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# Comparison of Global Observations and Trends of Total Precipitable Water Derived from Microwave Radiometers and COSMIC Radio Occultation from 2006 to 2013

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**Abstract**

We compare atmospheric total precipitable water (TPW) derived from SSM/I (Special Sensor Microwave Imager) and SSMIS (Special Sensor Microwave Imager Sounder) radiometers and WindSat to collocated TPW estimates derived from COSMIC (Constellation System for Meteorology, Ionosphere and Climate) radio occultation (RO) under clear and cloudy conditions over the oceans from June 2006 to December 2013. Results show that the mean microwave (MW) radiometer - COSMIC TPW differences range from 0.06-0.18 mm for clear skies, 0.79-0.96 mm for cloudy skies, 0.46-0.49 mm for cloudy but non-precipitation conditions, and 1.64-1.88 mm for precipitation conditions. Because RO measurements are not significantly affected by clouds and precipitation, the biases mainly result from MW retrieval uncertainties under cloudy and precipitating conditions. All COSMIC and MW radiometers detect a positive TPW trend over these eight years. The trend using all COSMIC observations collocated with MW pixels is 1.79 mm/decade, with a 95% confidence interval of (0.96, 2.63), which is in close agreement with the trend estimated by all MW observations (1.78 mm/decade with a 95% confidence interval of 0.94, 2.62). These two trends from independent observations are larger than previous estimates and are a strong indication of the positive water vapor-temperature feedback in a warming planet.

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## 1. Introduction

Clouds are important regulators for Earth's radiation and hydrological balances. Water vapor is a primary variable that affects cloud radiative effects and hydrological feedbacks. Accurate observations of long-term water vapor under both clear and cloudy skies are important for understanding the role of water vapor on climate, which is still one of the largest uncertainties in understanding climate change mechanisms (IPCC 2013). Trends in global and regional vertically integrated total atmospheric water vapor, or Total Precipitable Water (TPW), are important indicators of climate warming because of the strong positive feedback between temperature and water vapor increases. Accurate observations of TPW are therefore important in identifying climate change and in verifying climate models, which estimate a wide range of TPW trends (Roman et al. 2014).

The TPW depends on temperature (Trenberth and Guillemot, 1998; Trenberth et al., 2005). Global TPW can be derived from satellite visible, infrared, and microwave sensors (i.e., Wentz and Spencer, 1998; Fetzer et al. 2006; John and Soden, 2007; Fetzer et al. 2008; Noël et al. 2004). However, no single remote sensing technique is capable of completely fulfilling the needs for climate studies in terms of spatial and temporal coverage and accuracy. For example, while water vapor retrievals from visible and infrared satellite sensors are limited to clear skies over both lands and oceans, passive microwave (MW) imagers on satellites can provide all sky water vapor products, but only over oceans. These water vapor products are mainly verified by comparing to either reanalysis, radiosonde measurements, or other satellite data (i.e., Soden, and Lanzante, 1996; Sohn and Smith, 2003; Noël et al. 2004; Palm et al. 2008; Sohn and Bennartz, 2008; Wick et al. 2008; Milz et al. 2009; Prasad and Singh, 2009; Pougatchev et al. 2009;

Knuteson et al., 2010; Larar et al. 2010; Wang et al. 2010; Ho et al. 2010a, b). Results from these validation studies show that the quality of water vapor data from different satellite sensors varies under different atmospheric conditions. The change of reanalysis systems and inconsistent calibration among data may also cause uncertainty in long-term stability of water vapor estimates. In addition, it is well known that radiosonde sensor characteristics can be affected by the changing environment (Luers and Eskridge, 1998; Wang and Zhang, 2008). Ho et al. (2010b) demonstrated that the quality of radiosonde humidity measurements varies with sensor types, adding extra difficulties in making a consistent validation of long term water vapor products.

MW imagers are among the very few satellite instruments that are able to provide long-term (close to 30 years) all-weather time series of water vapor measurements using similar sensors and retrieval techniques (Wentz, 2015). The measured radiances at 19.35, 22.235, and 37.0 GHz from SSMIS and 18.7, 23.8, and 37.0 GHz from WindSat are used to derive TPW, total cloud water (TCW), wind speed, and rainfall rates over oceans (Wentz and Spencer, 1998). These four variables are retrieved by varying their values until the brightness temperatures calculated using a forward model match satellite-observed brightness temperatures. Because MW radiation is significantly affected (absorbed or scattered) by heavy rain, these four variables are only retrieved under conditions of no or light-to-moderate rain (Schlüssel and Emery, 1990; Elsaesser and Kummerow, 2008; Wentz and Spencer, 1998).

Recently version 7.0 daily ocean products mapped to a 0.25° grid derived from multiple MW radiometers were released by Remote Sensing System (RSS) (Wentz, 2013). Many validation studies have been performed by RSS by comparing the MW TPW retrievals with those from ground-based Global Positioning System (gb-GPS) stations (Mears et al, 2015; Wentz, 2015). Because the gb-GPS stations are nearly always located on land, these validation studies use stations located on small and isolated islands (Mears et al., 2015). RSS results for TPW collocated with those derived from gb-GPS over these island stations show that their mean differences vary from station to station, and can be as large as 2 mm. The mean difference also varies with surface wind speed, varying from 1 mm at low wind speeds to -1 mm at high wind (20 m/s) speeds. The difference is near zero for the most common wind speeds (6 to 12 m/s). Because the uncertainty of the input parameters and change of antenna for each GPS receiver (Bock et al., 2013), the mean TPW(RSS) – TPW (gb-GPS) can vary from -1.5 mm to 1.5 mm for a single MW radiometer (see Figure 4 in Mears et al., 2015). Wentz (2015) compared 17 years of Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) TPW collocated with gb-GPS TPW over the region from 45ºN to 45º S. The mean TMI- gb-GPS TPW bias was estimated to be 0.45 mm with a standard deviation (σ) of 2.01 mm.

Unlike passive MW radiometers and infrared sensors, radio occultation (RO) is an active remote sensing technique. RO can provide all-weather, high vertical resolution (from ~100 m near the surface to ~1.5 km at 40 km) refractivity profiles (Anthes, 2011). The basics of the RO measurement is a timing measured against reference clocks on the ground, which are timed and calibrated by the atomic clocks at the National Institutes for Standards and Technology (NIST). With a GPS receiver onboard the LEO (Low-Earth Orbiting) satellite, this technique is able to detect the bending of radio signals emitted by GPS satellites and traversing the atmosphere. With the information about the relative motion of the GPS and LEO satellites, the bending angle profile of the radio waves can be used to

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derive all-weather refractivity, pressure, temperature, and water vapor profiles in the neutral atmosphere (Anthes et al., 2008).

Launched in June 2006, COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) RO data have been used to study atmospheric temperature and refractivity trends in the lower stratosphere (Ho et al., 2009a, b, and 2012), and modes of variability above, within, and below clouds (Biondi et al., 2012, 2013; Teng et al., 2013; Scherllin-Pirscher et al., 2012; Zeng et al., 2012; Mears et al., 2012). Wick et al., (2008) (Wick2008 hereafter) demonstrated the feasibility of using COSMIC-derived TPW to validate SSM/I TPW products over the east Pacific Ocean using one month of data. Many studies have demonstrated the usefulness of RO derived water vapor to detect climate signals of El Niño–Southern Oscillation (ENSO; Teng et al., 2013; Scherllin-Pirscher et al, 2012; Huang et al., 2013), Madden-Julian Oscillation (MJO; Zeng et al., 2012), and improving moisture analysis of atmospheric rivers (Neiman et al., 2008; Ma et al. 2011).

