Additionally, imagery of the 31, 89 and 150 GHz channels are also useful for a number of applications and are described in the next section. The accuracy varies for each of these products and channels, and is also noted in Table 3. Historically, the passive microwave total precipitable water (TPW) product is considered to be the most reliable. Individually, many of these products may not meet the accuracy requirements of specific NOAA programs for all forecast and monitoring domains, but their utility is unparalleled when used in remote portions of the globe (where no other measurements are available), in cloud-covered regions, and when used in combination with other satellite and ground measurements. The 4-hour global coverage of the polar-orbiting operational satellite constellation (DMSP/MetOp/POES) and the near all weather capability of the passive MW sensors are their strongest attributes.

AMSU module	Number of Channels	Frequency Range (GHz)	Nadir Spatial Resolution (km)
AMSU A1	13	50.3, 52.8, 53.6, 54.4, 54.9, 55.5, 57.29 (6 bands), 89.0	48
AMSU A2	2	23.8, 31.4	48
AMSU B (MHS)	5 (5)	89, 150, 183.3 (±1, ±3, ±7) (89, 157, 183.3(±1, ±3), 190.3)	16

Table 2. Characteristics of the AMSU (and MHS) sensors.

Product	Surface Type	Resolution (km)	Accuracy (RMS)
Total Precipitable Water	Ocean	48	10%
Cloud Liquid Water	Ocean	48	10%
Rain Rate	Land & Ocean	16	30%
Ice Water Path	Land & Ocean	16	30%
Snow Cover	Land	16	15%
Snow Water Equivalent	Land	16	25%
Sea Ice Concentration	Ocean	48	20%
Surface Temperature	Land	48	10%
Surface Emissivity (23, 31 and 50 GHz)	Land	48	10%

Table 3. Characteristics of the current suite of operational AMSU products. Accuracy information updated from Ferraro et al. 2005a. RMS refers to root mean square error.

3. Applications

AMSU derived products are used in a number of operational applications at NOAA both as stand-alone products and as complements to others. This section will highlight some of these applications, as well as describe some emerging products that have the potential to contributing to operations.

a. Tropical rainfall potential

NESDIS has been producing operational areal Tropical Rainfall Potential (TRaP) forecasts of rainfall for land falling tropical cyclones since the early 2000's. TRaP

[2]Note that polar orbiting satellites cross the equator twice each day in a sun synchronous orbit – ascending (South to North) and descending (North to South) - which is commonly described in terms of LTDN and LTAN.

forecasts are 24-hour forecasts of total accumulated precipitation based on along-track extrapolation of satellite-estimated rain rates. These forecasts are derived from passive microwave sensors, including the AMSU (but also including the SSM/I, AMSR-E and TRMM Microwave Imager (TMI) sensors). TRaP has become a critical tool for NOAA forecasters at the Tropical Prediction Center (TPC), the Hydrometeorological Prediction Center (HPC), and at local weather forecast offices of the National Weather Service (NWSFO) in forecasting the distribution and amount of rainfall expected from the land falling storms. The TRaP products are accessible through the internet and through the National Advanced Weather Interactive Weather Processing System (N-AWIPS). TRaP is also used by meteorological agencies of other countries such as Australia, Japan and Taiwan.

TRaP forecasts are conceptually quite simple. To produce an areal TRaP, a satellite "snapshot" of instantaneous rain rates is propagated forward in time following the predicted path of the cyclone using track forecasts made at operational tropical cyclone warning centers in the region under threat. Every 15 minutes a new position is calculated and the spatial rain rates applied over a rectangular grid of approximately 8 km resolution; the 15-minute accumulations are summed over a period of 24 hours (Kidder et al. 2005). Three basic assumptions are made in the calculation of TRaP forecasts: (a) the satellite rain rate estimates are accurate, (b) the forecasts of cyclone track are accurate, and (c) the rain rates over a 24 h period can be approximated as steady state following the cyclone path. Errors in TRaP rainfall predictions can be attributed to flaws in one or more of these assumptions (Ferraro et al. 2005b; Ebert et al. 2005). In recent years, 6 h TRaP rainfall accumulations have been produced and archived as part of the operational processing of 24 h TRaPs. These provide useful short-period forecasts that can be used to generate time series of predicted rain evolution at locations of interest.

Figure 1 presents an example of a 24-h TRaP for Hurricane Ike as it was approaching the Texas and Louisiana coastlines on 12-13 September 2008. Figure 1b shows the anticipated 24 h rainfall which is based upon the instantaneous AMSU rain rates (Fig. 1a) and the TPC's predicted storm direction and speed over that time (shown in yellow in Fig. 1a). Also shown (Fig. 1c) is the 24 h Stage-IV (i.e., radar and rain gauge composite) accumulated rainfall for the same time period. Note the excellent agreement in terms of magnitude and area of the TRaP forecast as compared to the ground observations. There is a slight westward shift in the actual rainfall, apparently due to a slight forecast track error. However, for a 24 h advance forecast, the TRaP typically outperforms numerical weather prediction (NWP) model forecasts (Ferraro et al. 2005b).

The original TRaP product has recently been enhanced into an ensemble TRaP (eTRaP)[3] (which became operational on August 1, 2009) by weighting the individual components based on their known error characteristics (Ebert et al. 2009). In this manner, the forecaster will have a single set of products to examine rather than having to compare and evaluate individual TRaP's from the various polar-orbiting satellite estimates.

The eTRaP is a simple ensemble whose members are the 6-hourly totals from the single-orbit TRaPs. This ensemble approach allows the generation of probabilistic forecasts of rainfall in addition to deterministic rainfall totals similar to what is currently provided by the TRaP product. Each eTRaP is made up of forecasts using observations from potentially several microwave sensors (currently AMSU, TMI, SSM/I, and AMSR-E-initialized at several observation times) and possibly using several different track forecasts. The diversity among the ensemble members helps to reduce the large (and unknown) errors associated with a single-sensor, single-track TRaP. The large number of perturbations leads to ensembles with many members, allowing probability forecasts to be issued with good precision and reliability (Ebert et al. 2009).

An eTRaP is produced, centered on the synoptic hours (e.g., 00 UTC, 06 UTC, 12 UTC, 18 UTC), from single-orbit TRaP segments with start times within 3 hours of the synoptic hour. Therefore, a 00 UTC eTRaP is available to customers around 0315 UTC. The eTRaP consists of deterministic and probabilistic rain forecasts for each of four 6 h lead times (i.e., 00-06 h, 06-12 h, 12-18 h, 18-24 h) as well as the 24 h cumulative time period. Probabilistic forecasts at four rain thresholds are provided for each time period, including the 24-hour cumulative period. The thresholds chosen for computing probabilistic forecasts are 25, 50, 75 and 100 mm for 6 h forecast periods, and 50, 100, 150 and 200 mm for the 24 h forecast period. An example of an eTRaP for Hurricane Rita valid at 0000 UTC 25 September 2005 is presented in Fig. 2.

b. Total precipitable water (TPW) products

In terms of passive microwave products, TPW is perhaps the most widely used to support real-time forecasting applications, as it accurately depicts tropospheric water vapor and its movement. In particular, it has proven to be extremely useful in determining the location, timing, and duration of "atmospheric rivers" which contribute to and sustain flooding events (Ralph et al. 2004). Such

[3]http://www.ssd.noaa.gov/PS/TROP/etrap.html

Fig. 1(a).

