Evaluation of AIRS Precipitable Water Vapor against Ground-based GPS Measurements over the Tibetan Plateau and Its Surroundings

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Abstract

The Atmospheric Infrared Sounder (AIRS) on board the Aqua satellite provides the estimate of precipitable water vapor (PWV), which can be assimilated into numerical prediction models to improve precipitation forecasts. In this study, the AIRS retrieval of PWV is evaluated against ground-based GPS measurements at 24 stations over the Tibetan Plateau (TP) and its surroundings. First, the PWV estimates from the GPS delay signals at these stations are improved by applying a new scheme for computing the water-vapor-weighted mean atmosphere temperature, a key parameter in the GPS PWV retrieval. Compared with a traditional retrieval, this revision can improve the PWV estimate by up to 6% in some cases. Second, the newly retrieved PWV data are used to evaluate the AIRS product. Prior to the evaluation, an elevation correction is made to these GPS PWV data to account for the elevation difference between the GPS stations and the corresponding AIRS footprints. This correction effectively removed false negative biases in the AIRS product. Nevertheless, an average negative bias of 2 mm still exists in the AIRS product. A further analysis suggests that the negative bias may be attributed to the cloud-clearing algorithm in the AIRS retrieval scheme.

1. Introduction

The Tibetan Plateau with an area of roughly $2.5 \times 10^8$ km$^2$ has an average elevation of approximately 4000 m above sea level (ASL). It is well known that the TP’s thermal and dynamical processes have a profound influence on the formation of the Asia monsoon and thus both the weather
and climate of the Asian continent (Wang et al. 2008). In the monsoon season, the water vapor intrudes into the central and eastern TP, bringing summer precipitation. Moreover, the eastward movement of convective cloud systems developing over the TP may cause severe floods in east and southeast China (Liu et al. 2005). Thus, it is very significant to monitor the amount of precipitable water vapor (PWV) and its spatial and temporal variations in this area.

Many studies pointed out that assimilation of PWV into numerical weather prediction models can improve precipitation forecasts (Kuo et al. 1993; Shoji 2009). In the recent decades, novel techniques have been developed and applied to measure atmospheric PWV. The satellite-based method (Rodgers and Connor 2003) and GPS-based method (Bevis et al. 1994; Duan et al. 1996) are popular in this aspect. They provide new opportunities for improving weather forecasts.

The satellite-based atmospheric sounding provides an opportunity to observe atmospheric properties with large spatial coverage at a relatively high time resolution. The capability of atmospheric sounding has been upgraded to a new level with the launch of the *Aqua* satellite (Chahine et al. 2006), since three instruments aboard this satellite, including the Atmospheric Infrared Sounder (AIRS), the Advanced Microwave Sounding Unit-A (AMSU-A), and the Humidity Sounder for Brazil (HSB), form the AIRS sounding suite to retrieve the vertical profiles of atmospheric properties such as temperature and humidity. The sensor AIRS plays a leading role and the other two ones (AMSU-A and HSB) are mainly used for cloud clearing in the retrieval algorithm. However, AIRS PWV data must be validated before being used for operational or research purposes (Prasad and Singh 2009; Raja et al. 2008).

In the past decades, many GPS receiver networks have been constructed for many purposes such as geodetic and geophysical applications. Many studies showed that PWV data can be continuously derived from GPS signals according to their delays in the atmosphere with high accuracy at relatively low costs (Kuwagata et al. 2001). Thus, GPS-based PWV data is often used to validate satellite-based PWV retrievals and PWV reanalysis data from numerical weather prediction models (Bock et al. 2007; Liu et al. 2005; Noel et al. 2005). GPS-based PWV data has already been compared with AIRS PWV product in many validation tasks. These researches indicated that AIRS PWV data has a negative bias against GPS PWV data in the wet season and the converse occurs in the dry season (Prasad and Singh 2009; Raja et al. 2008). Moreover, these studies also put forward the possible reason for these biases. It is the discrepancies between the surface pressures at GPS sites and those used as inputs to the AIRS retrieval algorithm from the NCEP Global Forecast System (GFS) (Raja et al. 2008).

