Intercomparison of integrated water vapor retrievals from SSM/I and COSMIC

Gary A. Wick, Ying-Hwa Kuo, F. Martin Ralph, Tae-Kwon Wee, and Paul J. Neiman

Received 24 June 2008; revised 2 September 2008; accepted 18 September 2008; published 8 November 2008.

[1] Integrated water vapor (IWV) estimates derived from four different Special Sensor Microwave Imager (SSM/I) algorithms are collocated and compared with IWV retrievals using Global Positioning System radio occultation (GPSRO) soundings from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission. The values exhibit strong overall agreement lending support for the accuracy of both the COSMIC data and the traditional passive microwave IWV products. Differences among the products varying with latitude, cloud liquid water content, rain rate, and wind speed highlight key differences between the SSM/I algorithms. Additional differences related to the coarser COSMIC spatial resolution are also observed but are independent from the other dependencies. The differences appear independent of the bottom altitude of the GPSRO soundings. The results suggest a new method of quantifying the uncertainty in individual IWV retrievals as functions of coincident environmental parameters for application to data assimilation and numerical weather prediction.


1. Introduction

[2] Knowledge of the content and distribution of water vapor in the atmosphere is important for weather prediction and climate studies. Traditional satellite-based retrievals of the integrated water vapor (IWV) content (or precipitable water) over the oceans have utilized passive microwave observations such as from the Special Sensor Microwave Imager (SSM/I). While generally perceived as reliable, validation of these retrievals is hindered by the lack of direct measurements over the ocean. Much of the past validation [e.g., Sohn and Smith, 2003; Wenz, 1997; Jackson and Stephens, 1995] has been performed using coastal or island radiosonde sites. Not only is the validation limited by the assumption that the coastal results apply throughout the oceans, but microwave observations within ~100 km of land can be significantly influenced by the effect of land in the microwave sidelobes. Increasingly, ground-based Global Positioning System (GPS) receiver stations are providing improved IWV sampling over land [e.g., Wolfe and Gutman, 2000], but use of these data for validation of the oceanic satellite products is still limited to near-shore regions.

[3] Satellite-based GPS radio occultation (GPSRO) soundings from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission [e.g., Anthes et al., 2008] provide an important new source of all-weather, open ocean IWV retrievals. Launched in April 2006, COSMIC is currently providing approximately 2000 GPSRO soundings per day distributed uniformly around the globe. By measuring the phase delays of radio waves transmitted by GPS satellites as they are occulted by the Earth’s atmosphere, the COSMIC system can provide accurate vertical profiles of the bending angles of radio waves [Kursinski et al., 1997]. From the bending angles, vertical profiles of refractivity can be derived under the assumption of local spherical symmetry. By applying a one-dimensional variational retrieval (1D-Var), vertical profiles of temperature and moisture can be obtained. By integrating the retrieved moisture profiles, estimates of IWV can be calculated from COSMIC at the GPSRO sounding sites. While the absolute accuracy of these IWV estimates has yet to be conclusively demonstrated, they offer the potential to supplement and help evaluate the different passive microwave products.

[4] The objective of this paper is to provide a first step towards establishing the accuracy of the COSMIC IWV estimates and their potential utility in understanding differences between the existing SSM/I algorithms. This is accomplished through collocating and intercomparing IWV estimates derived from the COSMIC data and four different SSM/I algorithms as a function of multiple parameters potentially affecting the quality of the retrievals including the resolution, bottom altitude of the COSMIC soundings, latitude, wind speed, cloud liquid water content, and rain rate.

2. Data

[5] This initial regional intercomparison of IWV retrievals from the SSM/I and COSMIC arose from a detailed study of two significant atmospheric river events [see, e.g., Ralph et al., 2004] in late 2006 that brought significant precipitation to the west coast of the continental United States. The study bounds extend between 10–60° N latitude and 70–180° W longitude for the periods of November 1–16 and December 8–12, 2006 (see the domain and location of simultaneous observations in Figure 1). While limited in scope, the intercomparison incorporates nearly the full range of IWV values encountered globally (~0–7 cm) and treats a phenomenon whose observation and forecasting could potentially be improved through availability of the COSMIC data.

[6] SSM/I-derived IWV retrievals from the Defense Meteorological Satellite Program (DMSP) F-13 and F-14...
satellites were generated using the statistical algorithms of Weng [1995] (WEN), Schlüssel and Emery [1990] (their 3-frequency algorithm, S&E), Alishouse et al. [1990] (ALI), and Petty [1994] (PET). The retrievals were produced in orbital format with no gridding prior to collocation with the COSMIC data. Retrievals of the cloud liquid water content [Weng et al., 1996], wind speed [Goodberlet et al., 1990], and rain rate [Ferriday and Avery, 1994] were generated simultaneously from the brightness temperatures. The effective resolution of the SSM/I retrievals is approximately 50 km, with 25-km spot spacing resulting in about 50% oversampling. Statistical algorithms were considered initially based on available data and software.

