On the use of GPS measurements for Moderate Resolution Imaging Spectrometer precipitable water vapor evaluation over southern Tibet

Ning Lu,1 Jun Qin,2 Kun Yang,2 Yang Gao,2 Xiangde Xu,3 and Toshio Koike4

Received 26 April 2011; revised 7 October 2011; accepted 7 October 2011; published 15 December 2011.

Precipitable water vapor (PWV) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) near-infrared measurements from Terra and Aqua satellites have not been evaluated over southern Tibet, which has an elevated and complex topography. This study uses ground measurements from a network of 22 GPS receivers to evaluate the accuracy of MODIS PWV over this region. The evaluation shows that both the Terra and Aqua MODIS PWV have a high correlation with GPS measurements, but they generally tend to overestimate water vapor under clear-sky conditions, with scale factors from 1.06 to 1.19 and root mean square errors from 2.1 to 3.19 mm. The overestimation is mainly attributed to the systematic bias of MODIS PWV at sites below 3000 m, which increases with increasing water vapor, especially during the monsoon season, when the summer monsoon brings a large amount of water vapor from the tropical ocean to southern Tibet. In contrast, MODIS PWV at sites above 3000 m matches well with the GPS PWV. A linear fit model that was proposed and employed in previous studies is used to correct the errors of MODIS PWV at low sites. The performance of MODIS PWV is improved at each low site after the correction. The corrected MODIS PWV can represent the monthly variation of daily average GPS PWV within a 2% error. This evaluation study should facilitate the use of MODIS-derived water vapor in the models that calculate radiative forcing and simulate climate change over Tibet and its surrounding areas.


1. Introduction

Atmospheric water vapor plays an important role in global atmospheric energy and water cycles. Water vapor increases in close association with surface temperature changes through the radiative forcing effect and climate feedback [Trenberth et al., 2005; Wagner et al., 2006; Solomon et al., 2010]. Precipitable water vapor (PWV), a measurable parameter that mainly comprises tropospheric and stratospheric water, is used to study water vapor changes and their contributions to climate change. Water vapor carried by the Asian monsoon, which enters the global tropical stratosphere, is believed to be transported over the Tibetan Plateau because it provides a short circuit for cross-tropopause transport [Fu et al., 2006]. Among the Tibetan Plateau’s regions, southern Tibet is a critical area for water vapor transport. Water vapor changes over this region have a great impact on the rainy weather along the Yangtze River and on the downstream floods/droughts [Xu et al., 2004]. Therefore, accurate PWV information is essential to understanding the hydrological cycle, energy budget, and climate change over Tibet and its surrounding areas.

PWV, also referred to as total column water vapor, varies greatly in both space and time across Tibet [Zhai and Eskridge, 1997; Gao et al., 2003]; however, accurate ground observations are scarce over this vast land due to difficulties in measurement and maintenance. Satellite remote sensing is a much more feasible way to derive the PWV distribution. The Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites provides spatial and temporal PWV measurements. These measurements have been extensively evaluated against ground observations over most land areas [Li et al., 2003; Prasad and Singh, 2009; Thomas et al., 2011]. However, the accuracy of MODIS-derived water vapor is not well known over Tibet due to its
varied and elevated topography. Also, the average values of PWV over Tibet are much smaller than those over the surrounding low-elevation regions [Gao et al., 2003], meaning relative errors associated with elevation and elevation-relevant atmospheric environments could be magnified.

[4] An observational network of 22 GPS receivers over southern Tibet, supported by the Chinese–Japanese joint international cooperation program [Xu et al., 2008], was in operation for ten months in 2008 to measure PWV. In this study, these measurements are used to evaluate clear-sky PWV products as derived from MODIS near-infrared observations from the Terra and Aqua satellites. This study not only presents the errors in MODIS PWV products and their relation to land surface altitude, but it also demonstrates to what extent the MODIS PWV measurements acquired at specific times of the day can represent the daily average PWV of the climate.

2. Data

2.1. GPS

[5] The hourly GPS PWV data set was produced under the observation network for a New Integrated Observational System in the Tibetan Plateau (NIOST) during an intensive observation period (January–October 2008) [Xu et al., 2008]. Figure 1 shows the observation network. The elevation of all 22 GPS locations varies from 160 m to 4600 m. Surface air temperature and pressure data are measured simultaneously at each GPS location. Radio signals transmitted from the GPS satellites are delayed by the atmosphere before reaching the ground GPS receiver. The zenith total delay (ZTD) is computed using the software package GAMIT through the analysis of the GPS phase observations. ZTD is a sum of zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD). ZHD can be calculated by using the local surface pressure. ZHD subtracted from ZTD determines ZWD from which PWV can be inferred [Bevis et al., 1994]. Once ZWD is determined, it can be converted to PWV using the following expression [Wang et al., 2005]:

\[
PWV = \frac{10^6 \rho_w R_v (k_3 / T_m + k_2')}{ZWD},
\]

where \(\rho_w\) is the density of liquid water, \(R_v\) is the specific gas constant of water vapor, \(k_2'\) and \(k_3\) are the atmospheric refraction constants given by Bevis et al. [1994], and \(T_m\) is
The water-vapor-weighted mean atmospheric temperature, defined as

\[ T_m = \frac{\int (e/T) dh}{\int (e/T^2) dh}, \]  