Traditionally, radiosonde balloons are launched to collect air temperature and humidity data. However, the number of weather stations with radiosonde release over the TP and its surroundings is sparse owing to high elevations and harsh natural conditions (Divakarla et al. 2006). As showed in the validation work by Divakarla et al. (2006), there are no matchups between routine radiosonde observations and AIRS products in this region due to their different observation times. To the authors’ knowledge, no work has been carried out to validate AIRS PWV products against ground-based (radiosonde or GPS) measurements in this area. However, it is an indispensable step to verify AIRS PWV products for applications.

To this end, PWV data are retrieved at GPS stations, corrected for elevation difference between GPS stations and AIRS footprints, and then applied to validate AIRS PWV estimates in this region. Moreover, the possible reasons for the bias in AIRS PWV estimates against GPS PWV retrievals are investigated in order to provide hints for improvement of the AIRS PWV products. This article is organized as follows. The data and method is described in Section 2. In Section 3, the retrieval of GPS PWV is introduced. In Section 4, the procedure for data preparation is presented. The validation results and discussion are given in Section 5. The conclusions are drawn in the end.

2. Data and method

Before introducing the data, several main validation steps are given in order to make the readers understand the procedure for the present study. Firstly, a new parameterization is designed to estimate the water-vapor-weighted atmospheric temperature required by the GPS PWV retrieval algorithm. Secondly, two independent correction schemes are compared to determine which one is more suitable for correcting the bias induced by elevation difference between AIRS footprint and GPS station. Thirdly, AIRS PWV estimates are validated against elevation-corrected GPS PWV
retrievals. Finally, possible reasons for the bias in AIRS PWV estimates are investigated after analysis of its variation with elevation and season.

Three types of data are mainly used and briefly introduced in the following. GPS delay signals will be used to retrieve PWV data. These signals are collected at the 24 GPS stations (as shown in Fig. 1), which are built with the funding support from the China and Japan intergovernmental cooperation program—Japan-China Meteorological Disaster Reduction Corporation Research Center Project (Xu et al. 2008, hereafter referred to as the JICA project). At present, the GPS data with one-hour time resolution in the year 2008 at these sites from the JICA project will be taken to retrieve PWV with the algorithm described in the subsequent section.

In this study, a new scheme is proposed for the calculation of the water-vapor-weighted atmospheric temperature, as mentioned previously. The radiosonde data from the year 2000 to the present at totally 13 sites over the TP and its surroundings, which are obtained from the Integrated Global Radiosonde Archive (IGRA) (Durre et al. 2006), are divided into two groups, and exploited to calibrate and validate this new scheme, respectively. The group for calibration includes the following weather stations: BAIS, SIMAO, WEIN, QAMDO, and NAQU with the site numbers: 59211, 56964, 56691, 56137, and 55299; the validation group is made up of sites: LHASA, YUSHU, GANZ, CHENGDU, XICH, TENGCHONG, KUNMING, and MNZI with the site numbers 55591, 56029, 56146, 56294, 56739, 56778, and 56985. The IGRA dataset is available from the Climate Analysis Branch at the National Oceanic and Atmospheric Administration (NOAA) National Climate Data Center. At these stations where weather balloons...
are released, only BAIS, WEIN, NAQU, GANZ, XICH are equipped with GPS receivers for the JICA project.

The whole AIRS inversion algorithm is composed of seven modules including calibration, microwave retrieval, cloud clearing, initial infrared retrieval, physical retrieval, bias correction, and radiative transfer calculations. For more details on the AIRS sensor and its retrieval algorithm, readers are referred to the articles by Aumann et al. (2003) and Susskind et al. (2003). In this study, the AIRS standard Level 2 granule products (Version 5.2.2.0) are used. The footprint of this type of product is of approximately 40 km at nadir. AIRS products including PWV currently are available conveniently through the Goddard Earth Sciences Data Information and Services Center. The salient characteristic of the TP region is its high elevation and complex topography. The AIRS footprints, which correspond to the same GPS station, may have different mean elevations due to the differences in orbits when the satellite revisits. The AIRS products provide the altitude for its each footprint. The altitudes corresponding to each GPS stations during the year 2008 are extracted from the products, and then the statistics (minimum, maximum, and mean) of these altitude values for each station are calculated and summarized in Table 1. As can be seen, the elevation difference is quite large in some cases, reaching several hundreds of meters. For the same reason, elevation differences between the GPS sites, which are usually located in the valley areas, and the corresponding AIRS footprints may be large. As shown in Table 1, the maximum difference could arrive at a value of approximately 1000 m. This effect must be eliminated before the validation is performed. The details for the correction procedure will be presented in Section 4.

