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Key Points:
- A new data set containing Atmospheric Infrared Sounder observations and designed for climate model evaluation has been published
- This data set includes monthly mean gridded tropospheric air temperature, specific humidity, and relative humidity at eight pressure levels
- The standard error and number of observations, for an estimate of data uncertainty, along with three technical notes are also provided

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The Atmospheric Infrared Sounder Obs4MIPs Version 2 Data Set

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Abstract The Atmospheric Infrared Sounder (AIRS) Obs4MIPs (Observations for Model Intercomparison Projects) Version 2 data set includes monthly mean tropospheric air temperature, specific humidity, and relative humidity for each calendar month from September 2002 to September 2016, on a global 1° × 1° latitude-longitude spatial grid and on the Coupled Model Intercomparison Project eight mandatory vertical pressure levels from 1,000 to 300 hPa. It also includes standard error and number of observations, for an estimate of AIRS data retrieval error and sampling uncertainty. Three new technical notes describe the data set. This data set is designed for Coupled Model Intercomparison Project climate model evaluation and has been published at Earth System Grid Federation data centers since April 2018. It adds new monthly mean tropospheric relative humidity data to Obs4MIPs and updates and extends the monthly mean tropospheric air temperature and specific humidity data in AIRS Obs4MIPs Version 1 data set. The data source for this data set is the AIRS Version 6 Level 3 standard monthly mean air temperature, specific humidity, and relative humidity data products in the "TqJoint" grids from the AIRS and Advanced Microwave Sounding Unit A combined physical retrievals. This paper documents this data set in terms of motivation for this data set, data description, data origin and processing procedures, major improvements from the previous version, and caveats for its use in climate model evaluation.

Plain Language Summary We have published a new data set designed for climate model evaluation from the infrared and microwave atmospheric sounding system (Atmospheric Infrared Sounder and Advanced Microwave Sounding Unit A) on the NASA Aqua satellite. In this paper, we briefly describe the reasons for providing this data set, its detailed data structure, the original data and processing procedures used to generate this data set, major improvements in comparison to the previous version, and the issues to be considered for climate model evaluation with it.

1. Introduction

The Coupled Model Intercomparison Project (CMIP) is a major international multimodel research activity organized under the auspices of the World Climate Research Programme's Working Group on Coupled Modeling (Meehl et al., 2005, 2007; Taylor et al., 2012). It collects and archives the outputs from multiple climate models around the world in a standardized format and makes them publicly available through the Earth System Grid Federation (ESGF) data replication centers for analyses by the wider climate research community. The CMIP has become a central element of national and international assessments of climate change. The CMIP Phase 3 (CMIP3) multimodel data set (Meehl et al., 2007) has played an important role for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC, 2007), as has the CMIP Phase 5 (CMIP5) multimodel data set (Taylor et al., 2012) for the IPCC Fifth Assessment Report (AR5; IPCC, 2013). The upcoming IPCC Sixth Assessment Report (AR6), scheduled for publication around 2021, will rely mainly on the peer-reviewed analyses of the upcoming CMIP Phase 6 (CMIP6) experiments (Eyring et al., 2016). To increase the fidelity of IPCC assessment reports, the CMIP model experiments need rigorous evaluation by comparing the model outputs to the state-of-the-art observations and by quantifying the model errors that may lead to climate projection uncertainties (Flato et al., 2013; Randall et al., 2007).

To help CMIP model evaluation, Obs4MIPs (Observations for Model Intercomparison Projects) collects documented satellite data sets, organizes them according to CMIP standards, and makes them available at the ESGF data centers (Ferraro et al., 2015; Teixeira et al., 2014). Each Obs4MIPs data set contains a physical quantity that is output from one or more of the CMIP experiments. This technical alignment of observational products with climate model outputs can greatly facilitate climate model evaluation, development, and research. Guidelines have also been developed for Obs4MIPs product documentation that is of particular relevance for model evaluation. The Obs4MIPs was initiated with support from National Aeronautics and Space Administration (NASA) and the U.S. Department of Energy and has now expanded to include (1) contributions from a broader community and products that rely on a number of other agency's satellites (e.g., European Space Agency, European Organization for the Exploitation of Meteorological Satellites, National Oceanic and Atmospheric Administration, and Japan Aerospace Exploration Agency) and (2) guidance and support from the World Climate Research Programme Data Advisory Council.

