Remote Sensing Systems

One-Degree Monthly Satellite Microwave

Total Precipitable Water

1. Intent of This Document and Point of Contact (POC)

1a) This document is intended for users who wish to compare satellite derived observations with climate model output in the context of the CMIP/IPCC historical experiments. Users are not expected to be experts in satellite derived Earth system observational data. This document summarizes essential information needed for comparing this dataset to climate model output. References are provided at the end of this document to additional information.

This NASA dataset is provided as part of an experimental activity to increase the usability of NASA satellite observational data for the modeling and model analysis communities. This is not a standard NASA satellite instrument product, but does represent an effort on behalf of data experts to identify a product that is appropriate for routine model evaluation. The data may have been reprocessed, reformatted, or created solely for comparisons with climate model output. Community feedback to improve and validate the dataset for modeling usage is appreciated. Email comments to HQ-CLIMATE-OBS@mail.nasa.gov.

Dataset File Name (as it appears on the ESGF):

prw_SSMI_L4_RSSv07r00_198801-201512.nc

prw_SSMI_L4_RSSv07r00_198801-201512-CLIM.nc

1b) Technical point of contact for this dataset:

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2. Data Field Description

CF variable name, units:	prw (atmosphere_mass_content_of_water_vapor), kg m-2
Spatial resolution:	1.0 x 1.0 degrees latitude/longitude
Temporal resolution and extent:	Monthly averages, Jan 1988 - Dec 2014 in one file (increases yearly)
Coverage:	global oceans

3. Data Origin

The One-Degree Monthly Microwave TPW data set is constructed by merging together carefully inter-calibrated microwave total column water vapor also known as total precipitable water (TPW) values derived from a series of satellite microwave radiometer sensors. The data product is provided as one file with maps of monthly mean, monthly anomaly from annual cycle climatology, and twelve-month climatology time series over the ocean regions covering the time period of Jan 1988 to December 2014. The data product described here is also available at RSS and is referred to there as the Merged Total Precipitable Water 1-deg Monthly Climate Product (http://www.remss.com/measurements/atmospheric-water-vapor/tpw-1-deg-product).

The satellite microwave radiometer data used in creating this product are from 6 SSM/I on DMSP satellites (F08, F10, F11, F13, F14 and F15), 2 SSMIS on DMSP satellites (F16 and F17), AMSR-E on NASA's Aqua satellite, and the WindSat polarimetric radiometer on the NPP Coriolis satellite (all instruments are further described in Section 6 below with full names for each acronym). Each of these polar-orbiting instruments measures the Earth radiance at multiple frequencies and polarizations in the microwave spectrum. RSS obtains homogenous brightness temperatures using careful intercalibration and a consistently applied data processing scheme [*Wentz*, 2013]. On-orbit calibration is accomplished with observation of cold (cosmic background radiation) and hot (on-board warm source) targets. These measurements are needed to maintain consistency of values over time.

The transformation of satellite measured brightness temperatures to geophysical measurements is accomplished by using a consistent algorithm and a well-developed and tested radiative transfer model to simulate satellite measured brightness temperatures and derive a regression algorithm [*Meissner and Wentz*, 2004; 2012; *Wentz*, 1997]. The currently used algorithm at RSS is referred to as Version-7 and is consistently applied to each of the microwave radiometer instruments [*Hilburn et al.*, 2010]. Uniformity of process and intercalibration between instruments on the brightness temperature level ensures the variables coming from each platform can be successfully merged to produce a high-quality climate record.

The satellite-measured TPW values represent the depth in millimeters the atmospheric water vapor would be, if condensed at the surface, for a column of atmosphere above a given grid cell. The CF-compliant unit for this measurement is kg m^{-2}, which is equivalent (using the density of water) to 1 mm depth. TPW values range from 0 to 75 kg m^{-2}. By measuring microwave radiance near the water vapor emission line at 23.8 GHz, and at other frequencies where the atmosphere is more transparent, the TPW can be retrieved with high accuracy [*Wentz*, 1997; *Wentz et al.*, 2007]. This works best over the radiometrically dark ocean surface, and thus high-quality measurements are available only over the world's oceans. TPW retrieval is prevented only in regions with heavy rain and near land or sea ice. The near-polar orbiting satellite instruments provide daily coverage consisting of approximately 15 orbits per day, which we plot as ascending and descending swaths on a gridded map. For each instrument, the swaths and resulting gaps between swaths vary in width. When averaged over a month, the swath gaps can result in geographically varying data sampling. With the exception of areas bordering land and sea ice, the global oceans are well sampled throughout the month. In Figure 1 show the descending measurements made during a typical day for Windsat.