(2)

where \( e \) denotes the water vapor pressure and \( T \) is the atmospheric temperature.

The vertical profiles of atmospheric temperature and humidity can be used to calculate \( T_m \). However, these vertical profiles are usually unavailable at the GPS sites. To obtain \( T_m \), Bevis et al. [1992] found a strong linear relationship between \( T_m \) and the surface air temperature \( T_s \):

\[ T_m = a + bT_s. \] 

(3)

The fitted coefficients \( a \) and \( b \) are geographically and seasonally dependent [Ross and Rosenfeld, 1997]. The values of \( a \) and \( b \) for the United States are 70.2 and 0.72, respectively, as given by Bevis et al. [1992]. The values we derived using local radiosonde data for southern Tibet are 42.86 and 0.84, which are similar to those suggested by Liu et al. [2005]. The accuracy of GPS-estimated PWV by this method is claimed to be better than 2 mm according to previous comparisons [Emardson et al., 1998; Ware et al., 2000; Li et al., 2003; Prasad and Singh, 2009]. To confirm the accuracy of our PWV data, we also compared our hourly PWV data with an independent, 2-hourly GPS PWV product developed by the National Center for Atmospheric Research Earth Observing Laboratory (hereinafter referred to as NCAR/EOL data) [Wang et al., 2007]. There are two sites of NCAR/EOL data on the Tibetan Plateau, of which only one (KUNM (25.029°N, 102.797°E)) is near our data site (BEKM (25.008°N, 102.63°E)). The linear distance between the two sites is approximately 15 km, and their elevations are both approximately 2000 m. The comparison was performed at 2 h intervals for each day from January to October 2008. The two independent GPS PWV data in Figure 2 are well matched, with a mean bias close to 0 and a root mean square error of 1.47 mm. The comparison shows that our data are qualified and the good correlation of PWV data between the two sites implies that the spatial
distribution of atmospheric water vapor is homogeneous within a certain distance.

2.2. MODIS Near-IR Water Vapor Product

The MODIS Level 2 PWV products of Collection 5 from Terra (MOD05_L2) and from Aqua (MYD05_L2) are generated at a 1 km spatial resolution using the near-infrared algorithm during the day [Gao and Kaufman, 2003]. The near-infrared algorithm for retrieving MODIS PWV data relies on observations of water vapor attenuation of near-infrared solar radiation reflected by surfaces and clouds. The ratios of water vapor absorbing channels (0.935, 0.940, and 0.905 μm) with the nearby atmospheric window channels at 0.865 and 1.34 μm are used [Kaufman and Gao, 1992]. This differential absorption technique largely removes the effects of surface reflectance with wavelengths, and it can determine PWV with errors typically in the range between 5% and 10% [Gao and Kaufman, 2003; King et al., 2003].

Because MODIS PWV is sensitive to the presence of clouds in the field of view, only MODIS PWV values collected under clear-sky conditions were used in this study. Pixels with 99% confidence clarity were extracted using the MODIS cloud mask product. To overcome the problem of misregistration in the comparison, the MODIS PWV values were averaged over boxes of 3 × 3 pixels centered on the GPS receiver location. Geometric information for each swath image was obtained from MODIS geolocation product (MOD03). The hourly GPS PWV data closest to the MODIS acquisition time were chosen for comparison with the box-averaged MODIS PWV data under clear-sky conditions. The time difference between each matched pair of MODIS and GPS PWV data was limited to 30 min.