The Atmospheric Infrared Sounder (AIRS)/Advanced Microwave Sounding Unit A (AMSU-A) on the NASA Aqua satellite (Aumann et al., 2003; Chahine et al., 2006; Tian et al., 2010, 2006) is one of several current advanced atmospheric temperature and humidity sounding systems in space. Using multispectral coverage in infrared and microwave channels, the AIRS/AMSU-A sounding system retrieves vertical profiles of atmospheric temperature, specific humidity, and relative humidity with vertical resolution of around 2 km, horizontal resolution of about 45 km at nadir, twice daily temporal resolution, and daily near-global coverage, for cloud cover up to about 70% (Maddy & Barnet, 2008; Susskind et al., 2014; Wong et al., 2015). The AIRS temperature profiles are accurate from the surface to the lower stratosphere while the AIRS humidity profiles are accurate from the surface to the upper troposphere even for very dry conditions. Since the launch of the NASA Aqua satellite on 4 May 2002, the AIRS/AMSU-A sounding system has provided high-quality atmospheric temperature and humidity profiles spanning about one and half decades.

We have published the AIRS Obs4MIPs Version 1 (V1) data set in 2011 (Tian, 2011a, 2011b; Tian, Fetzer, et al., 2013). It includes the monthly mean tropospheric air temperature and specific humidity data for each calendar month from September 2002 to May 2011, on a global 1° × 1° latitude-longitude spatial grid, and on the eight CMIP5 mandatory vertical pressure levels from 1,000 to 300 hPa. The AIRS Obs4MIPs V1 data set is one of the first satellite data sets available in Obs4MIPs and one of the most frequently downloaded Obs4MIPs data sets for CMIP5 model evaluation (personal communication, Robert Ferraro, 2013). Tian, Fetzer, et al. (2013) documented the data origin, data description, data validation, and caveats for model-observation comparison of the AIRS Obs4MIPs V1 data set.

Tian, Fetzer, et al. (2013) also compared the AIRS Obs4MIPs V1 data set and CMIP5 model simulations and found two noticeable biases in CMIP5 models, that is, a tropospheric cold bias of ~2 K and a double-Intertropical Convergence Zone (ITCZ) bias. Tian (2015) further quantified the strengths of double-ITCZ bias in 44 CMIP3/5 models using the AIRS Obs4MIPs V1 data set and found that the strength of the double-ITCZ bias and equilibrium climate sensitivity (ECS) in CMIP3/5 models are negatively correlated. The models with a weak double-ITCZ bias have a high ECS value and vice versa. This suggests that the strength of double-ITCZ bias is a new emergent constraint for ECS and ECS is in the higher end of its range in models (~4.0 °C). It also demonstrates that AIRS data can help constrain model ECS and improve climate models and future climate prediction.

However, there are three obvious limitations for the AIRS Obs4MIPS V1 data set. First, the AIRS Obs4MIPs V1 data set extends only through May 2011. Second, it is based on the AIRS Version 5 (V5) Level 3 (L3) data instead of the newer AIRS Version 6 (V6) L3 data that have numerous changes and improvements in comparison to AIRS V5 L3 (Tian, Manning, et al., 2013). Third, the AIRS Obs4MIPs V1 data set does not include monthly mean tropospheric relative humidity, an important physical variable for climate model evaluation. Importantly, monthly mean relative humidity data calculated based on the monthly mean air temperature and specific humidity data in AIRS Obs4MIPs V1 are physically inconsistent and not suitable for climate model evaluation due to the different samplings of monthly mean air temperature and specific humidity data (Hearty et al., 2014; Tian, Fetzer, et al., 2013).

Under the auspices of the NASA Data for Operation and Assessment program, we recently generated and published the AIRS Obs4MIPs Version 2 (V2) data set (Tian, 2018a, 2018b, 2018c) to overcome the limitations of the AIRS Obs4MIPs V1 data set mentioned above by adding the monthly mean tropospheric relative humidity to Obs4MIPs and by updating and extending the monthly mean tropospheric air temperature and specific humidity in the AIRS Obs4MIPs V1 data set using the AIRS V6 L3 data. The purpose of this paper is to document the characteristics of the AIRS Obs4MIPs V2 data set.