### 3. GPS PWV sensing

As mentioned in the previous section, radio signals transmitted from the GPS satellites are delayed by the atmosphere before reaching the receiver antenna. This delay, called the zenith total delay

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<th>Name</th>
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(ZTD), is the sum of two components (Jade et al. 2005; Wang et al. 2005):

$$Z_T = Z_H + Z_W$$  \hspace{1cm} (1)

where $Z_T$ denotes the ZTD; $Z_H$, the zenith hydrostatic delay (ZHD) due to the induced dipole moment; and $Z_W$, the zenith wet delay (ZWD) due to the permanent dipole moment of water vapor. In this study, ZTD is computed with the software package GAMIT developed by the Massachusetts Institute of Technology through the analysis of the GPS phase observations. ZHD can be computed using the following formula:

$$Z_H = \frac{0.0022768 P_s}{1 - 0.00266 \cos 2 \varphi - 0.00028 h}$$  \hspace{1cm} (2)

where $P_s$ denotes the surface air pressure; $\varphi$, the latitude; and $h$, the altitude. ZWD can be obtained as the difference between ZTD and ZHD. Once ZWD is computed, it can be converted to PWV by the following expression:

$$PW = \frac{10^6}{\rho_w R_c (k_3/T_m + k_2)} Z_W$$  \hspace{1cm} (3)

where $PW$ denotes PWV; $\rho_w$, the density of liquid water; $R_c$, the specific gas constant of water vapor; $k_2$ and $k_3$, the atmospheric refraction constants, respectively; and $T_m$, the water-vapor-weighted mean atmospheric temperature defined as:

$$T_m = \frac{\int (e/T) dh}{\int (e/T^2) dh}$$  \hspace{1cm} (4)

where $e$ denotes the water vapor pressure, and $T$ is the atmospheric temperature.

As shown in Eq. (4), the vertical profiles of atmospheric temperature and humidity are required in order to calculate $T_m$. However, these vertical profiles are not always available at GPS sites. A simple empirical linear relationship, therefore, has been developed to calculate $T_m$ in terms of the surface air temperature as follows:

$$T_m = a + b T_a$$  \hspace{1cm} (5)

where $T_a$ is the near-surface air temperature; and $a$ and $b$ are the fitted coefficients. The most commonly used values of $a$ and $b$ are 70.2 and 0.72, respectively, which were derived by Bevis et al. (1992) using the radiosonde data in the United States. However, many studies showed that these two coefficients are site-dependent and needs local calibration.

As pointed by Wang et al. (2005), the accuracy of $PW$ depends strongly on the value of $T_m$, and thus it is very important to obtain $T_m$ as accurately as possible. However, Eq. (5) merely uses the near-surface air temperature to estimate $T_m$ and the information on the water vapor is not accommodated in it. So, it is not surprising that the two coefficients in Eq. (5) changes with locations. In this study, a new empirically based scheme is proposed to calculate $T_m$ (hereafter referred to as the new $T_m$ scheme) in order to improve the PWV retrieval accuracy according to GPS signal delays. In the new scheme, the effects of both the temperature and the water vapor are taken into account. As a matter of fact, several different equation forms for the new $T_m$ scheme are tried and the following one performs the best:

$$T_m = T_r \left[ a' + b' \left( \frac{T_a}{T_r} \right) + c' \left( \frac{T_a}{T_r} \right)^2 \right] R_h' \left( \frac{P}{P_s} \right)^{e'}$$  \hspace{1cm} (6)

where $T_r$ denotes the reference temperature which is taken as 273.15 K here; $T_a$, the near-surface air temperature at GPS sites; $R_h$, the relative humidity of near-surface air at GPS sites; $P$, the air pressure at GPS sites; $P_s$, the air pressure at sea level; and $a'$, $b'$, $c'$, and $d'$, the coefficients to be determined. Because the near-surface relative humidity is applied to explicitly embody the water vapor information of the atmosphere in Eq. (6), it is expected that this formula could explain the variability in $T_m$ better and provide its more accurate estimates as compared to Eq. (4).