3. Results and Discussion

The clear-sky MODIS PWV data from the Terra and Aqua satellites were first analyzed at each ground GPS site. The correlation coefficients, mean biases (between MODIS and GPS) and root mean square errors (RMSEs) at the 22 GPS sites are shown in Figure 3. Most of the correlation coefficients are approximately 0.9 or higher, the biases are between −1.5 to 1.5 mm, and the RMSEs are around 1.5–2.5 mm. The high correlation coefficients and low RMSEs demonstrate the good capability of the Terra and Aqua MODIS PWV products to estimate the amount of atmospheric water vapor. The Terra MODIS PWV has a mean correlation coefficient of 0.94, a mean bias of 0.15 mm and a mean RMSE of 2.14 mm. For the Aqua MODIS PWV, the mean correlation coefficient is 0.95, the mean bias is 0.17 mm, and the mean RMSE is 2.22 mm. The positive mean biases indicate that both Terra and Aqua MODIS PWV tend to overestimate the atmospheric water vapor on the Tibetan Plateau. Liu et al. [2006] found large RMSE values of MODIS PWV compared with GPS PWV over Gaize and Naqu in Tibet using the old version of MOD05_L2, with an RMSE of 3.48 mm and 2.93 mm, respectively. The large RMSE for the MODIS near-infrared PWV on the Tibetan Plateau was due to an error of surface pressure in the coding of
the operational near-infrared water vapor retrievals. In this study, the RMSE is 1.89 mm at Gaize (site GAIZ in Figure 1) and 1.71 mm at Naqu (site NAQU). The decrease in the RMSE indicates that the coding error has already been corrected in this version of MODIS products.

[11] After evaluating the MODIS PWV site by site, we found that it shows different characteristics at sites above 3000 m (high sites) and below 3000 m (low sites). As shown in Figure 4, the clear-sky MODIS PWV has a better correlation with the GPS PWV at low sites. The RMSE of the MODIS PWV at high sites is slightly lower than that at low sites (with RMSE of 2.1 mm versus 3.1 mm). The relative discrepancies in MODIS PWV, however, are slightly larger at high sites compared with the low sites (a relative RMSE of 19% versus 17%). The scale factors and intercepts in Figure 4 indicate a slight underestimation of the MODIS PWV for small water vapor amounts and a slight overestimation for large water vapor amounts. At the low sites, the differences between the MODIS and GPS PWV mainly increased with increasing water vapor. These differences correlate well with the GPS PWV, with a correlation coefficient of 0.56 which is significant ($p < 0.01$) at the 99% level of confidence. The same issue was found by Li et al. [2003], who used a linear fit model to correct the errors over Germany. They suggested that this bias is likely caused by uncertainties in the spectroscopic database. The large bias with a large amount of water vapor here also suggests that the MODIS PWV procedures may have some issues with the calculation of atmospheric transmittance for water vapor.

[12] The time difference between the GPS data and the overpassed MODIS data introduces errors into the validation of the MODIS PWV because atmospheric water vapor may change within the mismatch period. Therefore, the RMSE values in this study are relatively larger than previous studies using high-resolution GPS data, such as validation over Germany [Li et al., 2003], Southern California [Li et al., 2005], and Antarctica [Thomas et al., 2011]. The relatively large differences between the MODIS and GPS PWV data are partly due to these errors. However, this kind of uncertainty is random, and it does not affect the systematic errors found in the validation [Wang et al., 2007; Li et al., 2009; Prasad and Singh, 2009]. The elevation differences between the GPS sites, which are sometimes located in the valley areas, and the corresponding MODIS footprints may also increase the errors in the validation [Bock et al., 2007]. We used the elevation derived from the Shuttle Radar Topography Mission with a 1 km resolution to represent the surface elevation of the MODIS footprint. The elevation differences range from 0.23 to 69.17 m.

Figure 5. Monthly variation of clear-sky PWV of the Terra MODIS and the corresponding GPS (a) at sites above and below 3000 m, respectively, and (b) at all sites, along with the corrected Terra MODIS PWV. The daily mean GPS PWV is plotted as a reference. The atmospheric water vapor over the Tibetan Plateau increases substantially in May–September due to large-scale water vapor transports by the summer monsoon from the tropical ocean.
Therefore, the impact of elevation differences on the comparison is small.