Table 1
AIRS Observations for Model Intercomparison Projects V2 Data Set File Names and Contents

File names	File contents
ta_mon_AIRS-TA-v2.0_BE_gn_200209-201609.nc	The monthly mean air temperature (ta) in Kelvin
taStderr_mon_AIRS-TA-v2.0_BE_gn_200209-201609.nc	The standard error (Stderr) of air temperature in Kelvin
taNobs_mon_AIRS-TA-v2.0_BE_gn_200209-201609.nc	The number of observations (Nobs) of air temperature
TechNote_ta_AIRS_V2.pdf	The technical note of air temperature
hus_mon_AIRS-TA-v2.0_BE_gn_200209-201609.nc	The monthly mean specific humidity (hus) in kg/kg
husStderr_mon_AIRS-TA-v2.0_BE_gn_200209-201609.nc	The standard error (Stderr) of specific humidity in kg/kg
husNobs_mon_AIRS-TA-v2.0_BE_gn_200209-201609.nc	The number of observations (Nobs) of specific humidity
TechNote_hus_AIRS_V2.pdf	The technical note of specific humidity
hur_mon_AIRS-TA-v2.0_BE_gn_200209-201609.nc	The monthly mean relative humidity (hur) (unitless)
hurStderr_mon_AIRS-TA-v2.0_BE_gn_200209-201609.nc	The standard error (Stderr) of relative humidity (unitless)
hurNobs_mon_AIRS-TA-v2.0_BE_gn_200209-201609.nc	The number of observations (Nobs) of relative humidity
TechNote_hur_AIRS_V2.pdf	The technical note of relative humidity

Note. AIRS = Atmospheric Infrared Sounder.

2. Data Set Description

The AIRS Obs4MIPs V2 data set has been publicly available on the ESGF website (https://esgf-node.llnl.gov/projects/obs4mips) since April 2018. This data set includes monthly mean tropospheric air temperature (ta) in Kelvin, specific humidity (hus) in kg/kg, and relative humidity (hur) in 1. For each physical variable (ta, hus, or hur), there are corresponding standard error (Stderr) and number of observations (Nobs) for a rough estimate of the AIRS data retrieval error and sampling uncertainty. The Stderr estimates the retrieval error of the AIRS Level 2 (L2) observations in the 45-km AMSU-A field of regard (FOR) per 1° × 1° latitude-longitude grid cell. The Nobs estimates the effective number of the AIRS L2 observations in the 45-km AMSU-A FOR per 1° × 1° latitude-longitude grid cell. They are all provided for each calendar month from September 2002 to September 2016, on a global 1° × 1° latitude-longitude spatial grid and on the eight CMIP mandatory vertical pressure levels (plev) from 1,000 to 300 hPa (1,000, 925, 850, 700, 600, 500, 400, 300 hPa). Three technical notes (Tian, 2018a, 2018b, 2018c) that describe the key information needed to use this data set for CMIP climate model evaluation are also provided. The specifics of the AIRS Obs4MIPs V2 data sets are almost the same as its previous version (V1; Tian, Fetzer, et al., 2013). There are 12 files in total available on ESGF website associated with the AIRS Obs4MIPs V2 data set, including 3 PDF files for the technical notes and 9 netCDF data files. The file names and their contents are listed in Table 1.

As an example of AIRS Obs4MIPs V2 data, Figure 1 shows the monthly mean relative humidity (Figure 1a), its standard error (Figure 1b), and its number of observations (Figure 1c) at 500 hPa for September 2002. The monthly mean midtropospheric (500 hPa) relative humidity is in the range of 0 and 1.2 and its spatial distribution shows well-known dynamic features of the atmosphere, such as high relative humidity values due to deep convection and rising motions in equatorial regions (e.g., ITCZ) and high latitudes, and low relative humidity values due to subsidence over the subtropics. The standard error of monthly mean midtropospheric relative humidity is in the range of 0 and 0.17, typically about 15% of its mean value. The number of observations of monthly mean midtropospheric relative humidity varies between 0 and 210 and its spatial distribution shows the inhomogeneous samplings of the AIRS data due to the Aqua satellite's orbit and the AIRS physical retrieval algorithm (Fetzer et al., 2006; Hearty et al., 2014; Tian, Fetzer, et al., 2013; Yue et al., 2013). The AIRS sampling is low near the poles (~20 per month), and in cloudy regions such as the equatorial western Pacific warm pool (~100 per month) and the midlatitude storm tracks (i.e., north Pacific, north Atlantic, and 60°S latitude belts; ~80 per month). The AIRS sampling is high (~160 per month) near 70° latitude belts and in clearer regions, such as subtropics and midlatitude land regions (Hearty et al., 2014; Tian, Fetzer, et al., 2013). More discussion of this sampling issue can be found in section 5.