The objective of this study is to use COSMIC RO TPW to characterize the global TPW values and trends derived from multiple MW radiometers over oceans, including under cloudy and precipitating skies. COSMIC TPW from June 2006 to December 2013 are compared to the co-located TPW derived from MW radiometers over the same time period. Because RO data are not strongly sensitive to clouds and precipitation, COSMIC TPW estimates can be used to identify possible MW TPW biases under different meteorological conditions. We describe datasets and analysis method used in the comparisons in Section 2. The comparison results under clear skies and cloudy skies are summarized in Sections 3 and 4, respectively. The time series analysis is in Section 5. We conclude this study in Section 6.

## 2. RSS Version 7.0 Data and COSMIC TPW Data and Comparison Method

### 2.1 RSS Version 7.0 Data Ocean Products

The RSS version 7.0 ocean products are available for SSM/I, SSMIS, AMSR-E, WindSat, and TMI. The inversion algorithm is mainly based on Wentz and Spencer, (1998), where above a cutoff in liquid water column, water vapor is no longer retrieved. The various radiometers from the different satellites have been precisely inter-calibrated at the radiance level by analyzing the measurements made by pairs of satellites operated at the same time. This was done for the explicit purpose of producing versions of the datasets that can be used to study decadal-scale changes in TPW, wind, clouds, and precipitation, so special attention was focused on inter-annual variability in instrument calibration. The calibration procedures and physical inversion algorithm used to simultaneously retrieve TPW, surface wind speed (and thereby surface wind stress and surface roughness) and the total liquid water content are summarized in Wentz (2013) and Wentz (1997), respectively. This allows the algorithm to minimize the effect of wind speed, clouds, and rain on the TPW measurement.

The RSS version 7.0 daily data are available on a 0.25°x0.25° grid for daytime and nighttime (i.e., 1440x720x2 daily per day). Figures 1a-d shows the RSS V7.0 monthly mean F16 SSMIS TPW (in mm), surface skin temperature (in K), liquid water path (LWP, in mm), and rain rate (RR, in mm/hour), respectively. Figure 1 shows that the variation and distribution of TPW over oceans (Fig. 1a) is, in general, closely linked to surface skin temperature (Fig. 1b), which is modulated by clouds and the hydrological cycle (Soden et al., 2002). The distribution of monthly TPW is consistent with those of cloud water vapor distribution patterns where highest TPW values (and LWP and RR) occur in persistent cloudy and strong convective regions over the tropical west Pacific Ocean near Indonesia.

Because COSMIC reprocessed TPW data are only available from June 2006 to December 2013 (i.e., COSMIC2013), the SSM/I F15, SSMIS F16, SSMIS F17, together with WindSAT RSS Version 7.01 ocean products covering the same time period are used in this study. Table 1 summarizes the starting date and end date for RSS SSM/I F15, SSMIS F16, SSMIS F17, and WindSAT data. The all sky daily RSS ocean products for F15, F16, F17, and WindSat are downloaded from http://www.remss.com/missions/ssmi.

## 2.2 COSMIC TPW Products

The atmospheric refractivity N is a function of the pressure P, temperature T, water vapor pressure $P_W$, and water content W through the following relationship (Kursinski 1997; Zou et al. 2012):

$$N = 77.6\frac{P}{T} + 3.73\times10^5\frac{P_W}{T^2} + 1.4W_{water} + 0.61W_{ice} \quad (1)$$

where P is pressure in hPa, T is temperature in K, $P_W$ is water vapor pressure in hPa, $W_{water}$ is liquid water content in grams per cubic meter ($gm^{-3}$), and $W_{ice}$ is the ice water content in $gm^{-3}$. The last two terms generally contribute less than 1% to the refractivity and may be ignored (Zou et al., 2012). However, they can be significant for some applications under conditions of high cloud liquid or ice water content, as shown by Lin et al. 2010;

Yang and Zou 2012; Zou et al. 2012. We will neglect these terms in this study, but because we are looking at small differences between MW and RO TPW in cloudy and precipitating conditions in this paper, we estimate the possible contribution of these terms to RO TPW and the consequences of neglecting them here. Since both of these terms increase N, neglecting them in an atmosphere in which they are present will produce a small positive bias in water vapor pressure $P_W$ and therefore total precipitable water when integrated throughout the entire depth of the atmosphere.

Typical value of cloud LWC range from ~0.2 gm$^{-3}$ in stratiform clouds (Thompson, 2007) to 1 gm$^{-3}$ in convective clouds (Thompson, 2007; Cober et al. 2001). Extreme values may reach ~2 gm$^{-3}$ in deep tropical convective clouds (i.e., cumulonimbus). Ice water content values are smaller, typically 0.01 – 0.03 gm$^{-3}$ (Thompson, 2007).

For extremely high values of $W_{water}$ and $W_{ice}$ of 2.0 and 0.5 gm$^{-3}$, the contributions to N are 2.8 and 0.3 respectively. The values of N in the atmosphere decrease exponentially upward, from ~300 near the surface to ~150 at P=500 hPa. Using the above extreme values at 500 hPa, $W_{water}$ may contribute from up to 1.6% of N and $W_{ice}$ up to 0.2%. Thus we may assume that in most cases the error in N due to neglecting these terms will be less than 1%. The effect on TPW will be even less, since clouds do not generally extend through the full depth of the atmosphere. Finally, the ~200 km horizontal averaging scale of the RO observation footprint makes it unlikely that such extremely high values of water and ice content will be present over this scale. We conclude that the small positive bias in RO TPW introduced by neglecting the liquid and water terms in (1) will be less than 1%.

To resolve the ambiguity of COSMIC refractivity associated with both temperature and water vapor in the lower troposphere a 1D-var algorithm (http://cosmic-

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io.cosmic.ucar.edu/cdaac/doc/documents/1dvar.pdf) is used to derive optimal temperature and water vapor profiles while temperatures and water vapor profiles from the ERA-Interim reanalysis are used as a priori estimates (Neiman et al. 2008; Zeng et al. 2012).

Note that because RO refractivity is very sensitive to water vapor variations in the troposphere (Ho et al. 2007), and is less sensitive to temperature errors, RO-derived water vapor product is of high accuracy (Ho et al. 2010 a, b). It is estimated that 1K of temperature error will introduce less than 0.25 g/kg of water vapor bias in the troposphere in the 1D-var retrievals. Although the first guess temperature and moisture are needed for the 1D-Var algorithm, the retrieved water vapor profiles are insensitive to the first guess water vapor profiles (Neiman et al. 2008).