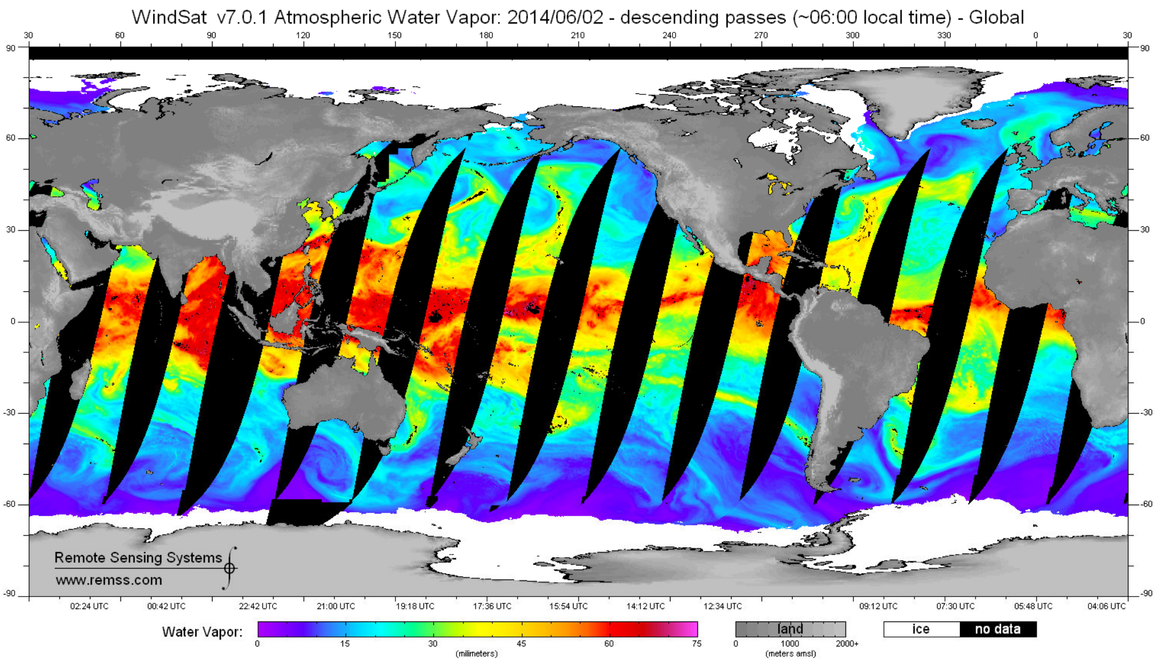

Figure 1: Color coded map of WindSat descending pass observations of TPW for a typical day (June 2, 2014).Land is shown as various shades of gray, ice is shown as white, and missing data is shown as black.

The Version-7 TPW values from the individual SSM/I, SSMIS, AMSR-E and WindSat instruments that are used to create this product are available from RSS and are freely available at ftp.remss.com. Further documentation on the RSS microwave radiometer products is available from www.remss.com/missions.

This merged TPW product is made using a two-step construction process. First, we make monthly 1-degree maps from individual satellite TPW values, keeping track of the number of observations per grid cell, the number of ice observations, and the mean day of month. We re-grid using cosine latitude weights to reduce the spatial resolution from 0.25 deg (RSS daily satellite products) to the 1-deg grid used here. In the second stage of processing, we apply quality control measures, apply small bias adjustments (< 0.15 mm) to each satellite. The values of these adjustements were found by comparing the retrievals from each satellite with measurements made by the Tropical Rainfall Measuring Mission (TRMM) Microwave radiometer, which has been in continuous operation from 1997 to the present. This part of the process in described in more detail in section 5.5 below. We then combine TPW values from all instruments using simple averaging. The resulting TPW product is constructed using the following requirements: We only calculate a TPW value for a specific 1-deg grid cell if the cell contains more than 160 observations during the month, if ice is present for less than 30 of the observations in that cell, and if the calculated mean day of the month (derived by averaging the time of the data falling within the cell) is within 6 days of the center day of the month.