The radiosonde data group for calibration as introduced in Section 2 is used to determine the five coefficients in the Eq. (6), and they are equal to −0.58306, 2.4252, −0.85134, 0.0527, and 0.012369, respectively. Simultaneously, the linear regression model as shown in Eq. (5) is also calibrated and validated using the same radiosonde dataset and procedure in order to compare with the new $T_m$ estimation scheme. The coefficients $a$ and $b$ are equal to 42.86 and 0.84, respectively. For the sake of completeness, the validation is also performed for the linear relationship with the coefficients obtained by Bevis et al. (1992). The calibration results are shown in Fig. 2 and the validation results are indicated in Fig. 3. As seen in these two figures, the new scheme can better explain and predict the variability of $T_m$ than the linear regression model in terms of root mean square error (RMSE), mean bias error (MBE), and determination coefficient ($R^2$).
In order to examine whether or not the new parameterization scheme for \( T_m \) (cf. Eq. (6)) improves the GPS PWV retrievals compared to the linear scheme, the following relative error is calculated:

\[
RE = \frac{PW_{\text{old}} - PW_{\text{new}}}{PW_{\text{new}}} \tag{7}
\]

where \( RE \) denotes the relative error; \( PW_{\text{old}} \), the PWV retrieved by the linear scheme; and \( PW_{\text{new}} \), the PWV retrieved by the new scheme. Table 1 gives the relative error of GPS PWV retrievals at each GPS site when using the linear model with the coefficients determined by Bevis et al. (1992) instead of the new scheme, showing that the new scheme can reduce the relative error by up to about 6% in some cases.

4. Data matchup for validation

Raja et al. (2008) validated AIRS PWV retrievals against the corresponding GPS PWV over the Contiguous United States (CONUS), showing that the AIRS algorithm can estimate PWV data with a RMSE of approximately 3.5 mm and a MBE of 0.5 mm although these two error metrics vary slightly with seasons. In this study, their validation results serve as the reference standard in order to examine whether or not the performance of AIRS PWV estimates exhibit different characteristics over the TP and its surroundings. Thus, the similar criteria are used to choose the matched pairs of AIRS and GPS PWV data, which are briefly as follows. Firstly, the horizontal distance between a GPS station and the center of AIRS footprint is less than...
0.5 degree (geographical projection). Secondly, the time difference between the GPS retrievals and the AIRS products is less than 30 minutes. Thirdly, the AIRS PWV estimates with the quality assurance flag (Qual_Temp_Profile_Mid) equal to 0 are chosen.

As described in Section 3, the elevation correction has to be performed to the GPS and AIRS PWV data. In this study, two independent correction schemes are implemented to correct the GPS PWV to the altitude at the AIRS footprint in order to verify each other. One scheme is developed by Bock et al. (2007) to validate the NWP model reanalysis PWV data against GPS PWV data in the following form (hereafter referred to as the correction scheme one):

\[
P_{W_{AIRS}} = P_{W_{GPS}} + \rho_v \frac{\Delta h}{C_0} \left(1 - \frac{\rho_v \Delta h}{2P_{W_{GPS}}} \right)
\]

where \(P_{W_{AIRS}}\) is the AIRS PWV; \(P_{W_{GPS}}\), the GPS PWV; \(\Delta h\), the height difference between GPS site and AIRS footprint; and \(\rho_v\), the water vapor density at the height of GPS receivers. The other scheme is designed in this study according to the equation presented by Leckner (1978) as follows (hereafter referred to as the correction scheme two):

\[
P_{W_{AIRS}} = P_{W_{GPS}} \exp \left(\frac{C_2 \Delta h}{1000}\right)
\]

where \(P_{W_{AIRS}}\) is the AIRS PWV; \(P_{W_{GPS}}\), the GPS PWV; \(\Delta h\), the height difference between the GPS site and AIRS footprint; and \(C_2\), the constant equal to 0.439.

The TP region is typical of high elevation and the atmospheric thermodynamic structure varies with the increasing altitude; moreover, this area is dominated by the monsoon climate. The validation is performed for each data group in an effort to investigate the dependence of the AIRS PWV estimates on the season and elevation, and simultaneously identify the possible error sources.