The horizontal footprint of a COSMIC observation is about 200 km in the lower troposphere and its vertical resolution is about 100 m near the surface and 1.5 km at 40 km. The COSMIC post-processed water vapor profiles version 2013.2640 collected from COSMIC Data Analysis and Archive Center (CDAAC) (http://cosmicio.cosmic.ucar.edu/cdaac/index.html) are used to construct the COSMIC TPW data. To further validate the accuracy of COSMIC-derived water vapor, we have compared COSMIC TPW with those derived from ground-based GPS (i.e., International Global Navigation Satellite Systems–IGS, Wang et al. 2007) which are assumed to be independent of location. Only those COSMIC profiles whose lowest penetration heights are within 200 meters of the height of ground-based GPS stations are included. Results showed that the mean global difference between IGS and COSMIC TPW is about -0.2 mm with a standard deviation of 2.7 mm (Ho et al., 2010a). Similar comparisons were found by Teng et al. (2013) and Huang et al. (2013).

### 2.3 Preparation of COSMIC TPW data for Comparison

In this study, only those COSMIC water vapor profiles penetrating lower than 0.1 km are integrated to compute TPW. To compensate for the water vapor amount below the penetration height, we follow the following procedure:

i) we assume the relative humidity below the penetration height is equal to 80%. This is a good assumption especially over oceans near the sea surface (Mears et al., 2015);
ii) the temperatures below the penetration height are taken from the ERA-interim reanalysis;
iii) we compute the water vapor mixing ratio below the penetration heights;
iv) we integrate the TPW using COSMIC water vapor profiles above the penetration heights with those water vapor profile below the penetration heights.

Pairs of MW and RO TPW estimates collocated within 50 km and one hour are collected. Wick2008 used MW-RO pairs within 25 km and one hour in time. To evaluate the effect of the spatial difference on the TPW difference, we also computed TPW differences for MW-RO pairs within 75 km, 100 km, and 150 km, and 200 km. We found the larger spatial difference increases the mean TPW biases slightly to +/- 0.25 mm and the standard deviations to +/- 1.91 mm, which is likely because of the high spatial variability of water vapor.

With a 0.25°×0.25° grid, there are about 20 to 60 MW pixels matching one COSMIC observation. The number of pixels varies at different latitudes. A clear MW-RO pair is defined as instances when *all* the TCW values for the collocated MW pixels are equal to zero. A cloudy MW-RO ensemble is defined as instances when *all* the TCW values from the collocated MW pixels are larger than zero. Partly cloudy conditions (some of

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pixels zero and some non-zero) are excluded from this study. The cloudy ensembles are further divided into precipitating and non-precipitating conditions. MW-RO pairs are defined as cloudy non-precipitating when less than 20% of MW pixels have rainfall rates larger than zero mm/hour. Cloudy precipitating MW-RO pairs are defined when more than 20% of the pixels have rainfall rates larger than zero. Because microwave radiances are not sensitive to ice, we treat cloudy pixels of low density like cirrus clouds as clear pixels.

## 3. Comparison of MW and RO TPW with clear skies

In total there are 26,678 F15-RO pairs, 31,610 F16-RO pairs, 31,291 F17-RO pairs, and 21,996 WindSat-RO pairs from June 2006 to Dec. 2013, respectively. Because microwave radiances are not sensitive to ice, we treat cloudy pixels of low density like cirrus clouds as clear pixels. Figures 2a-d show scatter plots for F15-COSMIC TPW, F16-COSMIC TPW, F17-COSMIC TPW, and WindSat-COSMIC TPW under clear skies. Figures 3a-d show that MW clear sky TPW from F15, F16, F17, and WindSat are all very consistent with those from co-located COSMIC observations. As summarized in Table 2, under clear conditions where SSM/I provides high quality TPW estimates, the mean TPW biases between F16 and COSMIC (F16- COSMIC) is equal to 0.03 mm with a standard deviation σ of 1.47 mm. The mean TPW differences are equal to 0.06 mm with a σ of 1.65 mm for F15, 0.07 mm with a σ of 1.47 mm for F17, and 0.18 mm with a σ of 1.35 mm for WindSat. The reason for larger standard deviation for F15 may be because the F15 data after August 2006 were corrupted by the "rad-cal" beacon that was turned on at this time (Hilburn and Wentz, 2008). F16 had solar radiation intrusion into the hot load during the time period, while F17 and WindSat had no serious issues.

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## 4. Global comparisons of MW and RO TPW with cloudy skies

### 4.1 Comparison of MW, RO, and Ground-based GPS TPW

Figures 3a-c depict the scatter plots for F16-COSMIC pairs under cloudy, cloudy non-precipitation, and precipitation conditions from June 2006 to December 2013 over oceans. While there is a very small bias (0.031 mm) for clear pixels (Fig. 2b), there is a significant positive TPW bias (0.794 mm) under cloudy conditions (Fig. 3a). This may explain the close to 0.4 mm mean TMI-gb GPS TPW biases found by Wentz et al., (2015) where a close to 7 years of data were used. Figure 3c depicts that the large SSM/I TPW biases under cloudy skies are mainly from the pixels with precipitation (mean bias is equal to 1.825 mm) although precipitation pixels are of about less than 6% of the total F16–COSMIC pairs. Because RO measurements are not significantly affected by clouds and precipitation, the biases mainly result from MW retrieval uncertainty under cloudy conditions. The fact that the MW-COSMIC biases for precipitation conditions (1.825 mm, Fig. 3c and 1.62-1.88 mm in Table 2) is much larger than those for cloudy, but non-precipitation conditions, indicates that significant scattering and absorbing effects are present in the passive MW measurements when it rains. The correlation coefficients for F15-RO, F16-RO, F17-RO, and WindSat-RO pairs for all sky conditions are all larger than 0.96 (not shown).

MW and gb-GPS TPW comparisons show similar differences as the MW-RO differences under the different sky conditions. We compared F16 pixels with those from gb-GPS within 50 km and 1 hour over the 33 stations studied by Mears et al. (2015) from 2002 to 2013. Figs. 4a-d depicts the scatter plots for F16-gb-GPS TPW under clear, cloudy,

cloudy non-precipitating, and cloudy precipitating conditions, respectively. The F16-gb-GPS mean biases are equal to 0.241 mm (clear skies), 0.614 mm (cloudy skies), 0.543 mm (cloudy-non precipitation) and 1.197 mm (precipitation), which are similar to those estimated from MW-RO comparisons (Table 2).

The above results show that the MW estimates of TPW are biased positively compared to both the RO and the ground-based GPS estimates, which are independent measurements. The biases are smallest for clear skies and largest for precipitating conditions, with cloudy, non-precipitating biases in between. Overall, the results suggest that clouds and especially precipitation contaminate the MW radiometer measurements to a small but significant degree.

### 4.2 Time Series of MW, RO, and Ground-based TPW Biases under Various Meteorological Conditions

To further examine how rain and cloud drops affect the MW TPW retrievals, we show how the F16-RO TPW biases vary under different meteorological conditions in Fig. 5. The bias dependence on wind speed (Fig. 5a) is small. Unlike the results from Mears et al., (2015), the mean TPW biases between F16 and COSMIC are within 0.5 mm with high winds (wind speed larger than 20 m/s). Fig. 5b indicates that the F16-COSMIC bias is larger with TPW greater than about 10 mm, which usually occurs under cloudy conditions. The F16-COSMIC biases can be as large as 2.0 mm when the rainfall rate is larger than 1 mm/hour (Fig. 5c), which usually occurs with high total liquid cloud water (Fig. 5d) conditions. The F16 TPW biases can be as large as 2 mm when total cloud water is larger than 0.3 mm (Fig. 5d). Fig. 5e shows that the larger F16-COSMIC TPW biases (2-3 mm) mainly occur over regions with surface skin temperature less than 270 K (higher latitudes, see Figure 1b). The F15, F17, and WindSat TPW biases under different meteorological conditions are very similar to those of F16 (not shown).