We then compute the monthly gridded climatology by averaging together spatially-smoothed gridded maps for each month of the year over the 20 year 1988-2007 period. Each monthly map for each satellite is smoothed using a 3 degree by 3 degree boxcar smooth. This serves to fill in small regions with missing data, and reduce sampling noise in the climatology. The monthly gridded anomalies are then computed by subtracting the climatology values for each location and month.

This merged TPW product contains monthly mean total precipitable water (TPW) values on a 1-degree grid, the 12-month climatology made from 1988 to 2007 data, and monthly TPW anomaly maps. There are no data values in regions of land, persistent ice, and coastal areas. There is information within the file that lists the sources of radiometer data that went into each monthly mean. This Obs4MIPS product is updated yearly.

4. Validation and Uncertainty Estimate

All measurements contain some degree of measurement error. Much of the uncertainty in a monthly mean TPW product is due to spatial-temporal sampling errors, uncertainty in intersatellite calibration, and systematic errors in the retrieval algorithm. Systematic errors in the retrieval algorithm can be important in regions where the typical atmospheric profile is markedly different than the profiles used to train the retrieval algorithm, but only lead to small errors in the mean state, and do not contribute substantially to errors in long-term changes in TPW. The contribution of measurement noise, which can be important for a single retrieval, is greatly reduced by averaging large numbers of measurements into each monthly grid point.

We know that the strong spectral signature of water vapor makes it a robust parameter to retrieve from microwave radiometer radiances and our previous comparisons of satellite TPW values with those from small-island radiosonde measurements of water vapor demonstrate RMS errors of approximately 1.2 kg m^{-2}[*Wentz*, 1997]. A more recent paper describes the comparison of RSS TPW values with ground-based GNSS values has been accepted for publication by the Journal of Geophysical Research [*Mears et al.*, 2015]. Here we found that satellite radiometer measurements are biased about 0.4 mm high compared to the GNSS measurements, which is within the roughly 0.5 mm absolute accuracy thought to characterize the GNSS vapor values. The standard deviation of the difference between satellite and GNSS measurements ranged from between 1.60 and 1.94 kgm^{-2} depending on the satellite used. Since this difference includes the errors in the GPS measurements as well as error due to spatial and temporal mismatch, we expect that the error in the satellite measurements is considerably less than these values. Twelve GPS stations had overlap time periods long enough to evaluate difference trends, yielding 59 satellite-station pairs when paired with different satellites. More than half (39 of 59) did not show a significant trend. The twenty pairs with significant trends did not show trends of predominantly one sign, suggesting that neither system is plagued by a system-wide drift in TPW. This result lends confidence to the long-term trends in the merged dataset.

We have also compared the data from the individual satellites with retrievals from the TMI instrument. TMI is a microwave imaging radiometer that included the capabilities of the SSM/I instruments, but orbits in a different orbit sampling only Earth's tropical regions. Because this orbit evolves rapidly in local measurement time, TMI measurements often occur that are closely collocated in both time and location with all of the other satellites (except F08 and F10, which ceased operation before the TRMM launch). The results of these comparisons are shown in Fig. 3 below. Most of the time, the TMI measurements show very little drift relative to the measurements from the other satellites, adding more confidence to the stability each of the components of the merged vapor dataset. There are periods of anomalous measurements for the F14, F15, and F16 satellites (shown in red). Since other TMI/radiometer comparison do not show these problems for measurements made at the same time, we conclude that the problems are due to the F14, F15, and F16 satellites, and these periods are excluded from the merged vapor product.

