Global variation of COSMIC precipitable water over land: Comparisons with ground-based GPS measurements and NCEP reanalyses

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1] Radio occultation (RO) observations of precipitable water (PW) from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) are compared with ground-based Global Positioning System (GPS) PW for 6 years (2007–2012). From comparisons of more than 120,000 collocated samples, differences in PW between RO and GPS exhibit a standard deviation of less than 3 mm with a global correlation of 0.96 to 0.97. The monthly mean RO PW is also compared to the National Centers for Environmental Prediction (NCEP) reanalyses. PWs over land for RO, GPS, and reanalyses are highly correlated in each hemisphere. We also used the RO data to explore the variation of the monthly mean PW in four regions (Tibetan Plateau, central Australia, Amazon Basin, and central Africa) where ground stations are few. This study highlights the characteristics of these PW climatologies, suggesting that the RO data are useful complements to global reanalyses and other data sets.


1. Introduction

2] Monitoring the global variation of precipitable water (PW) is important for understanding the mechanisms of convective clouds and water vapor (WV) transport [e.g., Businger et al., 1996; Emardson et al., 1998]. Observations from satellite passive infrared (IR) or microwave (MW) sensors (e.g., Special Sensor Microwave/Imager (SSM/I) and Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E)) are commonly used to derive global PW distributions. However, IR measurements cannot provide PW information under clouds, and it is difficult to invert measurements from MW sensors to retrieve accurate PW over land due to the complexity of surface emissivity. The active Global Positioning System (GPS) radio occultation (RO) measurements can be used to derive all-weather PW estimates over both land and ocean [Kursinski et al., 1997]. Since its launch in April 2006, the Formosa Satellite-3/Constellation Observing System for Meteorology, Ionosphere, and Climate (hereafter, COSMIC) has provided more than 3.2 million GPS RO soundings (~1500 soundings per day on average) to support scientific research and operational numerical weather prediction [Anthes et al., 2008; Anthes, 2011; Ho et al., 2013].

3] Because the time delay of the GPS radio signals is not affected by clouds or surface conditions (land or ocean), RO provides consistent PW measurements in all geographical locations. Although detailed analyses were not available, Mears et al. [2012] compared PW time series for COSMIC over land and ocean, ground-based GPS over land, and AMSR-E and SSM/I over ocean. Teng et al. [2013] carried out in-depth analyses of the COSMIC, SSM/I, and AMSR-E PW variations during El Niño-Southern Oscillation periods from 2007 to 2011. In another study, collocated estimates of PW from COSMIC and satellite microwave measurements showed high correlations in an atmospheric river off California [e.g., Wick et al., 2008]. However, these comparisons are mainly over oceans; extensive global comparisons of COSMIC PW over land with other observations and analyses have not been previously done.

4] One of the objectives of this study is to verify COSMIC PW observations over land by comparing them with the PW derived from the ground-based GPS. Many studies have demonstrated the accuracy of ground-based GPS PW retrievals by comparisons with other measurements and analyses [e.g., Rocken et al., 1997; Randel et al., 1996; Tregoning et al., 1998; Ware et al., 1997; Hagemann et al., 2003; Li et al., 2003; Wang et al., 2007; Vey et al., 2010]. Therefore, ground-based GPS PW measurements are considered “truth” in this comparison. In an extensive evaluation of 8 years (1997–2004) of data, comparisons between radiosonde PW and ground-based PW at 98 International Global Navigation Satellite Systems Service (IGS) stations around the globe showed a mean difference of 1.08 mm (drier for radiosonde data) with a standard deviation of 2.68 mm [Wang et al., 2007].

5] COSMIC PW values have also been compared with those from radiosondes and the Atmospheric Infrared Sounder during a short period of time (a few months) [see Ho et al., 2010b]. Ho et al. [2010a] demonstrated that PW differences between IGS and COSMIC are less than 0.2 mm with a standard deviation of 2.69 mm when COSMIC-IGS observation pairs in 2008 were within 2 h and 200 km. However, because the IGS stations are distributed mainly in developed countries over midlatitudes, to
number of total sample pairs is 127,155. The root-mean-square (RMS) difference, correlation, and the standard deviation are given. The number of total sample pairs is 127,155.

quantify COSMIC PW variation over land with sparse in situ observations, we further compare COSMIC estimates of PW with those from the NCEP reanalyses and highlight the time evolution of monthly mean PW in four different regions (Tibetan Plateau, central Australia, Amazon Basin, and central Africa) where GPS ground stations are very sparse. This is to demonstrate the value of RO-derived PW for analysis over land complementary to other observations and global reanalyses.