In Figure 6 we compare RSS V7.0 F16 MW TPW to the ground-based GPS TPW over various meteorological conditions. The magnitudes of the MW-gb-GPS TPW differences under high rain rate and high total cloud water conditions are somewhat smaller than those of MW-RO pairs (varying from about 0.5 mm to 2.0 mm), which may be because most of the MW-gb-GPS samples are collected under low rain rates (less than 1 mm/hour) conditions.

## 5. Eight Year Time Series and Trend Analysis under All Skies

### 5.1 Monthly Mean TPW Time Series Comparison

To further examine MW TPW long-term stability and trend uncertainty due to rain and water drops for different instruments, we compared time series of the MW and COSMIC monthly mean TPW differences from June 2006 to Dec. 2013. Figures 7a-d show the monthly mean F16-COSMIC TPW differences from June 2006 to Dec. 2013 for clear, cloudy, cloudy non-precipitation, and precipitation conditions. In general, the microwave TPW biases under different atmospheric conditions are positive and stable from June 2006 to Dec. 2013, as reflected in relatively small standard deviation values (Table 3). Except for F15, the standard deviations of the monthly mean TPW anomaly range are less than 0.38 mm (Table 3). In contrast, the F15-COSMIC monthly mean σ range from 0.48 mm to 0.69 mm with different conditions.

Table 3 also shows the trend in the RO estimates of TPW over the eight-year period of study. The trends are range from -0.12 mm/decade (WindSat, clear skies) to 2.52 mm/decade (F15, precipitation conditions). The overall trend is positive as discussed in the next section. Table 3 shows that in general the trends are more strongly positive under cloudy and precipitation conditions compared to clear conditions.

**5.2 De-seasonalized Trends of MW-RO Differences and TPW**

Fig. 8 depicts the de-seasonalized trends of the MW-RO TPW differences under cloudy skies for F15 (Fig. 8a), F16 (Fig. 8b), F17 (Fig. 8c), and Windsat (Fig.8d). Except for F15, the de-seasonalized trends of the MW-RO TPW differences for the MW radiometers are close to zero, indicating little change over these eight years. The trends of the biases associated with F16, F17, F18 and WindSat under all sky conditions range from -0.09 to 0.27 mm/decade (details not shown).

The reason for larger standard deviations of the MW minus RO differences for F15 (Tables 2 and 3 and Fig. 8a) is very likely because the F15 data after August 2006 were corrupted by the "rad-cal" beacon that was turned on at this time. Adjustments were derived and applied to reduce the effects of the beacon, but the final results still show excess noise relative to uncorrupted measurements (Hilburn and Wentz, 2008). RSS does not recommend using these measurements for studies of long-term change. Thus we consider the F15 data less reliable during the period of our study.

Fig. 9 shows the de-seasonalized time series of global monthly mean TPW for all MW radiometers and COSMIC under all sky conditions. The close to eight year trends for TPW estimated from both passive MW radiometers and active COSMIC RO sensors are positive and very similar in magnitude. The global mean trend of COSMIC RO TPW is 1.79 mm/decade with a 95% confidence interval of (0.96, 2.63) mm/decade while the global mean trend from all the MW estimates is 1.78 mm/decade with a 95% confidence interval of (0.94, 2.62). This close agreement between completely independent measurements lends credence to both estimates.

The positive trends in TPW from the independent MW and RO measurements reflect the positive feedback between TPW and global warming and are considerably greater than previous estimates over other time periods. For example, Durre et al. (2009) estimated a trend of 0.45 mm/decade for the Northern Hemisphere over the period 1973-2006. Trenberth et al. (2005) estimated a global trend of 0.40 +/- 0.09 mm/decade for the period 1988 to 2001. The 100-year trend in global climate models is variable, ranging from 0.55 to 0.72 mm/decade (Roman et al., 2014).

Although both MW and RO measurements demonstrate positive trends in TPW from 2006 to 2013, the trends in TPW vary over different regions. Fig. 10 shows the global map of TPW trend over oceans using all F16, F17, and WindSat data from 2006 to 2013. Fig. 10 shows that the positive trends in TPW exist mainly over central and north Pacific oceans, south of China and west of Austrian, south of South American, and east of America.

## 6. Discussion and conclusions

RSS water vapor products have been widely used for climate research. The newly available RSS V7.0 data products have been processed using consistent calibration procedures (Wentz, 2013). This was done for the explicit purpose of producing versions of

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the datasets that can used to study decadal scale changes in TPW, wind, clouds, and precipitation. These water vapor products are mainly verified by comparing to either reanalysis, radiosondes measurements, or other satellite data. However, because the quality of these datasets may also vary under different atmospheric conditions, the uncertainty in long-term water vapor estimates may still be large. In this study, we used TPW estimates derived from COSMIC active RO sensors to identify TPW uncertainties from four different MW radiometers under clear, cloudy, cloudy/non-precipitation, and cloudy/precipitation skies over nearly eight years (from June 2006 to Dec. 2013). Because RO data are not sensitive to clouds and precipitation, RO-derived water vapor products are useful to identify the possible TPW biases retrieved from measurements of passive microwave imagers under different sky conditions. We reach the following conclusions:

1) Clear sky biases: The collocated COSMIC RO TPW estimates under clear skies are highly consistent with the MW TPW estimates under clear sky conditions (within +/- 0.2 mm and with a correlation coefficient greater than 0.96). The mean TPW bias between F16 and COSMIC (F16- COSMIC) is equal to 0.03 mm with a standard deviation σ of 1.47 mm. The mean TPW differences are equal to 0.06 mm with a σ of 1.65 mm for F15, 0.07 mm with a σ of 1.47 mm for F17, and 0.18 mm with a σ of 1.35 mm for WindSat. These small values give us confidence in our approach to interpolate COSMIC data the last few hundred meters below the lowest penetration height. The consistent F15-COSMIC, F16-COSMIC, F17-COSMIC, and WindSat-COSMIC TPW under clear skies also show that COSMIC TPW can be used as good references to identify and correct TPW among different MW imagers for other sky conditions.

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2) Biases under cloudy skies: while there are very small biases for clear pixels, there are significant positive MW TPW biases (~0.80 mm) under cloudy conditions when compared to RO TPW. The large SSM/I TPW biases under cloudy skies result mainly from the pixels with precipitation. The mean bias is equal to 1.83 mm for COSMIC-F16 pairs, which is much larger than the bias for cloudy, but non-precipitation conditions. This indicates that the significant scattering and absorbing effects are present in the passive MW measurements when it rains. The F16 – Ground-based GPS mean biases are equal to 0.24 mm (for clear skies), 0.61 mm (for cloudy skies), 0.54 mm (for cloudy-non precipitation) and 1.2 mm (for precipitation) which are consistent with those from F16-COSMIC comparisons.

3) Biases among different instruments: using RO TPW estimates collocated with different MW instruments, we are able to identify possible TPW inconsistencies among MW instruments even they are not collocated. The de-seasonalized trends in MW-RO TPW differences for three MW radiometers (i.e., F16, F17, and WindSat) are close to zero, indicating consistency among these radiometers. However, the F15-COSMIC differences are larger and show a significant trend over the eight years of the study. It is likely that F15 data after August 2006 were corrupted by the "rad-cal" beacon that was turned on at this time.