5. Considerations for Model-Observation Comparisons

5.1 Temporal sampling biases

There are two types of temporal sampling biases to take into consideration:

1) The sun synchronous orbit of any polar-orbiting instrument yields retrievals at specific local times. Figure 2 shows the ascending node time for each instrument and the change in this value over time. Though TPW has little diurnal variability over the oceans, what exists fails to be resolved or well measured from only 2 points of the diurnal cycle, a morning and evening time window of roughly 6-10 am/pm. Merging of multiple instruments improves the sampling only slightly, typically widening the am/pm window. The one outlier from this time window, AMSR-E, measures at 1:30 AM and 1:30 PM (local time). No explicit diurnal correction is applied to account for any diurnal differences in TPW between AMSR-E and the other sensors.

2) In creating this merged product, there were 3 satellite-months that did not meet our data production requirements (as stated at the end of Section 3). We required that the average time of the calculated monthly mean fall within 6 days of the center of the month. This was not the case for: F08 in Jan 1988, F08 in Oct 1990 and F10 in Dec 1991 when the instruments operating at that time had data outages. In each case, the month values were needed for consistency of the time series so an exception was made. The threshold for these days was set so that the average time needed to fall within 10 days of the center of the month. These exceptions are early within the time-series and one can avoid any bias that may result by starting analysis in 1992.

5.2 Inhomogeneous spatial sampling

The quality of the TPW product is dependent on the number of data that are averaged into each grid cell. Sampling by polar-orbiting instruments is not homogeneous. For a given day of measurement, polar-orbiting instruments measure some regions with greater coverage and some regions without any coverage. In the Arctic, there are an extremely high number of observations due to overlapping measurement swaths by multiple instruments. In areas where the first and last orbits for a given day overlap, a greater sampling exits. Other regions have fewer values in the mean.

Land and ice proximity reduces the sampling as radiometers suffer from side lobe interference that prevents obtaining TPW values near land. Due to variations in instrument resolution, look angle, geographic conditions and spatial footprints, some pixels have more observations than others. This results in varying numbers of observations for a given grid cell and poorer quality averages near coastlines and along ice edges. See Figure 3 for a typical map of the number of observations in the merged product.

We account for sampling differences when constructing the product by requiring a minimum number of values for a mean to be calculated in any grid cell. We tested a variety of minimum observation requirements. We found that only along the coastlines and ice edges did the number of values drop below a threshold and poor quality data enter the product. We experimented to see how different thresholds affected resulting trends and determined little difference once a minimum threshold of 160 counts per cell per month was met. This requirement was used in constructing the product.