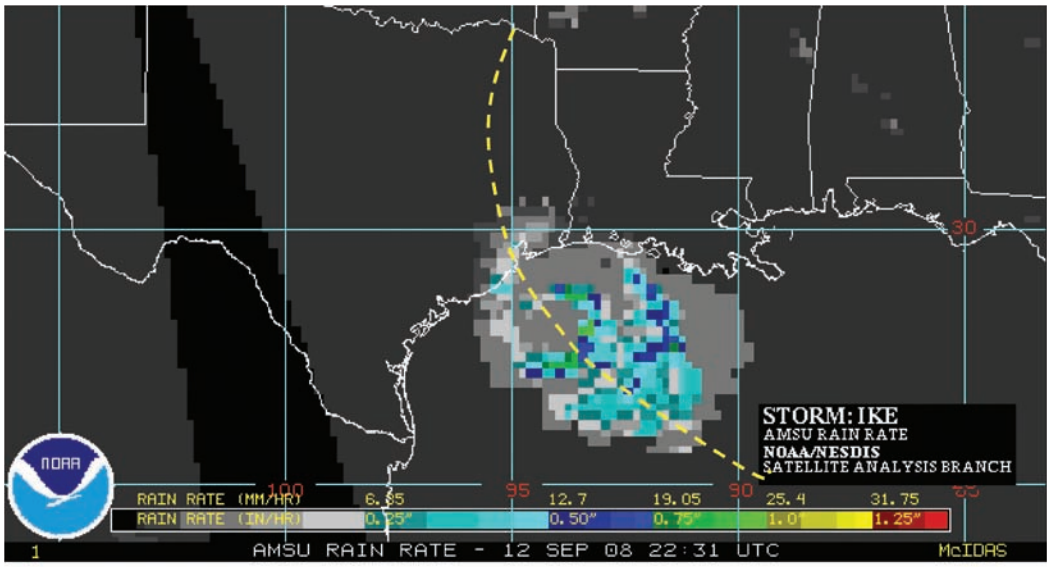

Fig. 1(b).

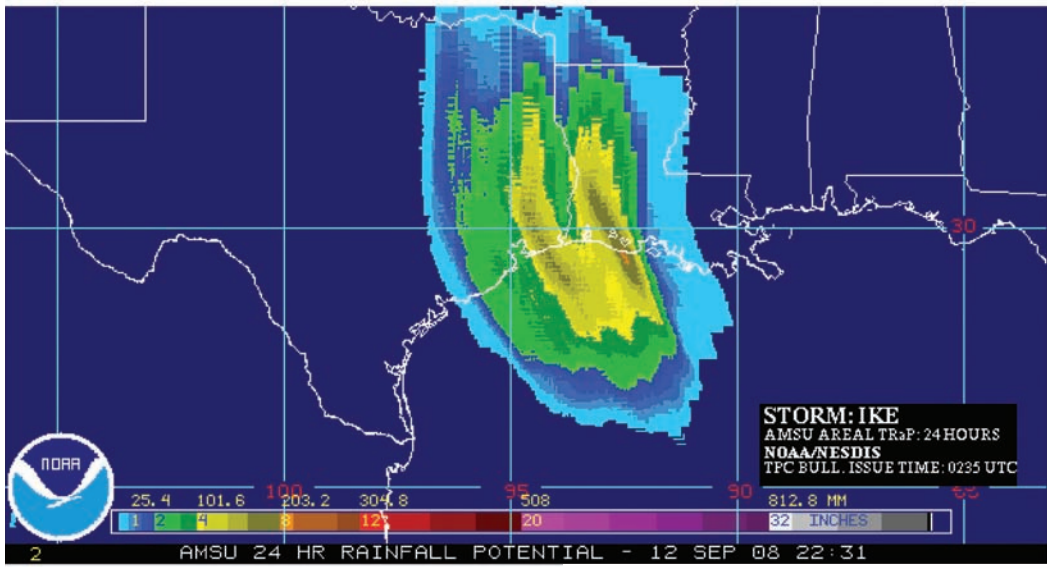

Fig. 1(c).

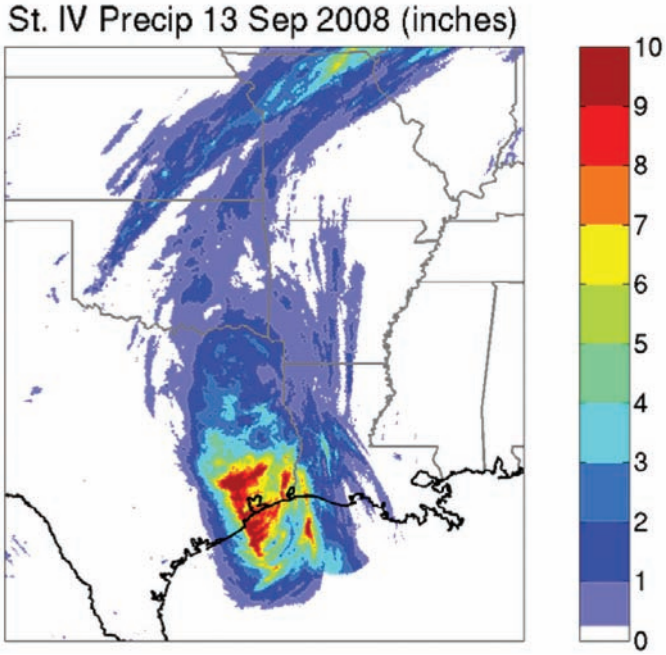

Fig. 1. (a) AMSU overpass for 2231 UTC on 12 September 2008. TPC best track forecast shown in yellow dashed line. (b) Tropical Rainfall Potential (TRaP) for Hurricane Ike for the 24-hr period ending 2231 UTC on 13 September 2008. The TRaP forecast was generated using the AMSU overpass in (a) and the TPC best track forecast. (c) 24 hour rainfall totals based on NOAA Stage IV radar-gauge estimates for approximately the same time period as the TRaP.