3. Data Origin and Processing Procedures

Launched into Earth orbit on 4 May 2002, Aqua is part of NASA's "A-Train" constellation, a series of high-inclination, Sun-synchronous satellites in low Earth orbit designed to make long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans (Stephens et al., 2002). The Aqua satellite

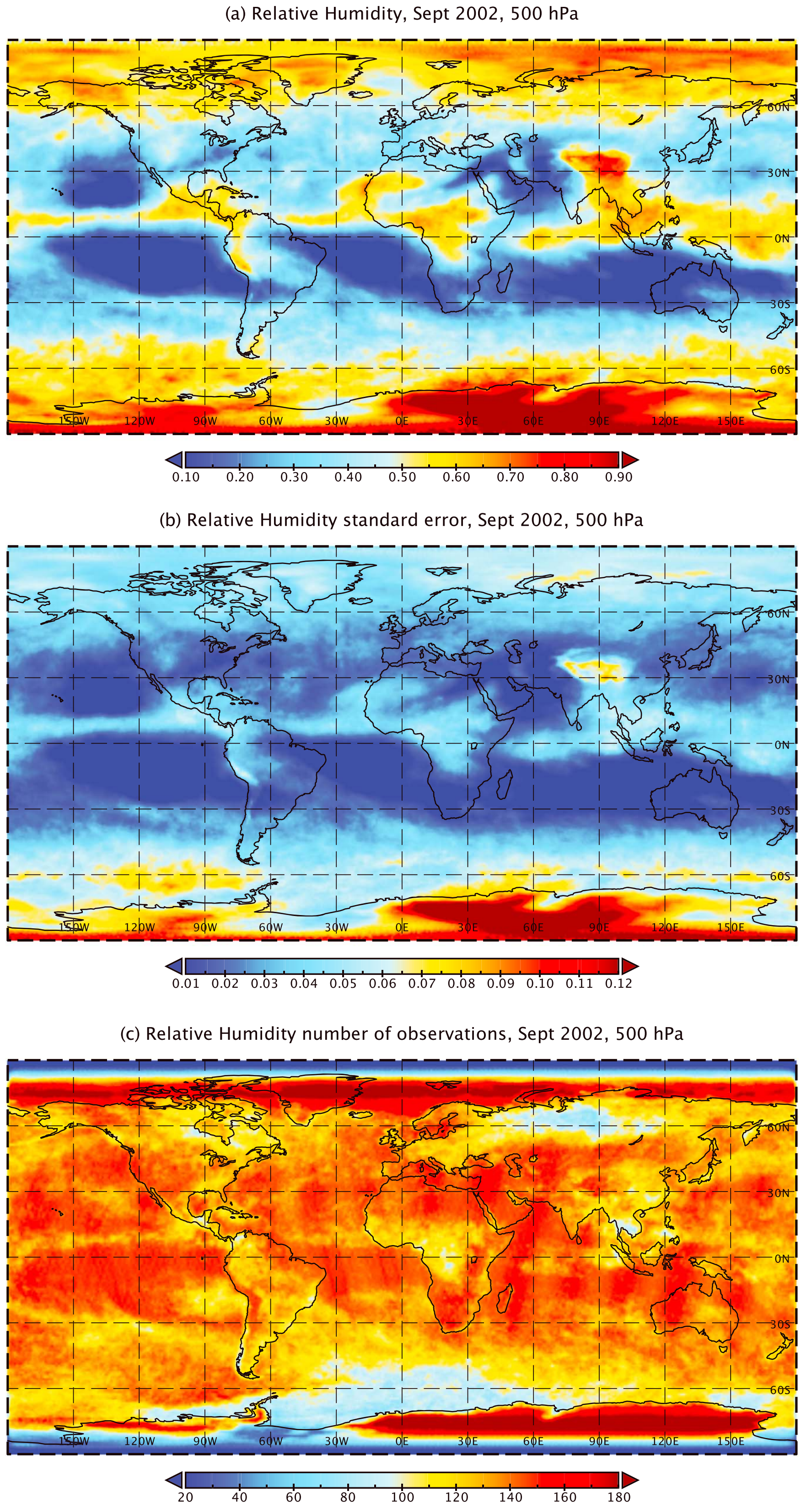

Figure 1. The monthly mean relative humidity (a), its standard error (b), and its number of observations (c) at 500 hPa for September 2002 from the Atmospheric Infrared Sounder Observations for Model Intercomparison Projects V2 data set.

orbits the Earth every 98.8 min with an equatorial crossing time going north (ascending) at 1:30 P.M. local time and going south (descending) at 1:30 A.M. local time in a Sun-synchronous, near polar orbit with an inclination of 98.2° and 705 km of operational altitude (Parkinson, 2003). There are six instruments on Aqua including AIRS and AMSU-A.