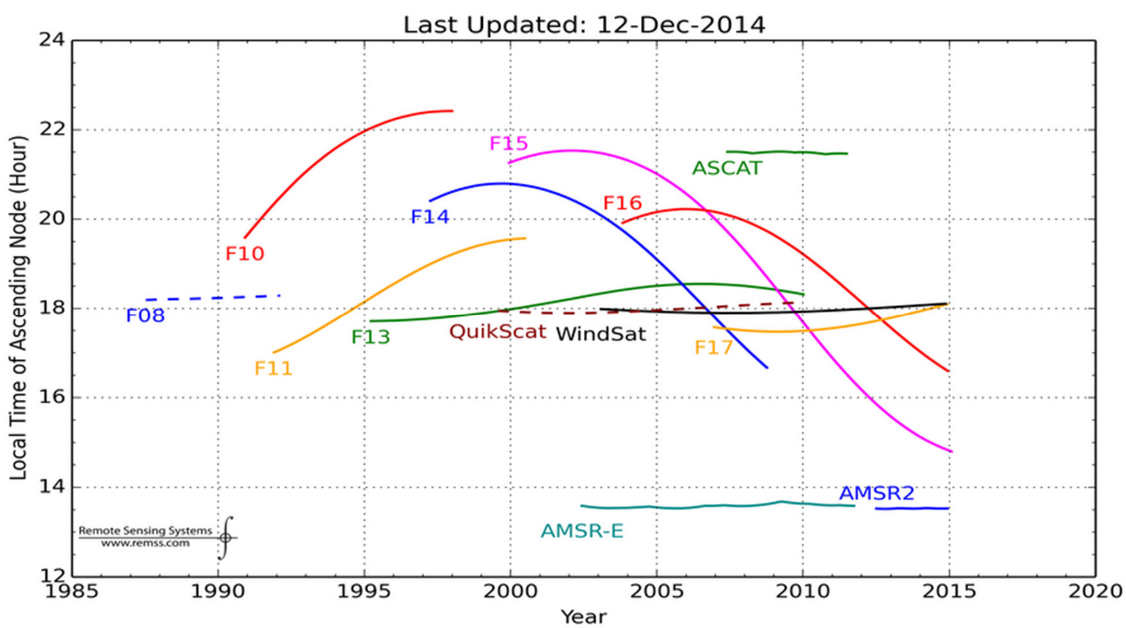

Figure 2: Local ascending crossing times for each microwave radiometer showing the change over the lifetime of the instrument. The SSM/I and SSMIS instruments are distinguished using the name of the DMSP satellite. F08 to F15 carry SSM/I and F16 and F17 have SSMIS. This plot is continually updated and available at www.remss.com/support/crossing-times. Though the plot represents all data processed by RSS, only the SSM/I, SSMIS, AMSR-E and WindSat data are used in this merged product. Note that data from the descending node of each satellite, with observations made 12 hours earlier, are also included in the merged product.

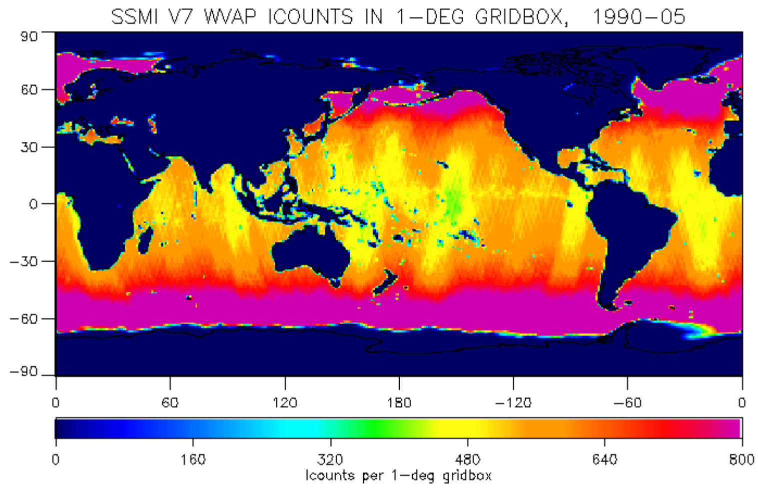

Figure 3: Number of TPW measurements included in the monthly average of May 1990.

5.3 Ice Effect on Product

Ice is likely to exist more at one end of a month than another (with the exception of floating icebergs) and ice removal is necessary. We developed a mean-day-of-month quality calculation to remove ice edge grid cells where the amount of ice increases or decreases throughout the month during seasonal changes. To handle icebergs that move between grid cells, we used the number of ice observations within a grid cell during the month to exclude when too much ice existed (number of ice observations must be <= 30). Even though these requirements were applied, it is still possible that some small ice effects remain in the product.

5.4 Rain Effects

Our analysis determined that light rain has little effect on TPW values measured by microwave radiometers and that removal of rain can have adverse effects on a climate product. Comparison of SSM/I F13 vapor values to GPS vapor in rain-free and rainy conditions convinced us that little difference can be attributed to rain. We also found that the use of an extended rain flag creates a geographic sampling problem by removing data from primarily rainy, high vapor tropical areas which results in lower mean vapor values and higher global trends. For this reason, we excluded heavy rain-affected data (in that our microwave instrument processing does not derive a TPW value in the presence of heavy rain), but we did not use any form of extended rain flag to remove nearby rain-affected data.