To demonstrate the capability of the MODIS PWV to characterize temporal variations in atmospheric water vapor, we averaged all of the ground GPS PWV measurements for each month along with all those from the corresponding MODIS PWV. Figure 5a compares the monthly Terra MODIS PWV with the monthly daily mean GPS PWV under clear-sky conditions. The Terra MODIS PWV showed the same variations as the daily mean GPS PWV for the first four months, but it started to overestimate the water vapor amount during the monsoon season (May–September), when the summer monsoon brings a large amount of water vapor from the tropical ocean to southern Tibet; therefore, the daily atmospheric water vapor varies. Note that the GPS PWV measured during the Terra time frame (dashed line with circle) fits well with the daily mean GPS PWV in the monthly average. The standard deviation between the monthly daily mean GPS PWV and Terra MODIS PWV is 0.86 mm. Given that the mean value of the daily mean GPS PWV is 14.19 mm, the error of the Terra MODIS PWV is ~6%. This error is attributed to the overestimation of Terra MODIS PWV at low sites. Figure 5b shows the monthly average of the Terra MODIS PWV at both high and low sites. It is obvious that the Terra MODIS PWV at the low sites overestimated the water vapor during the monsoon season, while the MODIS PWV at the high sites matched the GPS PWV well. The linear relationship shown in Figure 4 can be used to correct the MODIS PWV at sites below 3000 m [Li et al., 2003, 2005]. We used the linear fit as a model to calibrate the Terra MODIS PWV at the low sites and compared the calibrated MODIS PWV with the GPS PWV at each low site (Table 1). After this correction, the average correlation coefficients were nearly the same. However, the average scale factor decreased from 1.23 to 0.99, the average bias decreased from 0.17 to 0.08 mm, and the average RMSE decreased from 2.35 to 1.88 mm, which indicates that this linear fit model is applicable to correct the Terra MODIS PWV at low lands over southern Tibet. It is demonstrated once again the feasibility to use a linear fit model to calibrate MODIS near IR water vapor products with GPS data. Figure 5a demonstrates that the corrected Terra MODIS PWV values fitted well with their corresponding GPS PWV values in the monthly average and the monthly daily mean GPS PWV. The standard error between the monthly daily mean GPS PWV and the Terra MODIS PWV decreased to 0.28 mm. The error of the corrected Terra MODIS PWV was within 2%, and the corrected Aqua MODIS PWV had almost the same accuracy. This good fit demonstrates that the Terra and Aqua PWV measurements after error correction at low elevations can represent the monthly atmospheric water vapor well over southern Tibet. The corrected MODIS PWV could be useful when assimilated in to regional or global climate models, and it could help improve models that calculate radiative forcing and predict climate change.

4. Conclusions

This study presents an evaluation of Terra and Aqua MODIS PWV using ground measurements from a network of 22 GPS receivers over southern Tibet. The evaluation shows that the MODIS PWV has a good performance over this region. The Terra MODIS PWV has a mean correlation coefficient of 0.94, a mean bias of 0.15 mm, and a mean RMSE of 2.14 mm. The Aqua MODIS PWV has a mean correlation coefficient of 0.95, a mean bias of 0.17 mm, and a mean RMSE of 2.22 mm. Both the Terra and Aqua MODIS PWV tend to overestimate the atmospheric water vapor. The overestimation of the MODIS PWV mainly occurs at sites below 3000 m due to its systematic bias, which increases with increasing water vapor; this bias increases with the large amount of water vapor during the monsoon season. In contrast, the MODIS PWV at high sites matches well with the GPS PWV. The larger differences relative to the MODIS PWV are likely caused by uncertainties in the calculation of atmospheric transmittance for water vapor and by the time differences in matching hourly GPS and overpassed MODIS data.

The standard deviation between the monthly daily mean GPS PWV and Terra MODIS PWV is approximately 6%. After correcting the Terra MODIS PWV at the low sites using a linear model, its performance was improved at each low site. The monthly averages of the corrected Terra MODIS PWV fitted well with that of the daily mean GPS PWV, with the error between them decreasing to 2%. The corrected Aqua MODIS PWV had a similar performance. Therefore, PWV measurements from MODIS instruments should be able to represent the daily average water vapor at least on the monthly scale, demonstrating that MODIS PWV is suitable for studying the seasonal and annual impacts of water vapor on climate. The scale factors of the MODIS PWV relative to the GPS PWV indicate that the former should be calibrated before being applied in practice by using, for example, a linear model such as the one demonstrated in this paper. PWV measurements from MODIS instruments are themselves expected to offer greater potential for the Tibetan Plateau and its surrounding areas in the future, such as when facilitated by the use of Terra and Aqua MODIS-derived water vapor in climate change research and climate model simulation.

Acknowledgments. This study was supported by the National Natural Science Foundation of China (grants 41001215 and 41001037). The MODIS water vapor data were obtained from the Goddard Earth Sciences Distributed Active Archive Center (DAAC), and the GPS data were obtained from the New Integrated Observational System in the Tibetan Plateau (NIOST). We thank the Chinese Academy of Meteorological Sciences and the University of Tokyo for data support from JICA “China-Japan Meteorological Disaster Reduction Cooperation Research Center Project.” We would also like to thank Liangying Zhang for providing us with the NCAR/EOL GPS PWV products.
References


Y. Gao, J. Qin, and K. Yang. Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China.

T. Koike, Department of Civil Engineering, University of Tokyo, Tokyo 113-8656, Japan.

N. Lu, State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.

X. Xu, State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100081, China.