5. Results and discussion

The altitudes of AIRS footprints are extracted from the AIRS products at the corresponding GPS stations and their statistics are listed in Table 1. It is found that the altitudes of GPS stations are less than the ones of AIRS footprints in most cases, so a negative bias is expected for the AIRS PWV products over the TP and its surroundings, if no elevation corrections are made to them. This is observed in Fig. 4a. Figures 4b, c show the corrections results for all matchup pairs at the 24 GPS stations in the year 2008 with the correction schemes presented in the previous section. As seen in them, both schemes can reduce both the RMSE and MBE values of AIRS PWV estimates with almost the same magnitude when comparing with the GPS PWV retrievals. Because these two correction schemes are independent of each other and the similar correction results are obtained, this implies that they could be reliable. The AIRS PWV estimates adjusted by the correction scheme one are used in the following validation work. In an effort to further examine the performance of the elevation correction, the relative errors both before and after correction (by the scheme one) are calculated, binned, and then averaged according to the elevation height intervals. The results in Fig. 5 indicate that the relative errors obviously increase with increased elevation difference before correction, but this kind of correlation almost disappears after correction. Although the correction procedure could

Fig. 4. (a) Comparison between GPS and AIRS PWV without elevation correction. (b) Comparison results using the correction scheme one. (c) Comparison results using the correction scheme two.
eliminate one part of errors (cf., Figs. 4, 5), a negative bias (approximately $-2.6$ mm), which is much larger than the negative bias identified in the validation work over the Contiguous United States (CONUS) (Raja et al. 2008), still exists after the correction. As mentioned in the introduction section, several previous studies pointed out that the difference between the surface pressures at GPS sites and those used as inputs to the AIRS retrieval algorithm should be responsible for this negative bias. Thus, it is checked whether or not this pressure difference is the reason for the negative bias in the TP and its surroundings by comparing the surface pressures at the 24 GPS stations and the corresponding AIRS pressure inputs. Before comparison, the elevation correction should also be made to the pressure values in a similar manner to the PWV correction. The surface pressures at the GPS sites are adjusted to the altitudes of AIRS footprints using the following barometric formula:

$$P_{\text{AIRS}} = P_{\text{GPS}} \left(1 - \frac{\Delta h}{C_p T_a} g\right)^{3.5}$$

(10)

where $P_{\text{AIRS}}$ denotes the surface pressure at the altitude of AIRS footprint; $P_{\text{GPS}}$, the air pressure at GPS sites; $\Delta h$, the height difference between the GPS site and AIRS footprint; $T_a$, the near-surface air temperature at GPS sites; $C_p$, the specific heat of air at constant pressure; and $g$, the gravitational acceleration. Figure 6 indicates that the GFS surface pressures, which are used in the AIRS inversion algorithm, agree well with the corrected pressures at the GPS stations, and the AIRS pressures, however, still have a small negative bias of $-2.3$ hPa. This bias is negligible, and thus some other factors must be responsible for the error. The conclusion drawn by Raja et al. (2008), however, is that the pressure bias should be the reason for the PWV bias. As a matter of fact, the elevation correction was not made to the GPS or AIRS PWV data before the comparison in their work. The pressure bias was really caused by the elevation difference between the GPS stations and the AIRS footprints. It is expected that the AIRS PWV bias could be alleviated after elevation correction over the CONUS.

Since the thermodynamical structure of the atmosphere exhibits different patterns during the dry season (May, June, July, and August) and the wet one over the TP and its surroundings, the height
2000 meters is used as the delimiter to distinguish the area inside the TP and the region outside of the TP. In the following, the total GPS-AIRS pairs are, therefore, divided into four groups: dry season inside the TP, dry season outside of the TP, wet season inside the TP, and wet season outside of the TP. Then, the comparison is performed for each group of pairs.

As shown in Fig. 7, the negative bias changes with the season and the altitude, but all exhibit the negative bias. The negative bias in the wet season is greater than that in the dry season regardless of the elevation level. Furthermore, the negative bias at high elevations is smaller than that at low altitudes at the same season. As far as the RMSE value is concerned, the same pattern occurs. This is different from the finding by Raja et al. (2008) that AIRS PWV data has the negative bias wet season and the converse occurs in the dry season. Although the RMSE value (4.16 mm) for the whole matchups (in Fig. 4b) in the TP and its surroundings is similar to that (approximately 3.0–4.5 mm) in the validation results obtained over the CONUS (Raja et al. 2008), the bias value (2.57 mm) is much larger than that (about 0.5–1.2 mm) over the CONUS.