5.5 Accounting for Small Differences between Instruments

Even after our best efforts to intercalibrate the satellites at the brightness temperature level, small vapor biases on the scale of 0.1mm exist between the various satellites. These are characterized and removed via comparison the TMI instrument, which was recently recalibrated (Wentz, 2015). In Figure 4, we show monthly-mean time series of the difference (satellite minus TMI) between collocated measurements made by TMI and each of the satellites used in the merged product. To be considered to be collocated, the observations must be in the same 0.25 degree grid cell, and separated in observation time by less than 30 minutes. As noted above, F14, F15, and F16 exhibited periods of anomalous performance (shown in red) that are excluded from further processing. Ignoring these regions, the mean differences shown here are used to adjust the values for each of the satellites before merging. The exception is AMSR-E, which behaves slightly differently in the presence of light rain, which causes a slight regionally-dependent bias relative to the other instruments. This, combined with the tropical-only sampling of the TMI instrument leads to a small difference in global-mean difference for AMSU vs. the other satellites. To accounts for this we subtracted an additional 0.1 mm so that its global mean values are consistent. The biases applied to each satellite are shown in Table 1 below.

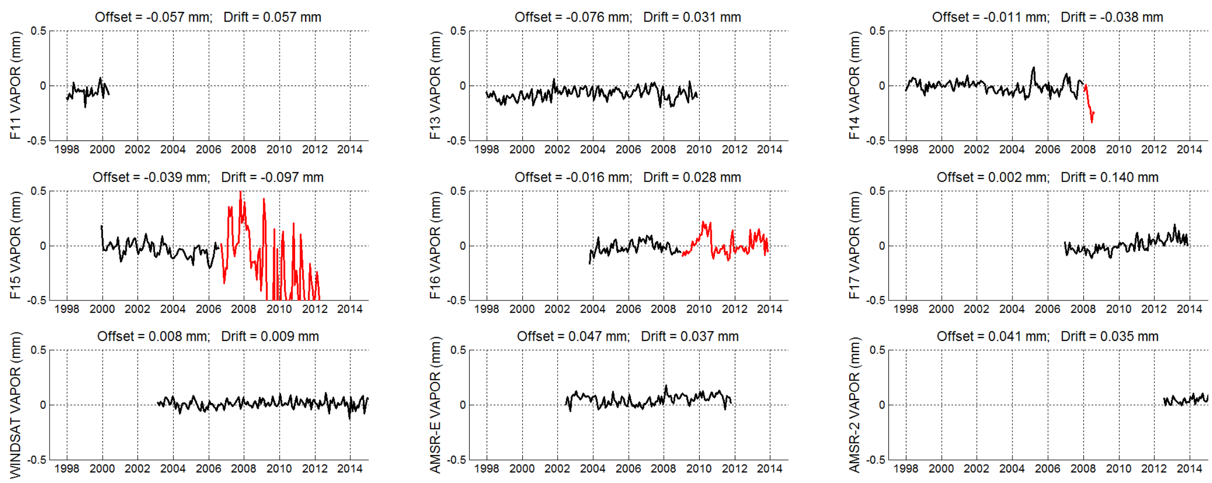

Figure 4. Time series of monthly-mean differences (satellite minus TMI) of collocated measurements between TMI and each of the satellites used in the merged vapor product. TMI is not used in the merged product. The F14, F15, and F16 satellites show periods of anomalous performance, shown in red. Data from these periods are not used in the merged product.

Table 1. Global adjustments applied to each satellite before merging

Satellite	Adjustment (mm)
F08	0.00
F10	0.00

F11	0.057
F13	0.076
F14	0.011
F15	0.039
F16	0.016
F17	0.002
AMSR-E	-0.147
WindSat	-0.008

To test the success of these adjustments, in Figure 5 we plot the global mean vapor for each satellite relative to the mean vapor from all satellites combined. Any bias or drift in a single satellite would be seen as an offset or slope in these time series. No large biases or drifts can be seen. There is a slight upward drift in the F17 vapor values. We will continue to monitor this issue to see if it continues on the same trend line or not.