4) Trend of TPW under all skies: The eight-year trends of TPW estimated from both passive MW radiometer and active COSMIC sensors show increasing TPW globally, with higher trends under cloudy conditions. The global mean trend of COSMIC RO TPW collocated with MW observations is 1.79 mm/decade with a 95% confidence interval of (0.96, 2.63) mm/decade. The global mean trend from all the MW estimates is 1.78

mm/decade with a 95% confidence interval of (0.94, 2.62). This close agreement between completely independent measurements lends credence to both estimates. These trends are significantly higher than other estimates and are a strong confirmation of the water vapor-temperature feedback in a warming global atmosphere.

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Table 1. Satellite Instruments Used in This Study

| Satellite | Instrument | Operation period |
|---|---|---|
| DMSP F15 | SSM/I | December 1999-present |
| DMSP F16 | SSMIS | October 2003-present |
| DMSP F17 | SSMIS | December 2006-present |
| Coriolis | WindSat | February 2003-present |

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Table 2: Mean and standard deviation of differences (MW minus RO) in TPW (in mm) between four MW radiometers and COSMIC RO under various sky conditions. The sample numbers for each pair are shown in the third position of each column.

| Sky condition | Mean/σ/N | | | |
|---|---|---|---|---|
| | F15 | F16 | F17 | WindSat |
| Clear | 0.06/1.65/3064 | 0.03/1.47/3551 | 0.07/1.47/2888 | 0.18/1.35/1802 |
| Cloudy | 0.80/1.92/23614 | 0.79/1.73/29059 | 0.82/1.76/28403 | 0.96/1.73/20194 |
| Non Precip | 0.49/1.69/17223 | 0.46/1.46/21854 | 0.47/1.49/21371 | 0.49/1.36/13004 |
| Precip | 1.64/2.28/6391 | 1.83/2.05/7205 | 1.88/2.08/7032 | 1.85/2.00/7190 |

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Table 3: Mean and standard deviation (std) of the mean in mm of the monthly time series of differences of MW minus RO TPW under various sky conditions. The trend of the RO estimates of TPW in mm/decade and the 95% confidence level are shown below the mean and σ values in each row.

| Sky condition | Mean/σ of monthly time series<br>RO trend (95% confidence levels indicated in ( ) | | | |
|---|---|---|---|---|
| | F15 | F16 | F17 | WindSat |
| Clear | 0.07/0.56<br>1.65 (0.47,2.84) | 0.05/0.28<br>1.09 (-0.28,2.46) | 0.08/0.27<br>0.21 (-1.22,1.65) | 0.23/0.38<br>-0.12 (-1.89,1.66) |
| Cloudy | 0.77/0.51<br>1.49 (0.40,2.58) | 0.78/0.18<br>2.02(0.87,3.16) | 0.82/0.15<br>1.85 (0.64,3.06) | 0.95/0.17<br>1.85 (0.68,3.01) |
| Non Precipitation | 0.46/0.48<br>0.86 (-0.24,1.95) | 0.45/0.17<br>2.02 (0.87,3.17) | 0.48/0.15<br>2.37 (1.23,3.50) | 0.47/0.19<br>2.12 (0.95,3.30) |
| Precipitation | 1.62/0.69<br>2.52 (0.55,4.480 | 1.81/0.31<br>1.32 (-0.53,3.17) | 1.88/0.29<br>0.26 (-1.59,2.10) | 1.88/0.32<br>0.39 (-1.25,2.04) |

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Figure 1. The RSS V7.0 monthly mean F16 SSM/I a) TPW (in mm), b) surface skin temperature (in K), c) liquid water path (LWP, in mm), and d) rain rate (RR, in mm/hour).

Figure 2. TPW scatter plots for the COSMIC and RSS Version 7.0 pairs under clear condition for a) F15, b) F16, c) F17, and d) WindSat.

Figure 3. TPW scatter plots for the COSMIC and RSS Version 7.0 F16 SSM/I pairs under a) cloudy, b) cloudy but non-precipitation, and c) precipitation conditions.

Figure 4. TPW scatter plots for the gb-GPS and RSS Version 7.0 F16 SSM/I pairs from June 2006 to December 2013 under a) clear, b) cloudy, c) cloudy but non-precipitation, and d) precipitation conditions.

Figure 5. Mean and standard of the mean for the F16-COSMIC TPW biases varying with a) wind speed (m/s), b) TPW (mm), c) rain rate (mm/hour), d) total cloud water (mm), and e) surface skin temperature (K). The vertical black bracket superimposed on the mean denotes the standard error of the mean. The green dashed line is the number of samples, indicated by the scale on the right.

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Figure 6. Mean and standard of the mean for the F16- gb-GPS TPW biases varying with a) wind speed (m/s), b) TPW (mm), c) rain rate (mm/hour), d) total cloud water (mm) and e) surface skin temperature (K). The vertical black bracket superimposed on the mean denotes the standard error of the mean. The green dashed line is the number of samples, indicated by the scale on the right.

Figure 7. The time series of monthly mean F16 – COSMIC TPW differences under a) clear, b) cloudy, c) cloudy but non-precipitation, and d) precipitation conditions. The black line is the mean difference for microwave radiometer minus COSMIC; the vertical lines superimposed on the mean values are the standard error of the mean. The number of the monthly MW radiometer- COSMIC pairs is indicated by the green dashed line (scale on the right Y axis).

Figure 8. The time series of de-seasonalized TPW differences (microwave radiometer – COSMIC) under cloudy skies for a) F15, b) F16, c) F17, d) WindSat. The black line is the mean difference for microwave radiometer minus COSMIC; the vertical lines superimposed on the mean values are the standard error of the mean. The number of the monthly MW radiometer- COSMIC pairs is indicated by the green dashed line (scale on the right Y axis). The trends are shown by solid red line. The 95% confidence intervals for slopes are shown in the parentheses.

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Figure 9. The de-seasonalized time series of global monthly mean TPW for all MW instruments and COSMIC under all sky conditions. The red and blue dashed lines are the best fit of de-seasonalized COSMIC and MW TPW time series, respectively.

Figure 10. The global map of TPW trend over oceans using all F16, F17, Windsat data from 2006 to 2013.