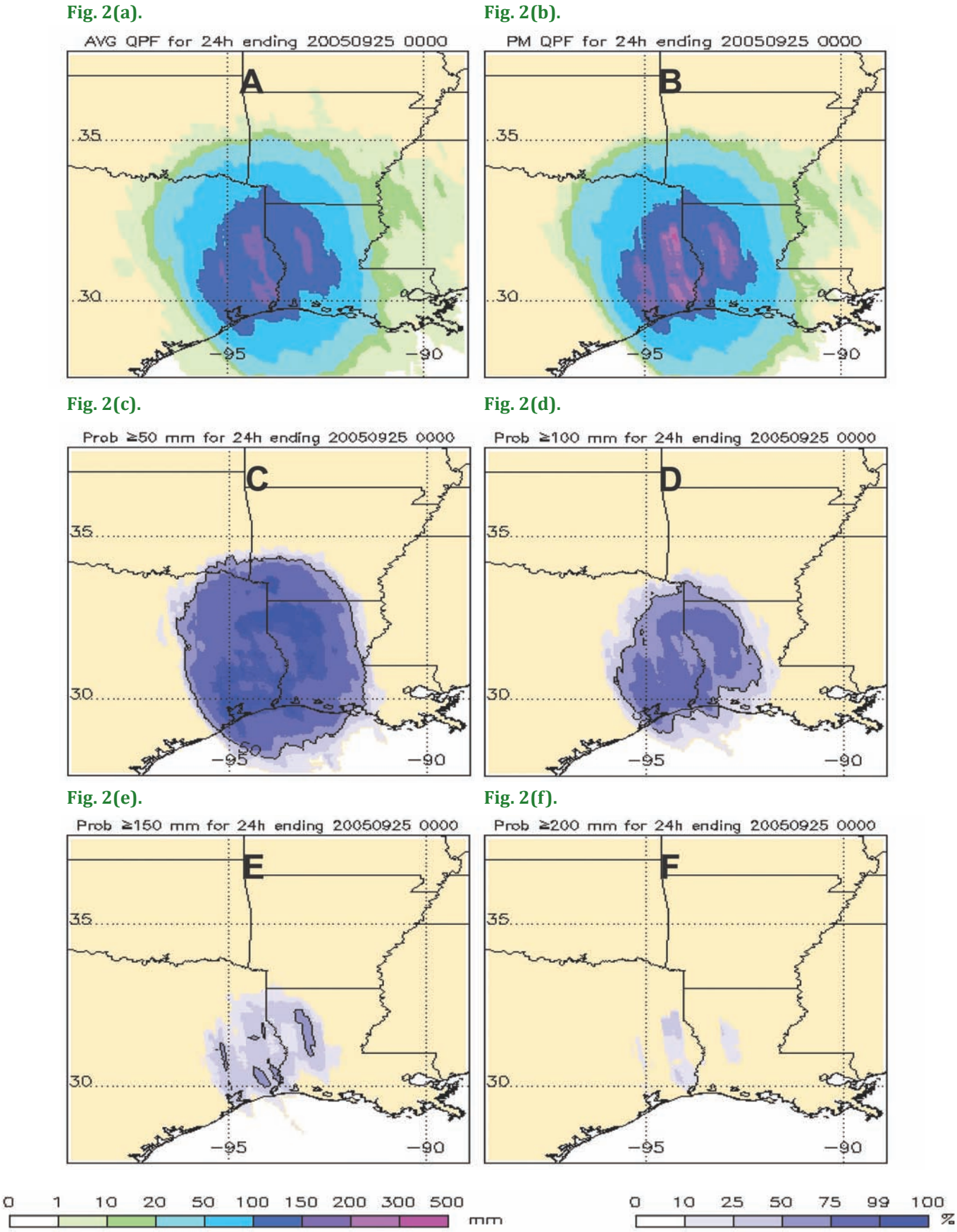

Fig. 2. eTRaP for Hurricane Rita as it was making landfall. The time period is for 24-hrs ending on 0000 UTC 25 September 2005. (a) Ensemble average 24-hr total in mm. (b) Ensemble maximum 24-hr rainfall total. (c) – (f) Probability (percent) of rainfall exceeding 50 mm, 100 mm, 150 mm and 200 mm, respectively.

phenomena are detectable throughout the United States, with the most common streaming from the tropical Pacific Ocean into the Western U.S. and from the Caribbean into the Eastern Seaboard.

Early uses of TPW were developed with the SSM/I (Kusselson 1993); however, the method has been expanded to include data from all passive microwave sensors, including AMSU. Recently, a multi-sensor approach has been developed and implemented at NESDIS in which passive microwave estimates from multiple satellites and sensors are merged to create a seamless TPW product that is more efficient for forecasters to use[4]. Because these estimates are restricted to oceanic regions, ground-based estimates over land that are derived from the Global Positioning System (GPS) are also included for product continuity across coastlines (Gutman et al. 2004). Figure 3 illustrates how these individual sources of TPW are brought together to form a single graphic; details are provided by Kidder and Jones (2007).