2. The Data and Comparison Methodology

We first compare collocated COSMIC RO and ground-based GPS PW. The PW data from COSMIC were calculated from postprocessed refractivity profiles (wet profiles) retrieved by the COSMIC Data Analysis and Archive Center with first-guess temperature and water vapor profiles from the European Centre for Medium-Range Weather Forecasts Reanalysis Interim in a one-dimensional variational inversion algorithm [Kuo et al., 2004]. RO data within 150 km and 1.5 h of the ground-based measurements were collected. For collocated comparison on PW between GPS and RO, this study employs a criterion stricter than that in Ho et al. [2010a] due to more RO data available in the 6 years. In total, 1062 ground stations, including all IGS stations and those of the SuomiNet network in the U.S., are used in this study. Since RO refractivity is a weighted average along a raypath rather than a point measurement for the retrieved water vapor (the horizontal footprint of RO data is around 200 km), we choose the criteria of 150 km to compensate somewhat for the horizontal weighting along the path. The ground-based PW data used in this study were downloaded from the National Center for Atmospheric Research (NCAR) (http://rda.ucar.edu/datasets/ds721.1) [Wang and Zhang, 2009]. The NCAR PW data are 2 h integrated data (i.e., mean PW for all the PW data within a 2 h interval), derived from ground-based GPS measurements of zenith path delay.

[7] With the matching criteria mentioned above, there are normally several RO retrievals per day for a particular ground station. The collocated RO data at one ground site may exceed several hundreds over 6 years. Since ground sites may be close to each other, the same RO retrieval may be counted when collected at different ground sites. To calculate COSMIC PW, we integrate the specific humidity upward from the lowest tangent point (i.e., ray perigee height) to the retrieved maximum height (40 km) and compensate for the layer of void data from the lowest ray perigee height (i.e., tangent point) to the surface by filling the WV value using a least-square fitting, following Teng et al. [2013]. To reduce sampling errors in comparison, the collocated RO data are discarded if the height of the lowest tangent point is more than 500 m above the elevation height of the GPS ground site. However, the limitation of 1 km rather than 500 m is adopted for uncollocated comparison on monthly mean PW since it will give more RO samples available for average.

[8] The NCEP/NCAR reanalysis (R-1) provides long-term water vapor product [Kalnay et al., 1996] for the needs of climate studies. The NCEP/the Department of Energy (DOE) reanalysis (R-2) project uses the state-of-the-art global data assimilation technique to generate products [Kanamitsu et al., 2002]. Both R-1 and R-2 produce global PW data at a resolution of 2.5° latitude by 2.5° longitude and temporal resolution of 6 h. Both PW data in R-1 and R-2 have been compared to the blended PW observations in 1988–1999 from the National Aeronautics and Space Administration Water Vapor Project (NVAP) [Sudradjat et al., 2005]. For hemispheric and spherical comparisons, the RO PW data after the least-square fitting are binned by 2.5° latitude by 2.5° longitude. We found that about 9–18% (increasing with year) of all spherical grids are not accounted in the 6 years due to the nonexistence of monthly RO samples.

[9] For application of RO data to regional variations, we show the evolution of monthly mean PW (mm) in 2007–2012 averaged over four regions: Tibetan Plateau (29.5°N–36°N, 80°E–100°E), central Australia (20°S–30°S, 120°E–140°E), Amazon Basin (0°N–10°S, 50°W–70°W), and central Africa (10°S–10°N, 15°E–35°E). These regions were selected because of their distinct climate features. Because there are few ground sites in these regions, the COSMIC PW estimates are compared to those from R-1 and R-2. Only RO retrievals that penetrate to within 1 km of the surface are used. The terrain height at an RO location is bilinearly interpolated from the terrain height data at 1° resolution. The number of qualified RO retrievals that fall into these regions ranges from several tens to hundreds each month.

3. Results

3.1. Global Comparisons of COSMIC and Ground-Based GPS PW

We first compare the global ground-based GPS PW over land with the collocated RO PW from COSMIC during 2007–2012. Figure 1 shows a scatterplot of the RO PW and ground-based GPS PW in 2007–2012. The red line indicates the linear regression nearly overlapping the diagonal line (in black). The root-mean-square (RMS) difference, correlation, mean difference, and the standard deviation are given. The number of total sample pairs is 127,155.
along with errors in either the RO or GPS PW estimates. After removing the largest outliers (exceeding four standard deviations), we found that the global correlation reached 0.97 with a root-mean-square (RMS) difference of 2.95 mm and a small mean difference of 0.31 mm (RO is drier). With such a small mean difference, we compared the monthly means of the collocated PW values at a number of IGS sites and found that the monthly mean RO PW estimates closely follow the time evolution of monthly mean values of GPS PW over the 6 years (figures not shown). We also found that the collocated RO PW indeed reproduces the latitudinal variations of monthly mean GPS PW (figures not shown).

3.2. Global and Hemispheric Comparisons of COSMIC, Ground-Based GPS, and NCEP Reanalyses

Due to the inhomogeneous distribution of the ground-based stations, the estimates of global and hemispheric average of ground-based GPS PW may be different from the corresponding averages of the RO PW observations from COSMIC, which are distributed more or less evenly over land and ocean. Figure 2 shows the monthly variations of PW from RO, GPS, R-1, and R-2 over 2007–2012 averaged over the entire Earth, Northern Hemisphere (NH) and Southern Hemisphere (SH). On the globe (land and ocean), the averages of R-1, R-2, and RO PWs exhibit a good agreement, with rather uniform difference of about 1.5–2 mm in all months. PW for R-2 is about 0.5 mm larger than that for R-1, which is consistent with the results in 1988–1999 [Amenu and Kumar, 2005]. Over land (global, NH, and SH), RO is very close to R-1 but still about 0.5 mm less than R-2 in July and August. We found that the negative deviations for RO are mainly distributed in colder months for both NH and SH. This implies that the dry bias in RO is less observed in a warmer environment. Over SH, the drier condition in warmer months in R-1 is in consistency with the deficit in higher PW in the Amazon Basin and central Africa, as shown below.