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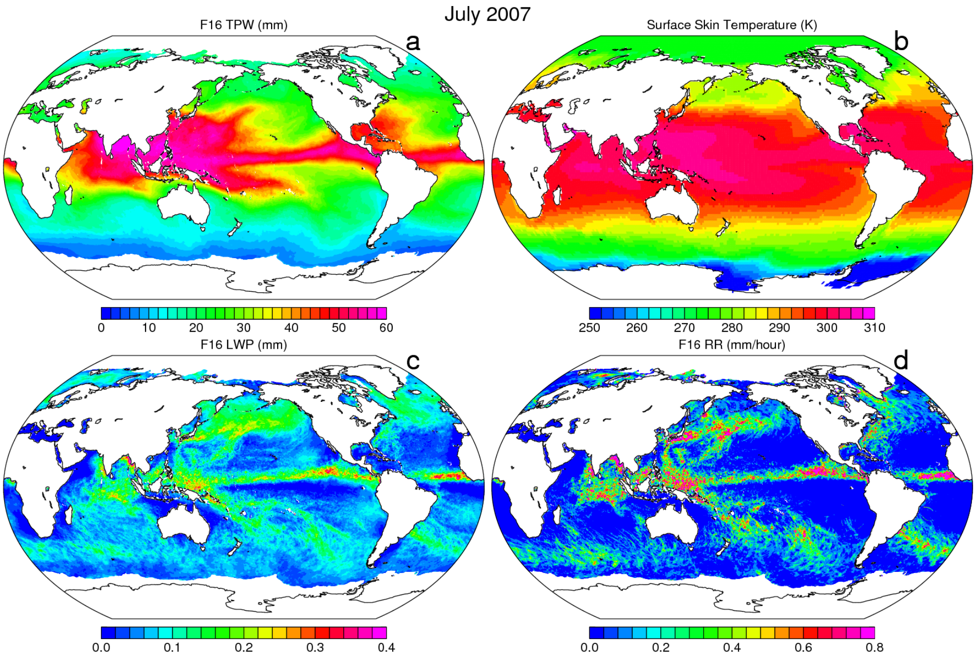


Figure 1. The RSS V7.0 monthly mean F16 SSM/I a) TPW (in mm), b) surface skin temperature (in K), c) liquid water path (LWP, in mm), and d) rain rate (RR, in mm/hour).

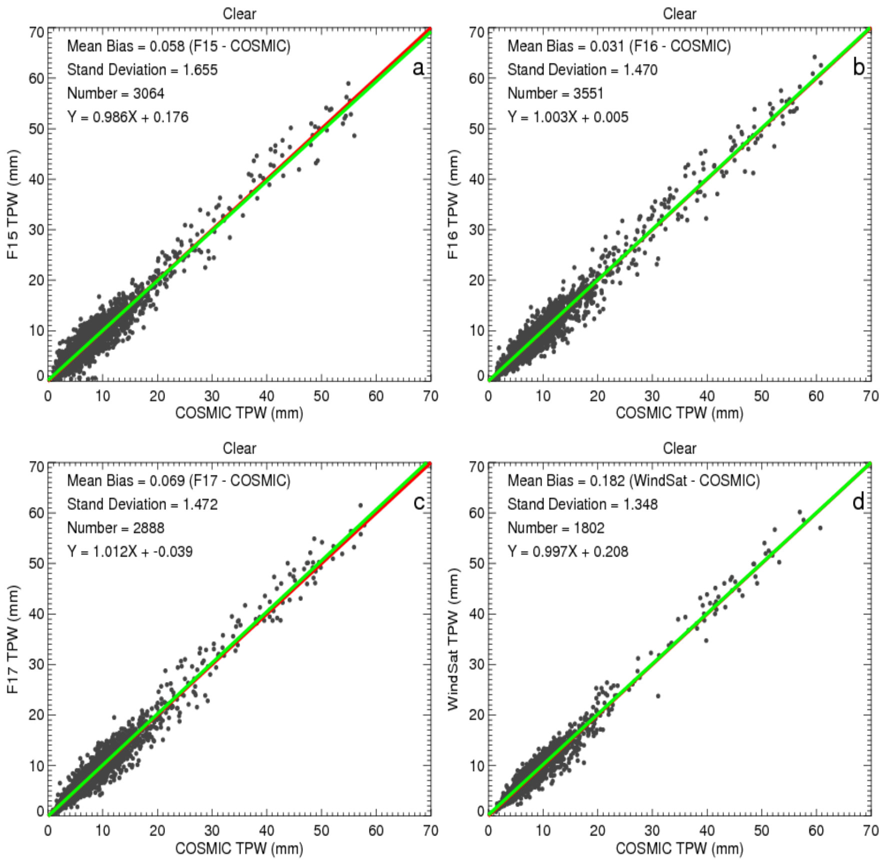


Figure 2. TPW scatter plots for the COSMIC and RSS Version 7.0 pairs under clear condition for a) F15, b) F16, c) F17, and d) WindSat.

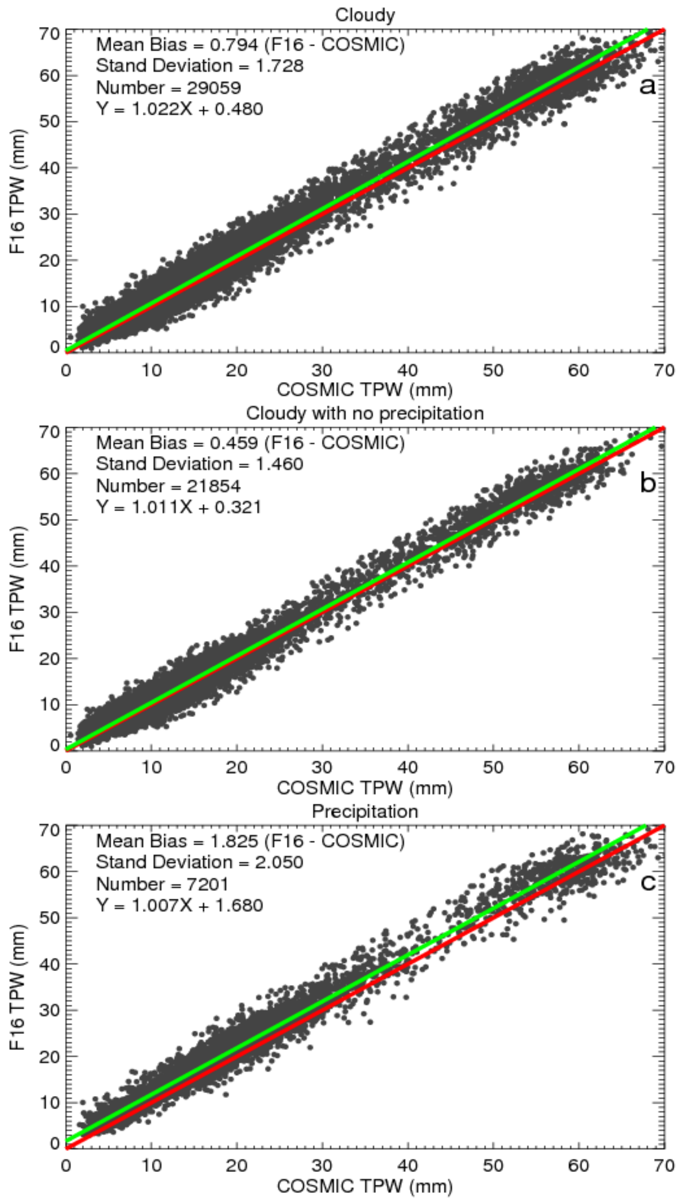


Figure 3. TPW scatter plots for the COSMIC and RSS Version 7.0 F16 SSM/I pairs under a) cloudy, b) cloudy but non-precipitation, and c) precipitation conditions.