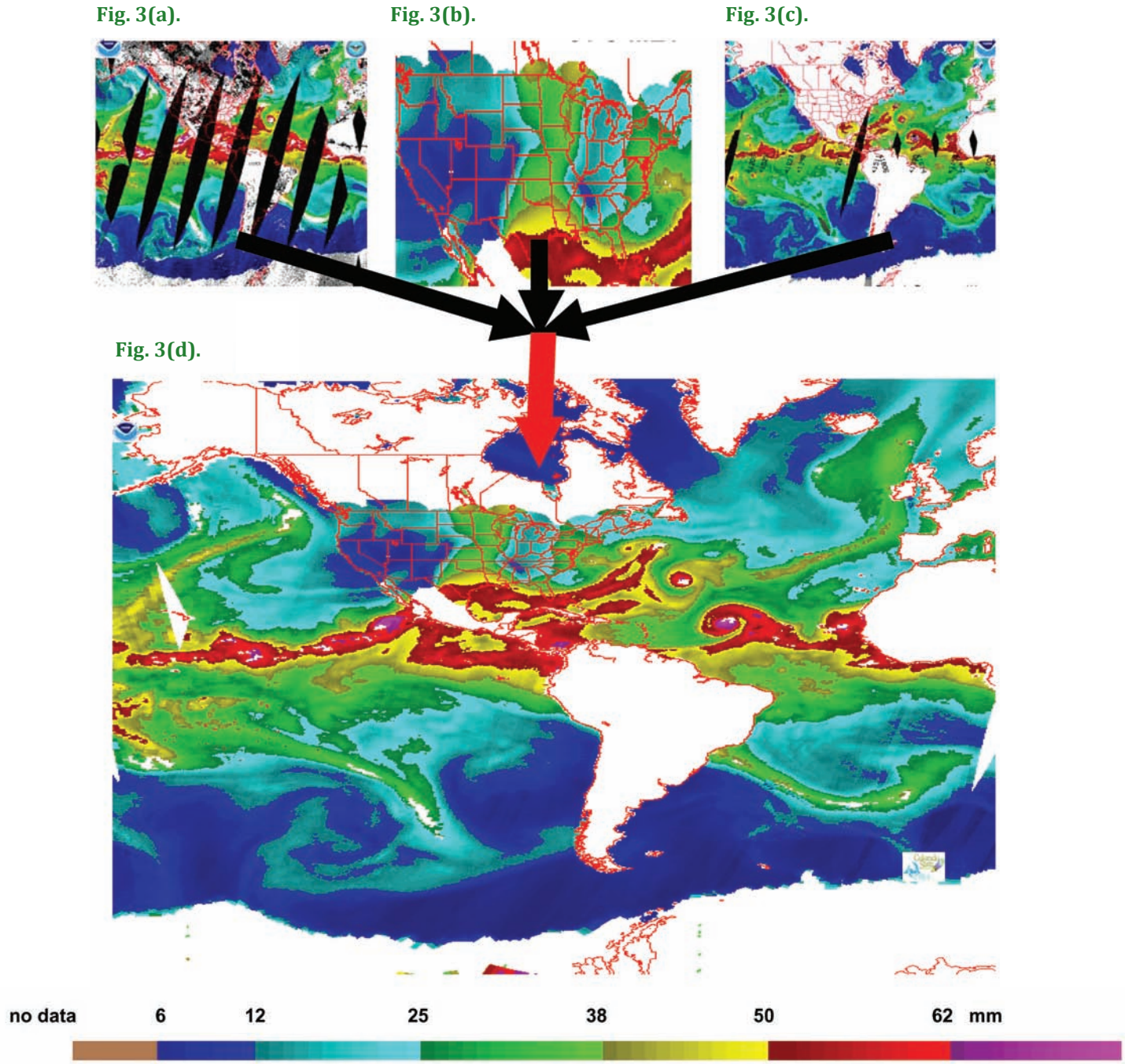

Fig. 3. Schematic illustrating how individual Total Precipitable Water (TPW) estimates (in mm) from (a) SSM/I, (b) GPS, and (c) AMSU are combined into a single TPW product (d).

[4]http://www.osdpd.noaa.gov/bTPW/

To illustrate how this product can be used in weather forecasting and analysis, Fig. 4 presents an example of a blended TPW product (Fig. 4a) for a record flooding event in the Mid-Atlantic States during June 2006. As highlighted by the black oval, a TPW plume, with origins in the Western Atlantic Ocean, is focused over the region with values approaching 60 mm. This helped NOAA/NESDIS Satellite Analysis Branch (SAB) analysts focus on this area for potential heavy rain generation and flash flooding, and alert forecasters of their concerns through their direct interactions with the NWSFO's, their briefings to HPC forecasters and the issuance of Satellite Precipitation Estimate (SPENES) text messages. During the following 48 hours, heavy rain developed and flooding occurred. The results were an area of 200 - 400 mm of rain that fell through June 27 (Fig. 4b) which contributed to flooding of a major highway in the Maryland suburbs of the Washington, D.C. metropolitan area (Fig. 4c) and resulted in at least one drowning and major problems for rush hour commuters.

Fig. 4(a).

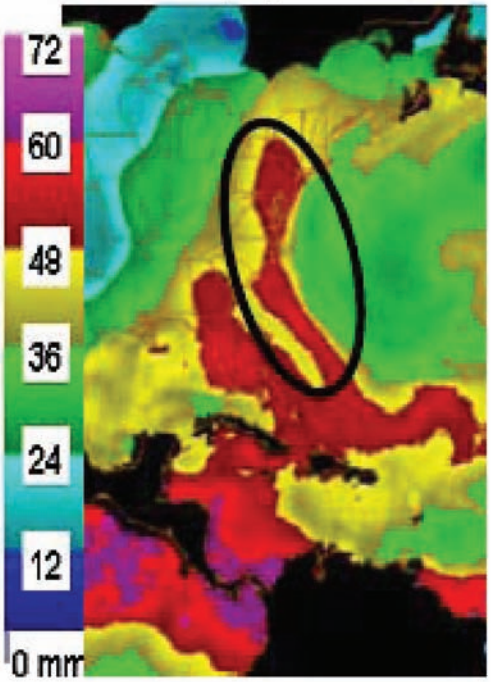

Fig. 4(b).

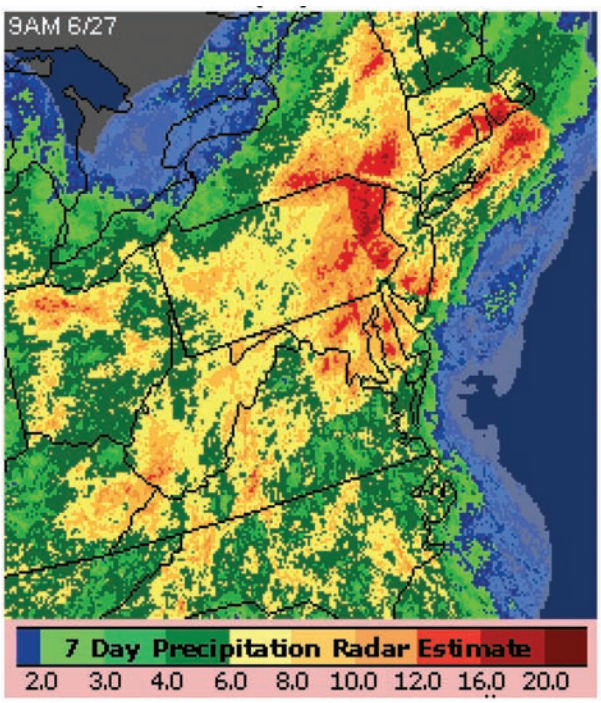

Fig. 4(c).

Fig. 4. (a) TPW estimates (mm) on the morning of 25 June 2006. Note the large plume of high TPW along the Atlantic seaboard, which contributed to record rainfall in this area based on WSR-88D radar estimates (b). The flooded road scene (c) is from Montgomery County, MD, which received approximately 10 inches of rain during the period from 25-27 June 2006; (c) is courtesy of the Associated Press.

c. Climate applications

All of the AMSU orbital products were reprocessed in 2007 using the latest set of algorithms so that a consistent time series is available. With nine years (2000 – 2008) of reliable AMSU retrievals, the data can be used for climate monitoring such as tracking seasonal to interannual variations. Note that the early period of NOAA-15 data experienced some sensor anomalies which makes such data not useful for climate applications; it was corrected in late 1999. Additionally, all of the most recent AMSU data are utilized in a number of combined precipitation data sets such as the NOAA Climate Prediction Center (CPC) MORPHing technique (CMORPH) (Joyce et al. 2004), TRMM Multi-satellite Precipitation Analysis (TMPA) (Huffman et al. 2007) and blended TPW products (Kidder and Jones, 2007) which span longer time periods. The merged precipitation products utilize the strengths of the MW and IR satellite data to produce the most accurate estimates. The MW instantaneous rates are considered more accurate than the IR, but the advantage of the GOES estimates is that they are more timely and are produced more often than the MW. Thus, the MW data are used to train the more frequent and timely IR measurements. Their combined use is far more accurate than using either MW or IR estimates alone (Joyce et al. 2004).