The AIRS and AMSU-A instruments are coaligned cross-track scanning nadir sounders. The AIRS instrument is a 2,378-channel grating spectrometer measuring infrared radiances at wavelengths in the range 3.7–15.4 μm with a horizontal resolution of about 13.5 km at nadir (Aumann et al., 2003). These wavelengths are sensitive to temperature and moisture profiles, clouds, minor gases, and surface properties. The AMSU-A instrument is a 15-channel microwave sounder measuring microwave radiances with a horizontal resolution of about 45 km at nadir. It is implemented as two independently operated modules: module 1 (AMSU-A1) has 12 channels in the 50- to 58-GHz oxygen absorption band that provide the primary temperature sounding capabilities and one channel at 89 GHz that provides surface and moisture information, while module 2 (AMSU-A2) has two channels—at 23.8 and 31.4 GHz—that provide information about the surface (i.e., surface emissivity and surface temperature), and about low-altitude moisture (i.e., water vapor, liquid water, and rain), particularly useful over ocean (Lambrigtsen, 2003). The AIRS and AMSU-A instruments scan the Earth's surface perpendicular to their direction of orbit with a scan angle of 49.5° at the swath edges and a swath width of ~1,650 km. The instruments cover the globe from pole to pole twice daily. Because the scanning swaths do not overlap at low latitudes, there are some gaps near the equator. However, these gaps are scanned within 2–3 days.

The AIRS and AMSU-A instruments have been NASA's advanced atmospheric temperature and moisture sounding system in space. The term "sounder" or "sounding" in the instruments' names refers to the fact that they provide temperature and water vapor information as a function of height. Their combined operations began on 31 August 2002 and ended when the AMSU-A2 instrument stopped working on 24 September 2016. The AIRS Obs4MIPs V2 data set includes the entire AIRS/AMSU-A record from September 2002 through September 2016.

The latest publicly available AIRS data products are produced using the AIRS V6 data processing system. The AIRS V6 data products have three processing levels: Level 1B (L1B), Level 2 (L2), and Level 3 (L3). The L1B data products are geolocated, calibrated observed infrared, microwave, and visible/near-infrared radiances as well as quality assessment data at the AIRS FOV (~15 km) or AMSU-A FOR (~45 km; swath). They are the data sources for the AIRS V6 L2 and L3 data products.

The L2 data products are geolocated, calibrated cloud-cleared radiances and two- or three-dimensional retrieved geophysical quantities at the AIRS FOV or AMSU-A FOR (swath). The L2 data products are generated from the L1B data products using geophysical retrieval algorithms. There are three types of geophysical retrieval algorithms to generate the L2 data products depending on the L1B data input from the AIRS and AMSU-A instruments. The AIRS-only retrieval algorithm uses the L1B infrared radiances from the AIRS instrument only, while the MW-only retrieval algorithm uses the L1B microwave radiances from AMSU-A instrument only. On the other hand, the AIRS/AMSU-A combined retrieval method uses an iterative, least-squares physical inversion of cloud-cleared infrared radiances, obtained from a combination of nine AIRS FOVs contained within each AMSU-A FOR (Susskind et al., 2014). Of the three L2 data types, only the AIRS/AMSU-A combined retrieved data products are used for the AIRS Ob4MIPs V2 data set.