The algorithm used to retrieve COSMIC bending angles and refractivity profiles from the raw phase measurements is described by Kuo et al. [2004]. The COSMIC 1D-Var retrievals of temperature and moisture profiles (http://cosmic-io.cosmic.ucar.edu/cdaac/doc/index.html) are initialized with a first guess profile from a numerical weather prediction (NWP) analysis. Retrievals were generated for initialization from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) analysis at 1° resolution. The NCEP GFS analyses do not assimilate atmospheric water vapor information from the SSM/I, making the COSMIC IWV retrievals initialized with the GFS independent from SSM/I. Our study period ends before operational assimilation of the COSMIC data began at NCEP on May 1, 2007. Separate retrievals initialized from the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis were very similar and are not considered further in this paper. The spatial resolution of the COSMIC IWV retrievals is ~250 km along the ray path and on the order of 1 km across the path. While coarse spatially, the COSMIC soundings provide enhanced vertical resolution (as high as 100 m near the surface) relative to other satellite soundings. The COSMIC soundings penetrate down to altitudes ranging from 2500 m to less than 5 m above the surface.

3. IWV Product Intercomparisons

A matched data set was generated from SSM/I and COSMIC retrievals collocated within 25 km in space and 1 hour in time. All SSM/I retrievals matched with a single COSMIC sounding (3 on average) were averaged together. For the region and period considered, 382 collocations were obtained as shown in Figure 1. Averages of the SSM/I retrievals collocated within 50 km, 75 km, 100 km, 150 km, and 200 km were also computed to evaluate the impact of spatial resolution on the retrieval differences.

The overall agreement between the SSM/I IWV algorithms and the COSMIC retrievals is illustrated in Figure 2 for the collocations within 25 km. In general, there is very good agreement between the independent SSM/I and COSMIC retrievals with only the S&E algorithm systematically less than the COSMIC retrievals at high water vapor contents. The strong agreement lends confidence to the COSMIC IWV retrievals.

Overall comparisons such as these, however, can mask systematic differences between the products in localized regions or environmental conditions as explored by Sohn and Smith [2003]. To identify sources of differences between the retrievals and to better quantify the corresponding uncertainty for application of the data, the differences were stratified as a function of multiple environmental parameters and retrieval characteristics. Quantities explored included the latitude, cloud liquid water (CLW) content, rain rate, wind speed, bottom altitude of the COSMIC sounding, and effective spatial resolution. The fractional differences between the SSM/I and COSMIC IWV retrievals binned by ranges of several of these parameters are shown in Figure 3.

Uncertainties in the COSMIC IWV retrievals might be expected to result from varying distributions of water vapor in the atmosphere and different bottom altitudes of the soundings. The overall differences with the SSM/I products, however, show no apparent systematic depen-
results in good agreement with the SSM/I values, at least within the region considered. On average, inclusion of the COSMIC data tends to slightly reduce the IWV from the GFS analysis used to initialize the retrievals (not shown). This reduction eliminates a small overall 1 mm bias between the GFS and WEN IWV values. While the variability in the difference between the GPS-retrieved and initial GFS IWV values is greater when the soundings extend closer to the earth’s surface (differences up to 8 mm, not shown) implying a larger range of adjustments of the GFS IWV values by the GPSRO data under these conditions, the biases with respect to the SSM/I products are not systematically different when the soundings terminate well above the surface. These results further support the COSMIC IWV retrievals.

The intercomparisons additionally highlight key differences between the SSM/I algorithms. A different latitudinal dependence is observed for the algorithms (Figure 3b) with only the WEN algorithm exhibiting negligible latitudinal variations with respect to the COSMIC values. The differences between the WEN and COSMIC IWV retrievals are shown via the color-coded symbols in Figure 1 further confirming that there is no significant coherent spatial pattern in the differences. Moreover, no increase in the differences is observed in coastal and near-shore regions, demonstrating that land contamination of the SSM/I retrievals is not a factor in the observed differences. Similar difference maps for the other algorithms illustrate the latitudinal dependence from Figure 3b but also show no strong impact of land contamination. Existence of zonal biases in IWV products is significant as they can negatively impact efforts to accurately estimate water vapor transports. Latitudinal variations, however, are typically correlated with dependencies on other parameters that more directly influence the individual measurements.