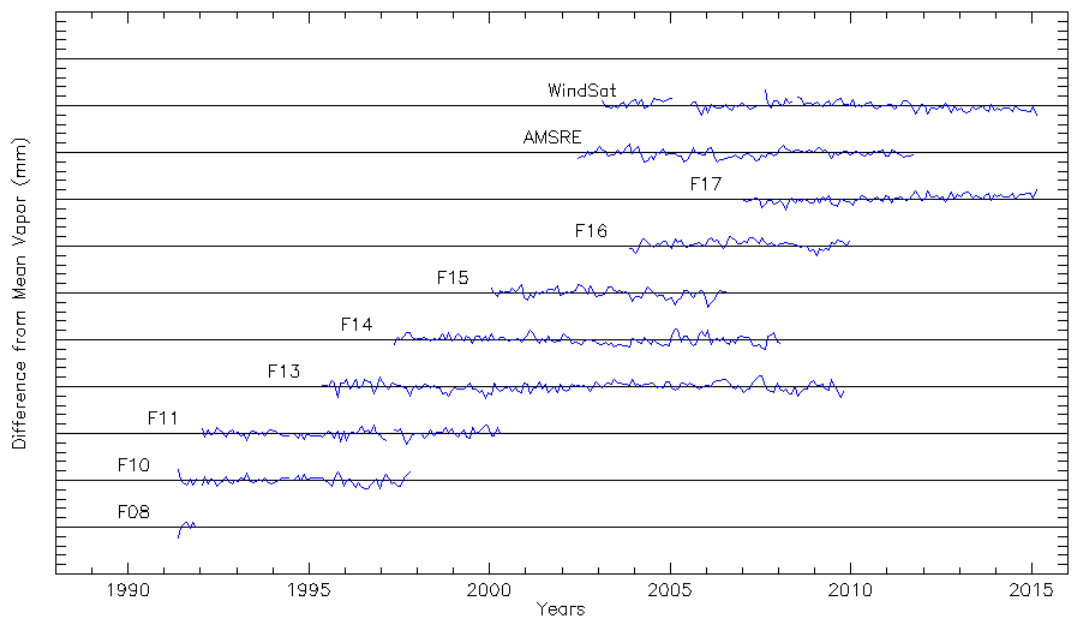

Figure 5. Monthly global mean time series for each satellite relative to the mean of all satellites operating at the given time. Each small tick mark on the y-axis corresponds to 0.1 mm. The early part of the F08 mission is not shown, because the plot only is meaningful when 2 or more satellites are operating at the same time.

5.6 Requirements for Ancillary Data Sets

The RSS microwave radiometer data processing has minimal requirements for ancillary data sets. Since wind direction, in relationship to satellite look angle can impact the emissivity; wind direction is needed for the retrieval algorithm. Wind direction from NCEP Global Data Assimilation System (GDAS) analysis (Derber et al, 1991) is used. Any error in wind direction specification has little effect on subsequent TPW retrieval errors.

6. Instrument Overview

The microwave radiometers used for this data product are very similar with the exception of WindSat (a polarimetric radiometer). At the time of product development, all microwave radiometers with Version-7 TPW data were incorporated (F08, F10, F11, F13, F14, F15 SSM/I; F16 and F17 SSMIS; AMSR-E; WindSat). Since TMI on TRMM was not yet reprocessed to V7, it was not included. The F18 SSMIS was already launched, but RSS has not yet processed the data, so it was not included. The GPM Microwave Imager (GMI) was launched in Feb 2014. We have just completed processing the GMI data to V7 and once released will include them in the product. We expect data from these 3 instruments will be added to the next merged product revision.

Each of the microwave radiometers used have a rotating antenna fed by a collection of feed horns. Each is in a sun-synchronous orbit. Spatial resolutions vary based on instrument altitude and beamwidth. Channel frequencies are not identical between instruments.

[SSM/I] The Special Sensor Microwave Imager (SSM/I) is carried aboard Defense Meteorological Satellite Program (DMSP) satellites F08, F10, F11, F13, F14 and F15 (no SSM/I on F09 and the F12 sensor failed soon after launch). The SSM/I have 4 frequencies: 19.35, 22.2, 37.0, and 85.5 GHz. All but 22 GHz have both vertical and horizontal polarizations [*Hollinger et al.*, 1990]. RSS downloads temperature data records from NOAA CLASS and processes the raw data to brightness temperatures and retrieves wind speed, TPW, cloud and rain rate daily maps. The daily maps are used in creation of this climatology TPW product. More information about the SSM/I instrument is at http://nsidc.org/data/docs/daac/ssmi_instrument.gd.html.