To demonstrate the use of such data on a global scale, Fig. 5 shows the global mean AMSU-derived precipitation for December – February (DJF) and June – August (JJA)

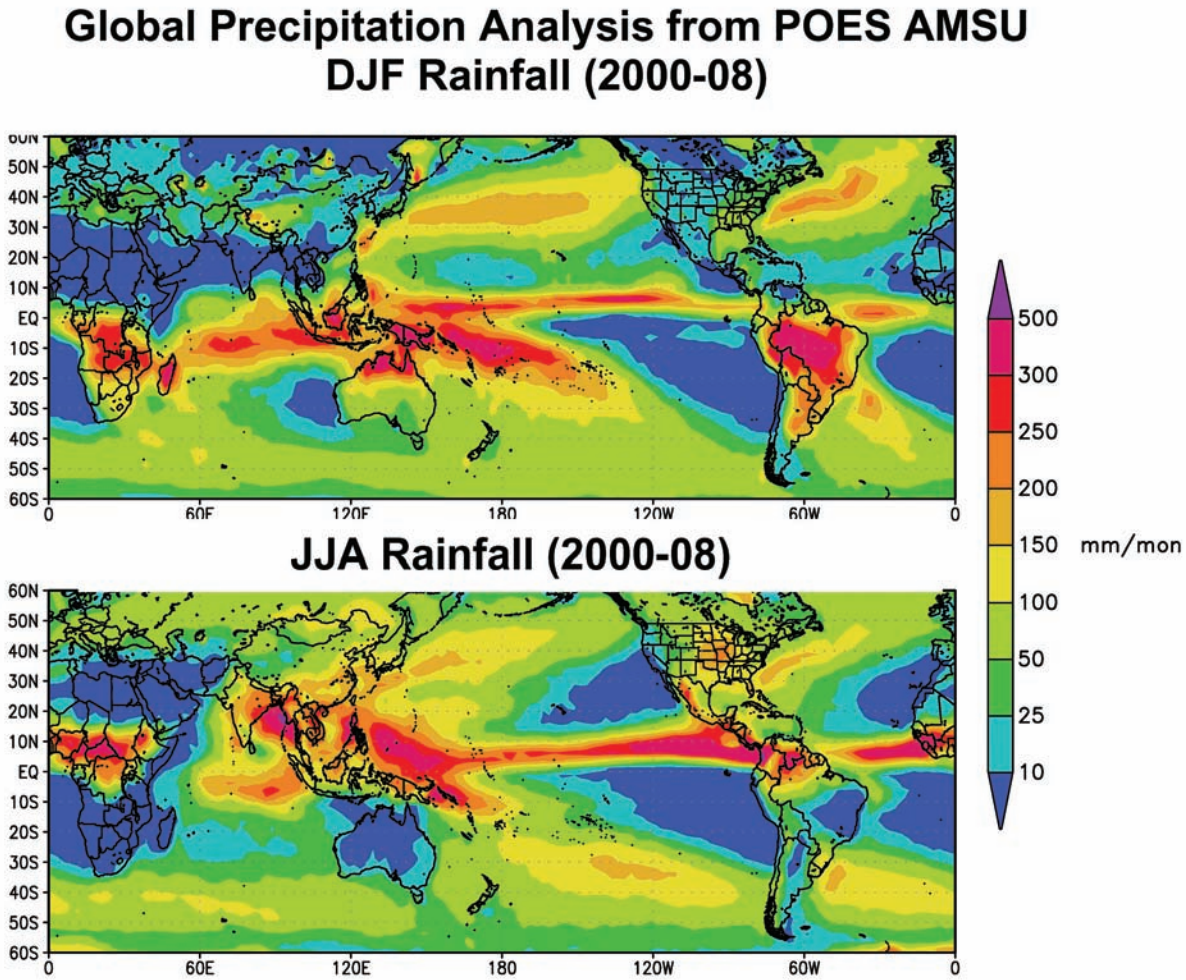

Fig. 5. AMSU derived rainfall climatology (2000 - 2008) for December, January, February (top) and June, July, August (bottom).

for the period 2000 - 2008. The heaviest rainfall is in the Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ) where up to 500 mm mon^{-1} falls, in particular, during JJA. A shift of the ITCZ northward is evident between DJF and JJA, whereas the mid-latitude storm tracks shift poleward during each hemisphere's respective summer, and are the most intense during winter. Other interesting regional phenomena are evident, such as the monsoonal regions in India and the southwestern U.S., and the increase in rainfall over land during the summer seasons.

For monitoring seasonal to interannual climate variations, Fig. 6 shows a time series of the monthly rainfall anomaly for the "Nino 4 region" (5 S – 5 N, 160 E – 150 W) of the tropical Pacific for both AMSU (Fig. 6a) and SSM/I (Fig. 6b). This region is strongly influenced by sea surface temperature (SST) changes due to warm/cold episodes (Fig. 6c). Note the strong correspondence between the rainfall (AMSU) and SST anomalies, clearly indicating AMSU's ability to accurately depict rainfall response due to changes related to El Niño-Southern Oscillation (ENSO). The warming SSTs enhance tropical convection while cooling suppresses it. For comparison, a similar product derived from the SSM/I (Ferraro et al. 1996) is shown and is very similar to what is found with the AMSU. AMSU's ability to track such seasonal to interannual changes offers operational centers such as NOAA's CPC the ability to monitor and predict their effects over the United States, where warm/cold SST events can have dramatic impact on precipitation patterns.

The relatively short time record limits the utility of AMSU as a stand-alone climate tool; however, combining its time series with those on other sensors such as SSM/I and TMI (dating back to 1987 and 1997, respectively) provides a tremendous data set already being exploited by the scientific community. This data will then be extended in the future with the current satellites in operation and eventually with the NPOESS ATMS and MIS sensors, and those other sensors that will be part of the upcoming NASA Global Precipitation Measurement (GPM) mission.

Fig. 6(a).

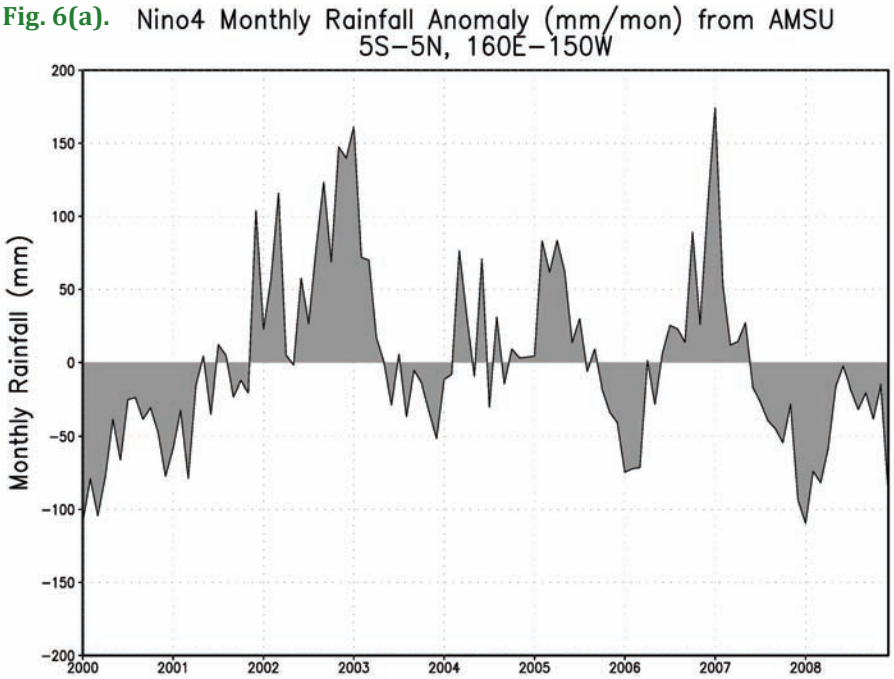

Fig. 6(b).