Different dependencies on the coincident wind speed (Figure 3c) and CLW content (Figure 3d) are also observed in the SSM/I – COSMIC differences for the individual algorithms. The dependence on wind speed closely resembles that for latitude, with the WEN algorithm again exhibiting the smallest dependence with respect to the COSMIC retrievals. Wind speed can correlate with latitude with lower speeds on average at lower latitudes, and compensation for the wind speed dependence explains much of the difference in the latitudinal dependence observed for this region in Figure 3b. In contrast, the WEN algorithm has the largest dependence on CLW with positive biases at higher CLW values. The dependence on rain rate (not shown) is similar to that for CLW as the highest CLW bin also includes rain rates largely between 1–4 mm hr$^{-1}$. This upper bin, however, corresponds to less than 7% of the collocations. Since the COSMIC GPSRO soundings are not significantly affected by these parameters [Kursinski et al., 1997], the dependencies may reflect different sources of uncertainty in the SSM/I algorithms. The SSM/I retrievals of IWV, wind speed, CLW, and rain rate use common channels, and variations in the other parameters influence the brightness temperatures used to retrieve IWV. The results suggest that these dependencies might not be entirely removed from the IWV products. The observed wind speed and CLW dependencies are generally consistent with the findings of Sohn and Smith [2003], who attributed

Figure 3. Fractional differences between the SSM/I and COSMIC IWV retrievals stratified by (a) bottom altitude of the COSMIC sounding, (b) latitude band, (c) wind speed, and (d) cloud liquid water content. Error bars estimated as the standard deviation of the mean for the corresponding bin are shown for the WEN algorithm and are similar for the other algorithms.
similar differences to the different frequencies included in the individual SSM/I algorithms. Additional observations of biases in CLW products potentially related to IWV have also been observed recently [Horváth and Gentemann, 2007].

Another factor contributing to the SSM/I and COSMIC retrieval differences is the different effective spatial resolution and sampling methods. Some of the larger differences between the SSM/I and COSMIC retrievals occur in regions of strong IWV spatial gradients. More generally, biases between the retrievals are found to be related to the difference between the SSM/I IWV value at the selected resolution and the average of the surrounding 2° × 2° region. This “local anomaly” was computed from the SSM/I data and used to evaluate comparisons with different effective SSM/I resolutions. The impact of the modified SSM/I resolution on the retrieval differences for the WEN algorithm is shown in Figure 4. The SSM/I retrievals are typically moister (drier) on average than the COSMIC retrievals when the central IWV value is moister (drier) than the average of the surrounding 2° × 2° region. The magnitude of the effect is generally reduced as the effective resolution of the SSM/I retrievals is decreased to 150 km. Where the IWV is uniform over a 2° × 2° region, the SSM/I and COSMIC retrievals agree extremely well with little mean bias. The dependence is similar for each of the other SSM/I retrieval algorithms. These results provide independent confirmation that the effective COSMIC GPS radio occultation resolution is on the order of 250 km, consistent with the measurement technique. The impact of the orientation of the COSMIC ray path was not considered here.

Despite the impact of spatial resolution, the observed CLW, wind speed, and latitudinal difference dependencies were found to be independent. Similar dependencies as presented above were observed for the different effective SSM/I resolutions. Regardless of whether there is little or no bias on average, localized differences between the SSM/I algorithms are found to exist depending on the instantaneous atmospheric and surface conditions.

4. Conclusions

Collocated regional retrievals of IWV from COSMIC and SSM/I exhibit strong overall agreement lending confidence in the retrievals from both sensors. This is among the first independent verification of the COSMIC IWV values. Variations in the bottom altitude of the GPSRO soundings do not appear to systematically affect the IWV differences. Despite the overall agreement and lack of absolute validation, the results also reveal differences between the SSM/I IWV algorithms. Differences between the retrievals exhibit varying dependencies on the latitude, wind speed, cloud liquid water content, and rain rate with the latitudinal dependence highly correlated with wind speed. The WEN algorithm exhibits the smallest wind speed dependence but an increased dependence on CLW and rain rate with respect to the COSMIC values. These findings are consistent with previous studies [Sohn and Smith, 2003] and likely result from the different frequencies utilized in the SSM/I algorithms. Comparisons with SSM/I data averaged over different spatial domains confirm the effective spatial resolution of the COSMIC retrievals and show the contribution of spatial gradients to the differences, but the dependence of the retrieval differences on the other parameters is independent of the effective SSM/I resolution.

The results suggest that it may be possible to quantify the uncertainty in individual SSM/I IWV retrievals in part as a function of parameters such as the CLW content or wind speed. Development of such detailed uncertainty estimates is important for operational assimilation of SSM/I IWV retrievals. These initial findings motivate future work to confirm that the positive agreement observed here applies similarly on a global scale over longer time periods. Additional work is underway to further demonstrate the absolute accuracy of the COSMIC water vapor retrievals through comparison with radiosonde data. If successful, the COSMIC data may prove useful in the future as a new independent source for evaluating traditional SSM/I-derived retrievals over the ocean.

References


Y.-H. Kuo and T.-K. Wee, University Corporation for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA. (gary.a.wick@noaa.gov)