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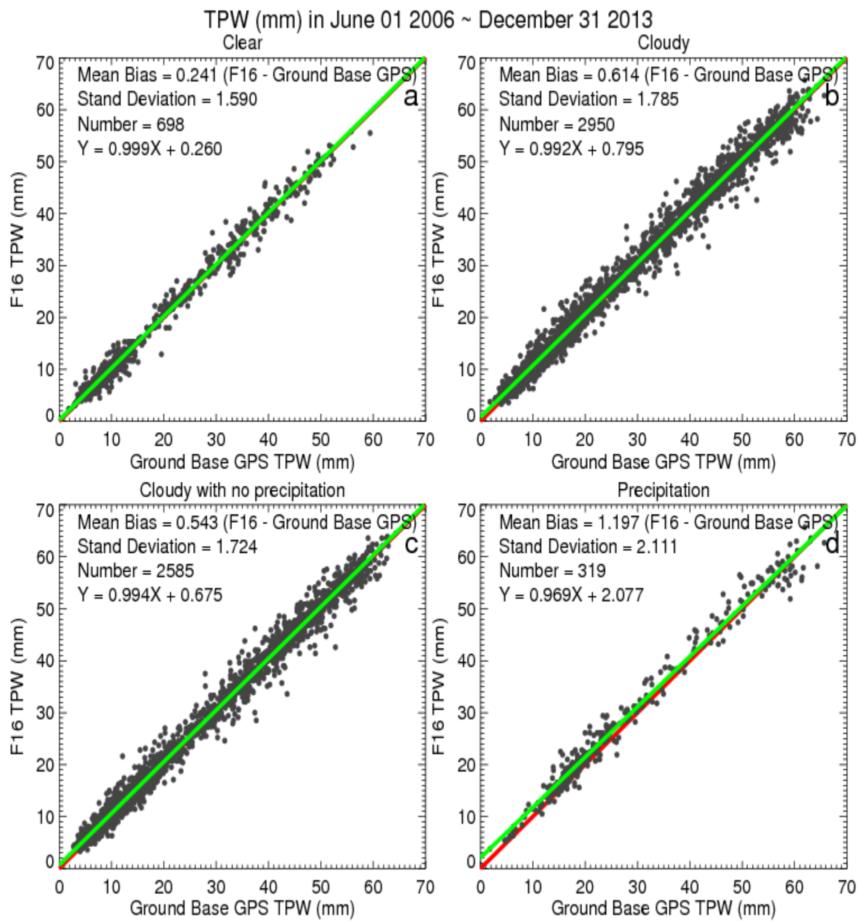


Figure 4. TPW scatter plots for the gb-GPS and RSS Version 7.0 F16 SSM/I pairs from June 2006 to December 2013 under a) clear, b) cloudy, c) cloudy but non-precipitation, and d) precipitation conditions.

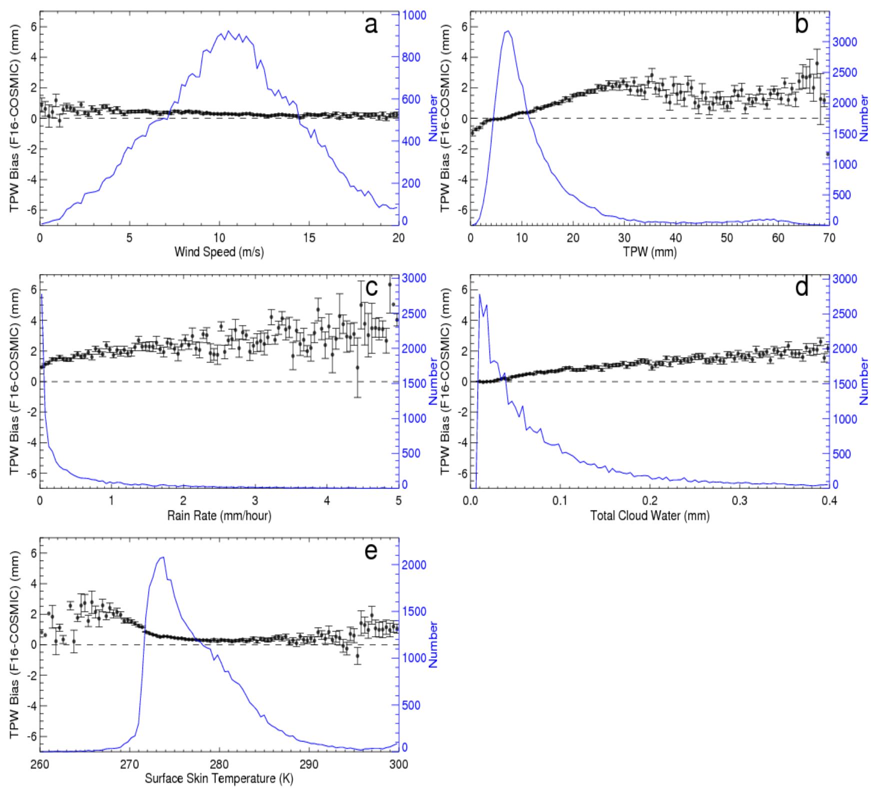


Figure 5. Mean and standard of the mean for the F16-COSMIC TPW biases varying with a) wind speed (m/s), b) TPW (mm), c) rain rate (mm/hour), d) total cloud water (mm), and e) surface skin temperature (K). The vertical black bracket superimposed on the mean denotes the standard error of the mean. The green dashed line is the number of samples, indicated by the scale on the right.

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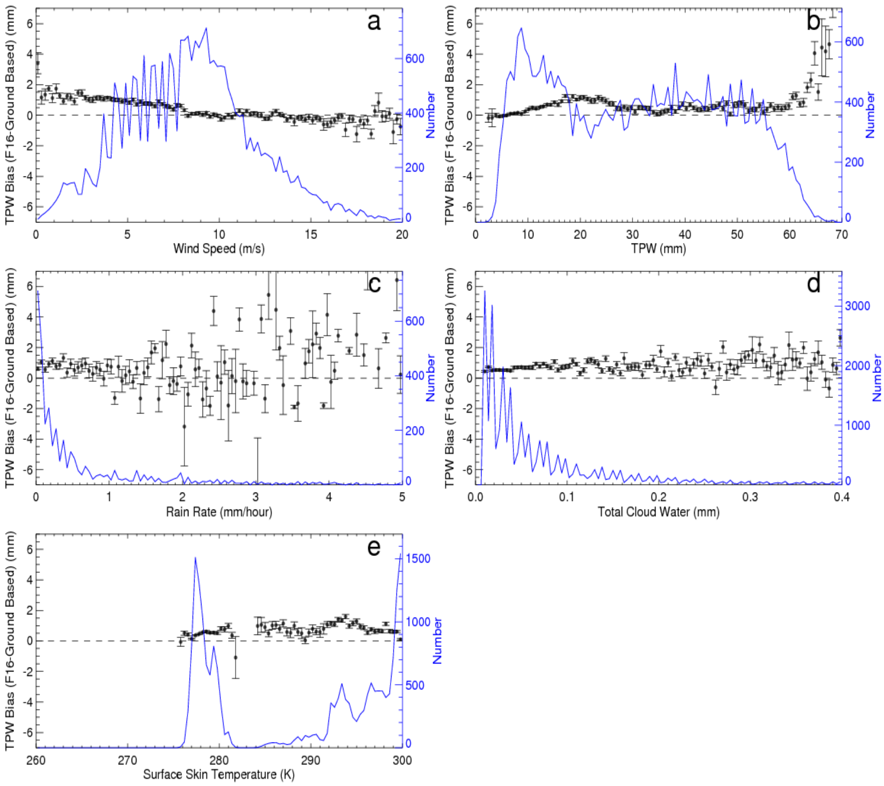


Figure 6. Mean and standard of the mean for the F16- gb-GPS TPW biases varying with a) wind speed (m/s), b) TPW (mm), c) rain rate (mm/hour), d) total cloud water (mm) and e) surface skin temperature (K). The vertical black bracket superimposed on the mean denotes the standard error of the mean. The green dashed line is the number of samples, indicated by the scale on the right.