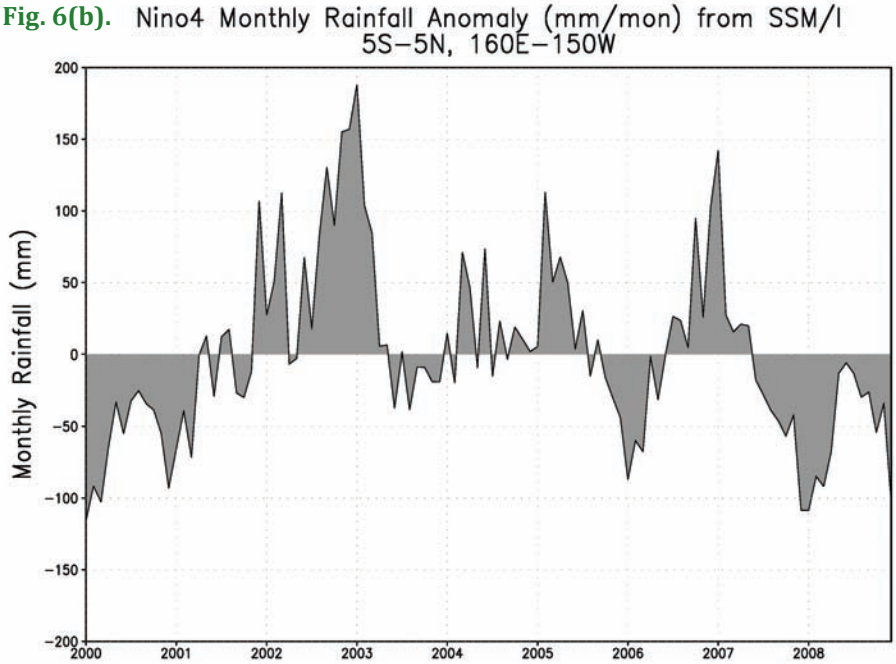

Fig. 6. Monthly rainfall anomalies (mm mon^{-1}) based on the January 2000 – December 2008 base period for the "Nino4" region (5 S – 5 N, 160 E – 150 W) of the tropical Pacific Ocean for (a) AMSU and (b) SSM/I. (c - on facing page) SST anomalies (deg K) for the same region and base period are also shown.

d. Emerging products – snowfall rate

There are other emerging products that are being derived from AMSU. These include hydrological products that are important in the winter season such as snowfall rate and snow water equivalent. This section will focus on the snowfall rate product.

Determining areas of precipitation in the form of snow (and subsequently, the snowfall rates), is an extremely difficult and challenging problem in remote sensing. IR data are not very sensitive to the rate of stratiform precipitation in general and snowfall in particular. Passive MW techniques, in particular those using frequencies above 85 GHz, have shown promise (e.g., Bennartz and Bauer 2003; Kongoli et al. 2003; Skofronick-Jackson et al. 2004). The main challenge is separating the surface snow cover influence from the precipitation signature. However, the opaqueness of the higher frequencies (due to the presence of water vapor) allows for the masking of the surface in temperate climate regions. Regions that are too cold and dry, and where the precipitation layer is shallow still pose challenges in the retrieval. Without sufficient atmospheric moisture, surface snow will be detected and cause false alarms in the precipitation detection. Missions such as CloudSat[5] and the upcoming GPM[6] will be useful to advance the science through the synergistic use of both passive and active MW systems.

In 2005, the operational AMSU precipitation product added a snow identification algorithm (Kongoli et al. 2003.), however, the conversion to a snowfall rate still remains in an evaluation phase because of the difficult nature of developing a reliable conversion between the IWP (ice water path) and surface snowfall rate. Nonetheless, work continues on this snowfall rate product and it may be elevated to operational status during the 2010-11 winter season.

[5]http://cloudsat.atmos.colostate.edu/
[6]http://gpm.gsfc.nasa.gov/

Fig. 6(c).

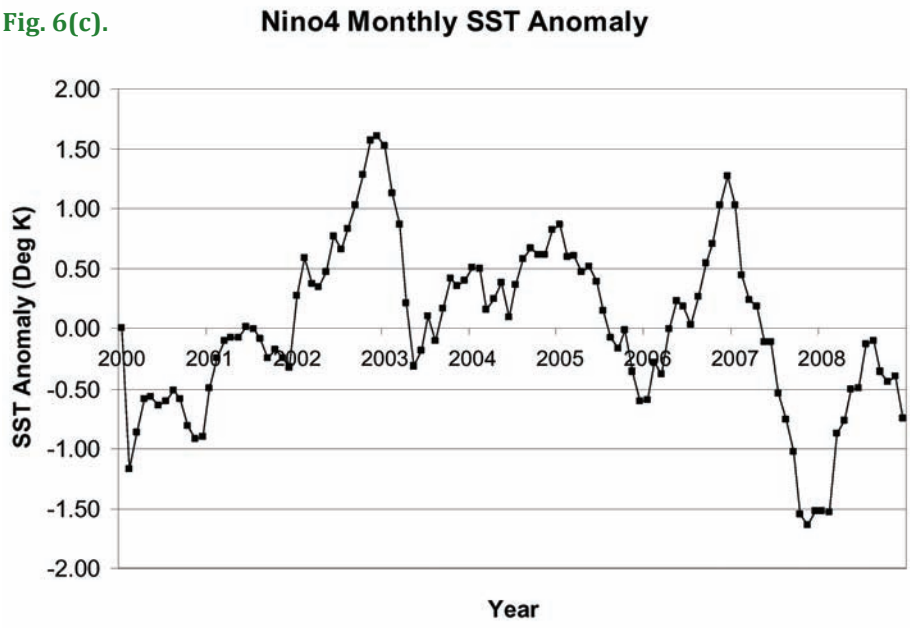

Figure 7 presents an excellent example of the potential utility of the AMSU snowfall rate product. Here, a 24 h time sequence of a winter weather event that tracked across the central and eastern U.S. (27-28 January 2009) is presented as it was being evaluated by NESDIS/SAB forecasters. As can be seen, the AMSU snow rate product depicts the progression of the main two snow features from southwest to northeast across the United States. The heaviest snowfall rates are 0.5 mm h^{-1} in water equivalent (the maximum allowed by the algorithm). To further evaluate the algorithm performance, surface observations for the last overpass in the sequence are overlaid on the black