Compared to the other three data sets, GPS PW shows significantly higher (lower) values in June to September (December to April) over global land as seen in Figure 2b. For GPS PW, we simply took the monthly average of all samples in the 6 years. Hence, the higher PW values over NH cannot be offset by the lower PW values over SH with much less samples available. Nevertheless, GPS PW on average is still a good approximation to the others for each hemisphere, with maximum deviations within 2 mm to R-2 (Figures 2c and 2d). We note that the amplitude range of the GPS PW in 2007–2012 is comparable to that in 1997–2004 [Wang et al., 2007] even though more IGS sites (a total of 574 stations on average in the 6 years) were available at later times and used in this study. The larger differences in GPS PW compared to the other three data sets may be more related to data sampling from irregular ground sites and are not attributable to the accuracy of ground-based measurement or the uncertainties of the involved data retrieval, since GPS PW in general possesses observation errors within 2 mm [e.g., Rocken et al., 1997; Wang et al., 2007].
3.3. PW Variations in Specific Regions

In this section, we compare the PW estimates from COSMIC and the NCEP reanalyses over several different regions where GPS ground measurements are sparse or non-existent. Figure 3 shows the monthly mean PW from 2007 to 2012 in four regions (Tibetan Plateau, central Africa, central Australia, and Amazon Basin) for R-1, R-2, and RO. Over the Tibetan Plateau, the annual cycles of PW for the three data sets are highly correlated; however, the RO values are generally smaller than the reanalyses. R-2 has slightly lowered the PW peak of R-1 in the midyear by about 1 mm. Over this highland (with an average elevation height of 4.84 km in reality, 4.02 km in R-1, and 4.096 km in R-2), these larger PW estimates from R-1 and R-2 are likely a result of the lower terrain height used in the NCEP global model, which has a coarse resolution of 2.5° and hence has significantly more water vapor.

It is not surprising to observe good agreement in PW comparisons between the three data sets for the other three low-land regions. The PW values in central Australia are in especially close agreement. In central Africa and Amazon Basin, maximum PW in RO exceeds R-1 and R-2 by several millimeters (mostly less than 2 mm), contributing to the deficit of R-1 in SH as seen in Figure 2d. It appears that R-2 is closer to RO than R-1 in these two regions associated with higher PW values.

The annual cycle of PW in central Africa is not as clear as in the other places, as shown by all the three data sets. Unlike a bell-shaped pattern of annual variability in the Tibetan Plateau and central Australia, annual PW change in the Amazon Basin looks hat shaped with a sharp minimum in August. We note that the interannual variability is not large in any of the regions, except for the salient peak at the beginning of 2011 in central Australia, which experienced a big flood at this time over its eastern part.

4. Conclusions

We have derived PW estimates from COSMIC RO retrievals and conducted comparisons with nearby ground-based GPS PW over 6 years (2007–2012). Excellent agreement was found between the two independent sets of PW observations, with a global correlation of 0.96 to 0.97 between RO and GPS from more than 120,000 samples. Collocated RO samples can reproduce the latitudinal variations of monthly mean GPS PW. The monthly mean RO PW observations are also compared to the mean PW in the 6 years from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis (R-1) and NCEP/the Department of Energy (DOE) reanalysis (R-2). PWs over land for the four data sets (RO, R1, R2, and GPS) are highly correlated in all months in each hemisphere, except for the larger PW in summer months in the Northern Hemisphere for GPS. We found that RO exhibits generally slight underestimates of average PW over the entire Earth by about 1.5–2 mm compared to the reanalyses, possibly due to the negative refractivity bias (or dry bias) in the lower troposphere in RO retrieval [Kuo et al., 2004].

We then compared the monthly mean PW for the three data sets (R-1, R-2, and RO) in four regions with different climates (Tibetan Plateau, central Africa, central Australia, and Amazon Basin) where ground-based observations are scarce. The RO samples well capture the annual and interannual variability of the PW features exhibited by R-1 and R-2. For highland like the Tibetan Plateau with less RO samples available, both R-1 and R-2 exhibit much larger PW compared to the RO data, possibly because of the significantly lower surface elevations in the reanalysis.

In summary, the COSMIC PW data are reliable, not only for individual sample, but also for statistical global applications. The COSMIC follow-on mission will launch...
six low Earth orbit satellites (LEOs) in 2016 and another six LEOs in 2018 and will provide approximately 10,000 RO soundings per day, more than 5 times that of COSMIC [Chu, 2013]. RO data at such a higher density would be useful for further quantifying the spatial and temporal evolution of water vapor over the globe.

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References