[SSMIS] The Special Sensor Microwave Imager Sounder is carried on the Defense Meteorological Satellite Program (DMSP) satellites F16, F17 and F18. F16 launched in October 2003, F17 launched Nov 2006, and F18 launched October 2009. All remain in operation at the time of this document. The sensor has 24 distinct channels, but only the frequencies and polarizations matching SSM/I are used by RSS for data retrieval: 19.35, 22.2, and 37.0 GHz (V and H-polarization except for 22 GHz V only) [*Kunkee et al.*, 2008]. The temperature data records are downloaded by RSS from NOAA CLASS. More detailed information on the SSMIS is available at http://nsidc.org/data/docs/daac/ssmis_instrument/index.html

[AMSR-E] This radiometer was launched in May 2002 on the NASA Aqua satellite and operated until October 2011. The Aqua satellite has a sun-synchronous orbit. It is part of the satellite formation called the "A Train" (afternoon train) in which satellites cross the equator, from south to north, within a few minutes of each other at around 1:30 p.m. local time [*Kawanishi et al.*, 2003]. RSS obtains AMSR-E raw data from the National Space Development Agency of Japan (NASDA). We process the raw data into daily geophysical products on a 0.25 deg grid. These gridded, daily data are used in the merging process. More details about AMSR-E are available from http://nsidc.org/data/docs/daac/amsre_instrument.gd.html

[WindSat] The Coriolis platform is an NPOESS preparatory project (NPP) project to demonstrate the capabilities of new sensors, including the polarimetric radiometer WindSat. The instrument began operation January 2003. It has 5 frequencies: 6.8, 10.7, 18.7, 23.8, and 37.0 GHz. The 10, 18 and 37 GHz channels are fully polarimetric [*Gaiser et al.*, 2004]. This allows for retrieval of not only wind speed, but also wind direction. The lower frequency channels are used for SST retrieval. The 23.8 GHz channel has dual-polarization and is highly sensitive to water vapor. More details on WindSat and its unique measuring capabilities are available at http://www.nrl.navy.mil/WindSat/Description.php

7. References

We advise users to cite this data product using the following reference:

> Remote Sensing Systems, 2013, updated YYYY. Monthly Mean Total Precipitable Water data set on a 1-degree grid made from Remote Sensing Systems Version-7 Microwave Radiometer Data, accessed on *[date accessed]*. Santa Rosa, CA, USA. Available at http://www.remss.com .

http://www.remss.com/measurements/atmospheric-water-vapor/tpw-1-deg-product

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Kawanishi, T., T. Sezai, Y. Ito, K. Imaoka, T. Takeshima, Y. Ishido, A. Shibata, M. Miura, H. Inahata, and R. W. Spencer (2003), The Advanced Microwave Scanning Radiometer for the Earth Observing Systems (AMSR-E), NASDA's contribution to the EOS for global energy and water cycle studies, *IEEE Transactions on Geoscience and Remote Sensing*, *41*(2), 184-194.

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Wentz, F. J., L. Ricciardulli, K. A. Hilburn, and C. A. Mears (2007), How much more rain will global warming bring?, *Science*, *317*, 233-235.

Wentz, F. J. (2015) A 17-Year Climate Record of Environmental Parameters
Derived from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager, submitted to *Journal of Climate*.

8. Revision History

Rev 0 – 15 Dec 2014 - This is a new document [D. Smith]

Rev 1– 3 Feb 2015 - Added references for error estimates [C. Mears]

Rev 2– 14 Mar 2015 - Rewrote several sections to describe new bias adjustments based on TMI [C. Mears]

Rev 3– 10 June 2015 – Made several small changes suggested by the Obs4MIPS team. The largest change was the addition of a new figure showing the daily orbital pattern of measurements. [C. Mears]