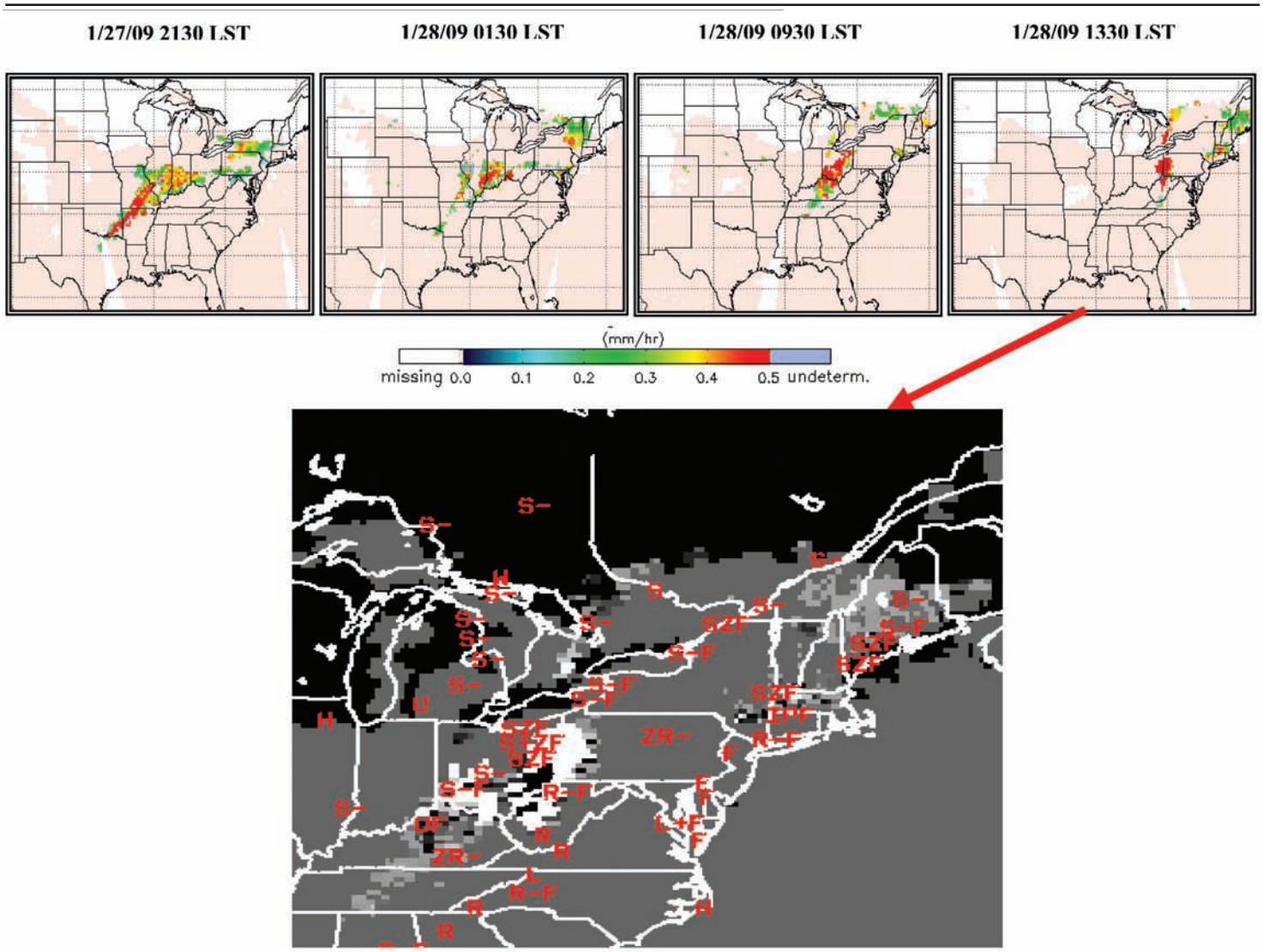

Fig. 7. Experimental AMSU snowfall rates (mm h water equivalent) for a 24 h sequence for 27-28 January 2009 (upper color images). Regions in white indicate areas where no retrieval was made, while the salmon color is precipitation free. Shown in black and white image (lower panel) is the last AMSU overpass at 1330 LST on 28 January 2009 which has surface observations superimposed in red.

and white AMSU precipitation product; areas of snow depicted by AMSU are shown in the various grey shades. In the main snow band in PA, WV and OH, the surface reports indicate light to moderate snow which confirms the AMSU product. However, there are regions where no snow was retrieved by the algorithm and it is speculated that this snow was either too shallow or the atmosphere was too dry and cold; for the former, the AMSU is simply not sensitive enough to pick out this feature and for the latter, the present algorithm will not attempt a retrieval under these atmospheric conditions. The reason is that the algorithm avoids regions where the atmosphere is too dry and the confusion between the surface snow and falling snow would result in too many false alarms (Kongoli et al. 2003).

The scientific community continues to work on this retrieval problem through data being analyzed from the CloudSat mission (e.g., Liu 2008). Additionally, it is anticipated that after the GPM core satellite launch in late 2013, excellent quality data will be obtained from collocated passive and active MW sensors and that significant advances will be made in snowfall retrievals.

4. Summary and Future

In this paper we have presented a short summary of the operational hydrological products generated at NOAA/NESDIS from the Advanced Microwave Sounding Unit. Over the past 10 years, these products have become an integral part of NOAA's operations, primarily in the areas of forecasting and warning, and climate monitoring. Integrated with similar products from DMSP SSM/I and SSMI/S and NASA research satellite missions (TRMM and EOS), a wealth of information is available to forecasters which complement other information from GOES, in-situ measurements and numerical weather prediction models.

Specific examples for total precipitable water (atmospheric rivers), rainfall (eTRaP and climate) and snowfall rates were presented. We also discussed how some of these products have been composited and blended using similar information from multiple satellites and in-situ data, thus offering the forecaster one product to look at as opposed to the same product from many different satellites. This should serve to improve the forecasters' ability to synthesize the wealth of information available to them, and as a result, increase the timely delivery of more accurate forecasts to the public.

NESDIS plans on continuing to generate these products from passive MW sensors on future polar-orbiting operational satellites, including the NPOESS Preparatory Project (NPP) ATMS sensor and the NPOESS ATMS and MIS sensors. Data from ATMS on NPP should begin to be available in 2011 and from MIS on NPOESS-C2 in 2016. Additionally, NESDIS is moving towards an advanced retrieval package known as MIRS[7] (Microwave Integrated Retrieval System) that will be portable to any passive MW sensor and utilize the same basic physical retrieval scheme (Boukabara et al. 2007). MIRS will become the primary product generation system after NOAA-15, -16 and -17 cease operations.