The L3 data products are regularly averaged and gridded retrieved geophysical quantities on global 1° × 1° latitude-longitude grids, at specified vertical pressure levels, for the ascending and descending orbit separately, and at specified temporal resolutions (Tian, Manning, et al., 2013). The L3 gridded data products are derived from the L2 swath data products. The L2 quality control (QC) flags determine which of the L2 data products are combined to create the L3 data products. For the Standard grids (ascending and descending) within AIRS V6 L3 standard products, one QC flag per each physical variable (field) is used to collect all the L2 data products where the QC level is 0 (best) or 1 (good). This ensures that these grids have the most complete set of data available for each field and level, but the use of different ensembles for different physical variables can complicate comparisons across physical variables or levels. The "TqJoint" (short for joint QC on T and q) grids (ascending_TqJoint and descending_TqJoint) in AIRS V6 L3 standard data products apply a single, unified QC criterion for all physical variables: TSurfAir_QC must be 0 (best) or 1 (good). This criterion ensures a physically consistent relative humidity product and the TqJoint grids contain data for a

Table 2
Atmospheric Infrared Sounder Data Uncertainty Estimates for Different Geophysical Conditions

Geophysical variables	Geophysical conditions	Uncertainty estimates
Air temperature	Nonpolar ocean, 1,000–300 hPa	1 K
	Nonpolar land, 850–300 hPa	1 K
	Nonpolar land, 1,000–850 hPa	1–2 K
	Polar, 1,000–300 hPa	1–2 K
Specific humidity	Nonpolar ocean, 1,000–300 hPa	15–25%
	Nonpolar land, 850–300 hPa	15–25%
	Nonpolar land, 1,000–850 hPa	30–40%
	Polar, 1,000–300 hPa	30–40%
Relative humidity	Subtropical ocean, 1,000–300 hPa	15%
	Polar land, 1,000–300 hPa	15–25%

common set of observations across water vapor and temperature at all pressure levels. However, the actual number of observations for temperature and water vapor can be different for the lowest levels because of the details of the retrieval process. This limitation will be fixed in the upcoming AIRS Version 7 L3 product. Of the two L3 grid types, only the TqJoint grid data products are used for the AIRS Ob4MIPs V2 data set.

For each grid map of mean values there are corresponding maps of standard deviation, counts, minimum, maximum, and in some cases error estimate. The L3 data products contain retrieved parameters on standard pressure levels roughly matching instrument vertical resolution and are designed for use by the research and application community. Temperature and humidity profiles are reported on 24 pressure levels from 1,000 to 1 hPa (1,000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 15, 10, 7, 5, 3, 2, 1.5, and 1 hPa) or 12 pressure levels from 1,000 to 100 hPa (1,000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, and 100 hPa). The AIRS Obs4MIPS V2 data are reported on the subset of these levels between 1,000 and 300 hPa.

The L3 data products are separated into ascending and descending orbit separately, where "ascending or descending" refers to the direction of movement of the subsatellite point at equator crossings. The ascending direction of movement is from Southern Hemisphere to Northern Hemisphere, with an equatorial crossing time of 1:30 P.M. local time for Aqua; the descending direction of movement is from Northern Hemisphere to Southern Hemisphere, with an equatorial crossing time of 1:30 A.M. local time for Aqua. Outside of the polar zones, these correspond, respectively, to daytime and nighttime. The temporal resolutions of the L3 data products are daily, 8-day (half of the 16-day Aqua orbit repeat cycle) and monthly (calendar). The multiday data product means are simply the arithmetic mean weighted by the counts of the daily data combined in each grid box, with standard deviations, counts, minima, maxima, and error estimates similarly aggregated.

The AIRS tropospheric temperature and humidity data products have been validated against a variety of other tropospheric temperature and humidity measurements, including those from in situ instruments (e.g., radiosondes and ship-based measurements; Divakarla et al., 2006; Tobin et al., 2006), several other ground-based and satellite-based remote sensing instruments (Fetzer et al., 2008), as well as model-generated analysis and reanalysis data (Divakarla et al., 2006). Table 2 summarizes these findings. The uncertainty estimates are calculated based on the difference between the AIRS data products and radiosonde observations and are valid in the troposphere between the surface and 300 hPa.

The data source for this AIRS Obs4MIPs V2 data set is the AIRS V6 L3 standard monthly mean air temperature, specific humidity, and relative humidity data products in the TqJoint grids from the AIRS/AMSU-A combined retrievals obtained from the Goddard Earth Science Data Information and Services Center (https://disc.gsfc.nasa.gov; AIRS, 2013). The AIRS/AMSU-A combined retrievals are available from September 2002 to September 2016, the time period of this AIRS Obs4MIPs V2 data set.