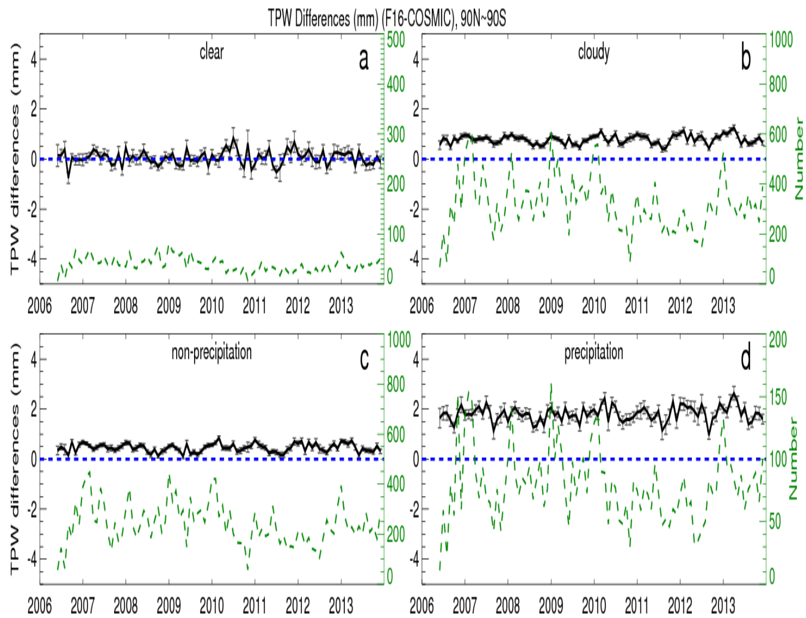


Figure 7. The time series of monthly mean F16 – COSMIC TPW differences under a) clear, b) cloudy, c) cloudy but non-precipitation, and d) precipitation conditions. The black line is the mean difference for microwave radiometer minus COSMIC; the vertical lines superimposed on the mean values are the standard error of the mean. The number of the monthly MW radiometer- COSMIC pairs is indicated by the green dashed line (scale on the right Y axis).

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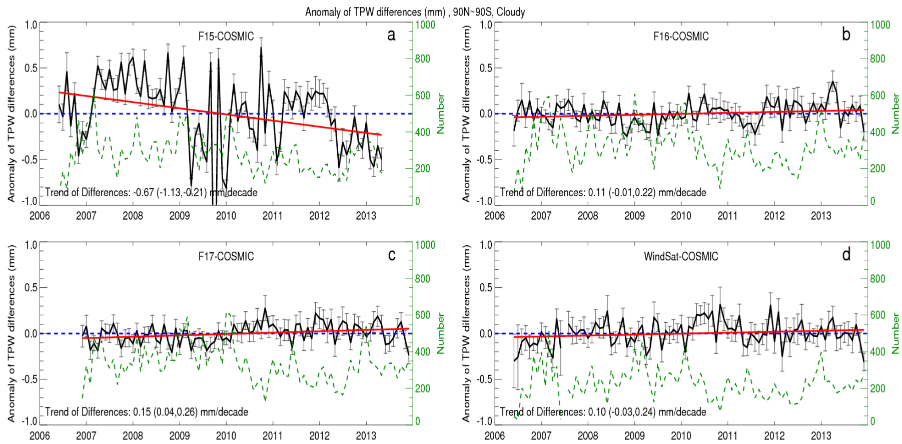


Figure 8. The time series of de-seasonalized TPW differences (microwave radiometer – COSMIC) under cloudy skies for a) F15, b) F16, c) F17, d) WindSat. The black line is the mean difference for microwave radiometer minus COSMIC; the vertical lines superimposed on the mean values are the standard error of the mean. The number of the monthly MW radiometer- COSMIC pairs is indicated by the green dashed line (scale on the right Y axis). The trends are shown by solid red line. The 95% confidence intervals for slopes are shown in the parentheses.

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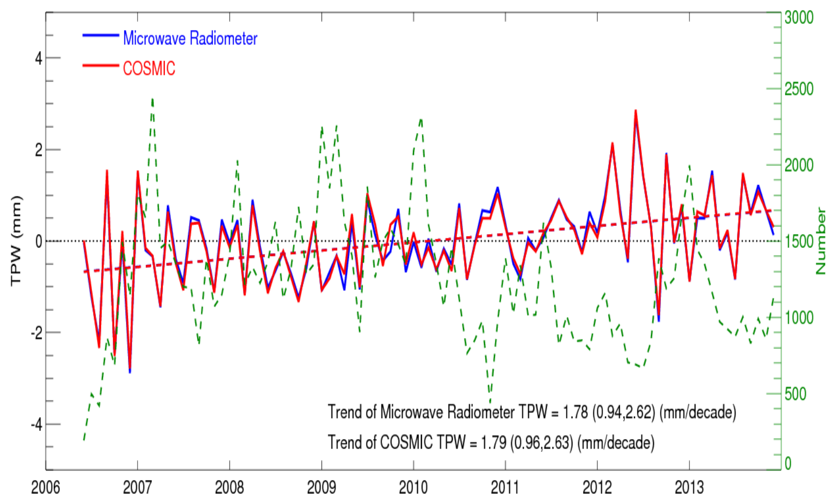


Figure 9. The de-seasonalized time series of global monthly mean TPW for all MW instruments and COSMIC under all sky conditions. The red and blue dashed lines are the best fit of de-seasonalized COSMIC and MW TPW time series, respectively.

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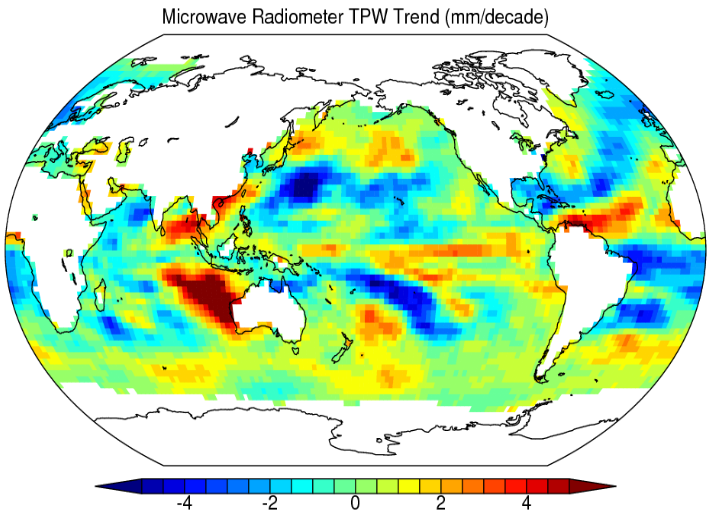


Figure 10. The global map of TPW trend over oceans using all F16, F17, Windsat data from 2006 to 2013.