Authors

Ralph Ferraro is a Physical Scientist with NOAA/NESDIS in College Park, MD. He is currently Chief of the Satellite Climate Studies Branch; his research activities include the development of advanced retrieval algorithms for precipitation with NOAA and NASA satellites. He received the B.S. in Meteorology from Rutgers University in 1980 and the M.S. in Meteorology from the University of Maryland in 1982.

Sheldon Kusselson has been an operational satellite meteorologist in NESDIS' Satellite Analysis Branch since 1979. His primary focus has been with satellite precipitation and in addition, he has been the polar microwave focal point for his branch since 1991. He received the B.S. in Meteorology from Pennsylvania State University in 1975.

Stan Kidder is a Senior Research Scientist at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University. He received the Ph.D. in Atmospheric Science from Colorado State University in 1979. He specializes in applying satellite data to meteorological problems.

Limin Zhao is a Physical Scientist with NOAA/NESDIS/OSDPD. She received the M.S. in Meteorology from the University of Oklahoma in 1994 and the M.S. in Atmospheric Physics from University of Science and Technology of China in 1984. She has worked in the fields of radar meteorology, mesoscale modeling, data assimilation and satellite remote sensing, and is now the focal point for NESDIS operational precipitation products.

Huan Meng is a Physical Scientist at NOAA/NESDIS. She received the Ph.D. in hydrology from Colorado State University in 2004. Her research interests are algorithm development using satellite microwave measurements in general, and snowfall rate retrieval using AMSU data in particular.

[7]http://www.osdpd.noaa.gov/ml/mirs/

References

Bennartz, R., and P. Bauer, 2003: Sensitivity of microwave radiance at 85-183 GHz to precipitating ice particles. *Radio Sci.,* 33(4), 8075, doi:10.1029/2002RS002626.

Boukabara, S., F. Weng, and Q. Liu, 2007: Passive microwave remote sensing of extreme events using NOAA-18 AMSU-A and MHS. *IEEE Trans. Geosci. Remote Sens.,* 45**,** 2228-2246.

Ebert, E.E., S. Kusselson and M. Turk, 2005: Validation of NESDIS operational tropical rainfall potential (TRaP) forecasts for Australian tropical cyclones. *Aust. Meteorol. Mag.*, 54, 121-135.

_____, A. E. Salemi., M. Turk., M Spampata and S.J. Kusselson, 2009: Validation of the ensemble Tropical Rainfall Potential (e-TRaP) for land-falling tropical cyclones. *16th Conference on Satellite Meteorology and Oceanography,* Phoenix, AZ, Amer. Meteor. Soc.

Ferraro, R.R., F. Weng, N. Grody, and A. Basist, 1996: An eight year (1987-94) climatology of rainfall, clouds, water vapor, snowcover, and sea-ice derived from SSM/I measurements. *Bull. of Amer. Meteor. Soc.,* 77*,* 894-905.

_____, R.R., S.J. Kusselson and M. Colton, 1999: An introduction to passive microwave remote sensing and its applications to meteorological analysis and forecasting. *Natl. Wea. Dig.,* 22**,** 11-23.

_____, F. Weng, N. Grody, L. Zhao, H. Meng, C. Kongoli, P. Pellegrino, S. Qiu, and C. Dean, 2005a: NOAA operational hydrological products derived from the AMSU. *IEEE Trans. Geo. Remote Sens.,* 43**,** 1036 – 1049.

_____, P. Pellegrino, M. Turk, W. Chen, S. Qiu, R. Kuligowski, S. Kusselson, A. Irving, S. Kidder, and J. Knaff, 2005b: The Tropical Rainfall Potential (TRaP) Technique. Part II: Validation. *Wea. Forecasting,* 20**,** 465 – 475.

Gutman, S.I., S.R. Sahm, S.G. Benjamin, B.E. Schwartz, K.L. Holub, J.Q.Stewart, and T.L. Smith,2004: Rapid retrieval and assimilation of ground based GPS precipitable water observations at the NOAA Forecast Systems Laboratory: Impact on weather forecasts*. J. Meteor. Res. Japan*, 82, 351-360.

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 Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrometeor.*, 8, 38–55.

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. *J. Hydrometeor.*, 5, 487–503.

Acknowledgments

The authors would like to thank the contributions of all current and past members of the NOAA Microwave Surface and Precipitation Products (MSPPS) team: Sid Boukabara, Wanchun Chen, Charles Dean, Chris Duda, Ingrid Guch, Norm Grody, Cezar Kongoli, Doug Moore, John Paquette, Paul Pellegrino, Pam Taylor, Fuzhong Weng, Jiang Zhao, and Cheng-Zhi Zou. In particular, we would like to dedicate this paper to Paul Pellegrino who recently passed away and was always a driving force on making the AMSU and TRaP products "bigger and better"; he will be missed by us all. In addition, we are grateful to the continuous support from NOAA's Polar Product Manager, Tom Schott, who has made the AMSU-based MSPPS products a success. We also acknowledge the contributions of Elizabeth Ebert and Michael Turk on the TRaP/eTRaP products and John Forsythe and Andy Jones on the blended TPW product. Finally, we truly appreciate the excellent suggestions by the reviewers to improve the manuscript!

Kidder, S. Q., S. J. Kusselson, J. A. Knaff, R. R. Ferraro, R. J. Kuligowski, and M. Turk, 2005: The Tropical Rainfall Potential (TRaP) Technique. Part I: Description and Examples. *Wea. Forecasting*, 20, 456-464.

_____, and A.S. Jones, 2007: A blended satellite total precipitable water product for operational forecasting. *Journal of Atmos. Oceanic Technol.*, 24, 74-81.

Kongoli, C., P. Pellegrino, R. Ferraro, N. Grody, and H. Meng, 2003: A new snowfall detection algorithm over land using measurements from the Advanced Microwave Sounding Unit (AMSU). *Geophys. Res. Lett.*, 30**,** 1756-1759.

Kusselson, S.J., 1993: The operational use of passive microwave data to enhance precipitation forecasts. *13th Conference on Weather Analysis and Forecasting*, Vienna, Virginia, Amer. Meteor. Soc., 434-438.

Liu, G., 2008: Deriving snow cloud characteristics from CloudSat observations. *J. Geophys. Res.*, 113, D00A09, doi:10.1029/2007JD009766.

Ralph, F.M., P.J. Neiman, and G.A. Wick, 2004: Satellite and CALJET aircraft observations of atmospheric rivers over the eastern North Pacific Ocean during the winter of 1997/98. *Mon. Wea. Rev.*, 132, 1721-1745.

Skofronick-Jackson, G., M. Kim, J. Weinman, and D. Chang, 2004: A physical model to determine snowfall over land by microwave radiometry. *IEEE Trans. Geosci. Remote Sens.,* 42**,** 1047- 1058.