We have retained the original 1° × 1° latitude-longitude grid of the AIRS V6 L3 data for the AIRS Obs4MIPs V2 data set. We have provided the AIRS air temperature, specific humidity, and relative humidity data only in the lowest eight CMIP mandatory pressure levels from 1,000 to 300 hPa. Since the original 24 or 12 pressure levels of the AIRS V6 L3 temperature or humidity profile products are a superset of the eight CMIP mandatory pressure levels, there is no need for reprocessing in the vertical pressure levels. In addition, simple unweighted arithmetic means of the ascending and descending monthly air temperature and humidity mean values and associated number of observations and standard error are reported. Nobs estimates the effective number of the AIRS L2 retrievals on the ~45-km AMSU-A FOR centered in each 1° × 1° latitude-longitude grid cell. To estimate the effective number of FORs, we first count the number of ~15-km AIRS FOVs per 1° × 1° latitude-longitude grid cell in the AIRS V6 L3 files and then divide the AIRS L3 FOV count by 9 and truncate. A minimum of 20 AIRS FOV observations (~3 AMSU-A FOR observations) per 1° × 1° latitude-longitude grid box per month is required for the ascending and descending nodes separately, except for latitudes beyond 80°N/S. The limit at high latitudes is relaxed to compensate for a much lower number of observations since the AIRS V6 L3 data are on an equal angle grid and the Nobs is influenced by a combination of the orbit of the satellite and the grid location. Since the standard error is not provided for the monthly mean relative humidity data in AIRS V6 L3, it is estimated using the standard errors of monthly mean air temperature and specific humidity in AIRS V6 L3 using the following formula: $\sigma_{RH}^2 = \frac{\sigma_q^2}{q_{sat}^2} + \left[RH\left(\frac{L}{R_v T} + \frac{c_p}{R_d}\right)\right]^2 \frac{\sigma_T^2}{T^2}$. Here, σ_T, σ_q, and σ_{RH} indicate the standard errors of air temperature (T), specific humidity (q), and relative humidity (RH). $c_p = 1{,}004$ J/K/kg is the specific heat capacity of air at constant pressure. q_{sat} is saturation mixing ratio and calculated based on the formula $q_{sat} = 621.97\times\frac{e_s}{p-e_s}$. e_s is the saturation water vapor pressure and calculated using the Clausius-Clapeyron relation. $L = 2.5 \times 10^6$ J/kg is latent heat of vaporization. $R_d = 287$ J/K/kg and $R_v = 461$ J/K/kg are gas constants for dry air and water vapor, respectively.

4. Major Improvements From the AIRS Obs4MIPs V1 Data Set

The major improvements of the AIRS Obs4MIPs V2 data set in comparison to the AIRS Obs4MIPs V1 data set are summarized as here:

1. The AIRS Obs4MIPs V2 data set is based on the AIRS V6 L3 data products while the AIRS Obs4MIPs V1 data set is based on the AIRS V5 L3 data products. The AIRS L3 data products have numerous improvements from V5 to V6 (Tian, Manning, et al., 2013): (1) Fraction of useful retrievals (yield) is significantly higher in the troposphere; (2) the known spurious, long-term trend of retrieved atmospheric temperature first noted by Divakarla et al. (2006) has been mitigated; (3) improved surface properties and near-surface profiles of temperature and moisture; (4) all retrieved physical quantities are accompanied by error estimates and simple QC flags, including profile quantities; (5) moisture and trace gas standard products are provided at pressure levels instead of layers; (6) L3 data products include temperature and moisture profiles from a common set of L2 profiles over all atmospheric levels and physically correct relative humidity data, suitable for climate process studies; (7) the AIRS/AMSU-A combined retrievals exclude failed AMSU-A channels 4 and 5 over the entire mission to avoid discontinuities. These improvements for AIRS L3 data products from V5 to V6 indicate that the AIRS V6 L3 data products are better than the AIRS V5 L3 data products and as is the AIRS Obs4MIPs V2 data set better than the AIRS Obs4MIPs V1 data set.
2. The AIRS Obs4MIPs V2 data set extends from September 2002 to September 2016, while the AIRS Obs4MIPs V1 data set covers from September 2002 to May 2011.
3. Monthly mean tropospheric relative humidity data are included in the AIRS Obs4MIPs V2 data set, but not in the AIRS Obs4MIPs V1 data set. This can help the climate community to better evaluate the relative humidity simulations in CMIP climate models using the AIRS data. This is important because key climate feedbacks due to water vapor and clouds are hypothesized to depend on how relative humidity changes in a warming climate, and climate change projections by global models strongly depend on how well relative humidity is simulated in these models (Dessler & Sherwood, 2009; Held & Shell, 2012; John & Soden, 2007; Sherwood et al., 2010).