It is doubted that the reason for the negative bias of the AIRS PWV products over the TP and its surroundings is caused by using the temperature profile retrievals with large errors, and furthermore this problem with these retrievals is induced by the failure of the AIRS cloud-clearing algorithm as compared to their performance over the CONUS. Thus, two examinations are subsequently carried out to check the relationship between the PWV negative bias and the error in the temperature retrieval and the one between the AIRS retrieved temperature bias and the cloud fraction at the AIRS footprint.

Because there are no matchups between the routine radiosonde data and the AIRS soundings as pointed out in the work by Divakarla et al. (2006), the comparison between the AIRS profiles and the
corresponding radiosonde ones could not be performed. As described in the previous section, the near-surface air temperatures are available at the GPS stations. It is possible to compare them with the AIRS near-surface air temperatures and this can provide a hint about the relationship between errors in the AIRS temperature retrievals and ones in the AIRS PWV estimates. Similarly, the elevation correction should be made to these temperatures due to the altitude difference between the GPS site and the AIRS footprint. However, there is no reliable formula to achieve this task. Thus, the near-surface air temperatures at the 4 GPS stations (BAIS, XINJ, CQBB, and DAXI) below 500 m ASL are used in the comparison because the terrain are relatively flat and the elevation effect could be ignored near these sites. The comparison results are shown in Fig. 8a. The PWV differences between the GPS-AIRS pairs at these stations are binned according to their near-surface temperature differences and then averaged in Fig. 8b. At the same time, the comparison between the GPS and AIRS PWV data is carried out in Fig. 8c. As can been seen, the bias in the AIRS PWV data is highly correlated with the temperature bias, and furthermore the negative temperature bias has a stronger impact on the PWV than the positive temperature bias does.

Because cloud-clearing radiances are used in the AIRS retrieval algorithm, the negative bias in the AIRS near-surface temperatures may occur if the cloud clearing algorithm does not achieve its task satisfactorily. In order to confirm this, the near-surface temperature differences between AIRS retrievals and in-situ measurements are binned according to the cloud fraction intervals, and then averaged as shown in Fig. 9. As seen, the temperature bias tends to increase with increased cloud fractions. These results indicate that the cloud-clearing algorithm is highly likely not to perform as well as it does over the CONUS, and the accuracy of the retrieved atmospheric temperature and moisture profiles are unsatisfactory to obtain high-quality PWV in the TP and its surroundings. Thus, the AIRS algorithm needs inspection in order to obtain the PWV retrievals with high quality.

6. Concluding remarks

The satellite-based PWV products such as AIRS provide a valuable data source to be assimilated
into numerical weather prediction models in order to improve the precipitation forecast accuracy. However, these PWV products need validation before any operational or research application. In this study, the GPS-based PWV retrievals are used to achieve this task in the TP and its neighborhood. Since the terrain is very complicated in this region, the commonly used scheme to compute the water-vapor-weighted mean atmospheric temperature $T_m$, which is required in retrieving the PWV with GPS wet delays, is examined against the new scheme presented in this research. The results show that the new one could improve the $T_m$ estimates and then the GPS PWV retrievals. For the similar reason, the elevation correction is needed when the AIRS PWV products are compared with the GPS PWV retrievals at the 24 GPS stations in this region.

The validation results indicate that the negative bias always exists no matter whether it is the dry season or the wet one and moreover the negative bias inside the TP is less than the one outside of the TP. The same error pattern exists in the RMSE sense. These validation results exhibit different patterns from those over the CONUS. Although the RMSE for the whole matchups in this TP and its surroundings have a similar value to the one in the CONUS, the bias shows a large discrepancy in these two regions.

The investigation is performed to find the reason for the negative bias. The surface pressure difference between the GPS stations and the inputs to the AIRS algorithm is examined, showing that the GFS could provide the reliable surface pressure and this pressure difference should not take responsibility for the PWV negative bias. The AIRS near-surface temperatures are compared with those collected at the 4 GPS stations with a flat terrain. It is found that the PWV negative bias is highly correlated with the temperature bias. The unsatisfactory performance of the cloud-clearing algorithm may cause errors in the temperature profile retrievals. The correlation between the AIRS near-surface temperature biases and the AIRS cloud fractions is identified, showing that uncertainties in the AIRS cloud-clearing radiances may cause the AIRS PWV negative bias in the TP and its neighborhood.

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