5. Caveats for Climate Model Evaluation

As a satellite-derived data set, the AIRS Ob4MIPs V2 data set differs from climate model outputs in several ways. In particular, there is a sampling difference between the AIRS Ob4MIPs V2 data set and climate model outputs because the climate model outputs are sampled on regular spatial and temporal grids while the AIRS Ob4MIPs V2 data are not. The AIRS instrument is in a Sun-synchronous low Earth orbit with a limited swath width and a limited sampling of the diurnal cycle and synoptic events. The AIRS sampling is also influenced by clouds, aerosols, coastlines, and other factors that affect its ability to perform successful physical retrievals (Fetzer et al., 2006; Hearty et al., 2014; Tian, Fetzer, et al., 2013; Yue et al., 2013). Users of this data set should be aware of and consider the sampling issues of the AIRS data when performing model-observation comparisons. These sampling issues are discussed below. We are currently working on the sampling bias estimates for this data set that will be reported in the future.

1. Asynoptic time sampling: Because the Aqua satellite is in a Sun-synchronous, near polar orbit, AIRS samples the atmosphere at two fixed local solar times (e.g., 1:30 A.M. and 1:30 P.M. at the equator)

and cannot fully resolve the diurnal cycle away from the poles (the diurnal cycle is well sampled at the highest latitudes). In contrast, typical model monthly averaged outputs contain the averaged values over a time series of data within a fixed time interval (e.g., every 4 or 6 hr). For temperature and humidity over oceans and in the upper atmosphere with a small diurnal cycle, this local time sampling difference is not likely a problem. However, for temperature and humidity in the boundary layer or over lands strongly influenced by the diurnal cycle, this local time sampling difference should be considered.

2. Inhomogeneous grid sampling: The monthly mean data in this data set are an average of all observational data available in a given grid cell (see Figure 1c), so the number of observations used for averaging varies among grid cells. Because of the convergence of longitude lines near the poles, the time range of data collection broadens moving from the equator toward either pole, with the ranges in the polar regions including all times of day and night (Hearty et al., 2014; Parkinson, 2003). Thus, there are more observations in the regions near the poles (~70° to ~85°) than the rest of the globe and the diurnal cycle is more completely sampled there.
3. Cloud-induced sampling: The AIRS coverage is limited by the presence of optically thick clouds because AIRS is an infrared measurement instrument. The combination of infrared and microwave radiances allows retrieval of tropospheric air temperature and humidity profiles for infrared cloud fraction (the product of emissivity and coverage) up to only about 70% (Susskind et al., 2014). This limitation of infrared sounding makes the AIRS observations scene-dependent and, in turn, causes a spatially inhomogeneous sampling as illustrated on Figure 1c. The AIRS sampling is low (~80 per month) in cloudy regions, such as the ITCZ (e.g., the equatorial western Pacific warm pool) and the midlatitude storm tracks (e.g., north Pacific, north Atlantic and 60°S latitude belt). The AIRS sampling is high (~160 per month) in clearer regions, such as subtropics and midlatitude land regions (Hearty et al., 2014; Tian, Fetzer, et al., 2013).
4. Missing data: The AIRS instrument was placed in a safe mode from the end of October 2003 to mid-November 2003 to avoid possible damage from a large solar flare. Our preparation of this data set requires a minimum 20 AIRS FOV observations for each grid cell from each of ascending and descending orbits. With only a half month data, many grids cells do not meet this criterion for November 2003. The only significant outage since December 2003 was the safe mode event from 9 to 26 January 2010. Thus, there are only about a half month data for January 2010. In addition, the data are also incomplete for September 2016 because of the power failure of AMSU-A2 on 24 September 2016.

6. Summary

A new data set including monthly mean tropospheric air temperature, specific humidity and relative humidity from the NASA infrared and microwave atmospheric sounding system (AIRS and AMSU-A) on the Aqua satellite designed for CMIP climate model evaluation has been generated and published on ESGF data centers. This data set adds new monthly mean relative humidity data to Obs4MIPs and updates and extends by 5 years the monthly mean air temperature and specific humidity data in AIRS Obs4MIPs V1 data set using AIRS V6 L3 data product. The standard error and number of observations, for an estimate of data retrieval error and sampling uncertainty, along with three technical notes describing the data set are also provided. The AIRS Obs4MIPs V2 data set is publicly available at the ESGF website (https://esgf-node.llnl.gov/projects/obs4mips).

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