Applicability of AIRS Monthly Mean Atmospheric Water Vapor Profiles over the Tibetan Plateau Region

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ABSTRACT

The research explores the applicability of the gridded (level 3) monthly tropospheric water vapor (version 5) retrievals from the Atmospheric Infrared Sounder (AIRS) instrument and the Advanced Microwave Sounding Unit (AMSU) on board the NASA Aqua satellite over the Tibetan Plateau by comparing them with carefully processed radiosonde data. Local correlation analyses indicate that below 200 hPa, the AIRS/AMSU monthly water vapor retrievals are highly consistent with radiosondes over the whole plateau region, especially in the southeastern part and between 300 and 600 hPa. Relative deviation analyses further show that the differences between monthly mean AIRS/AMSU water vapor retrieval data and radiosondes are, in general, small below 250 hPa, in particular between 300 and 600 hPa and in high-altitude areas. Combined with a further direct comparison between AIRS/AMSU water vapor vertical retrievals and radiosonde observations averaged over the entire domain, these results suggest that the gridded monthly AIRS/AMSU water vapor retrievals can provide a very good account of spatial patterns and temporal variations in tropospheric water vapor content in the Tibetan Plateau region, in particular below 200 hPa. However, differences between AIRS/AMSU retrievals and radiosondes are seen at various levels, in particular above the level of 250 hPa. Therefore, for detailed quantitative analyses of water budget in the atmosphere and the entire water cycle, AIRS/AMSU retrieval data may need to be corrected or trained using radiosondes. Two fitting functions are derived for warm and cold seasons, although the seasonal difference is generally small.

1. Introduction

Regarding its dynamic and thermodynamic effects, the Tibetan Plateau plays a very important role in affecting not only regional weather and climate but also the large-scale atmospheric circulation and climate over East Asia and even the entire Northern Hemisphere. To improve our knowledge of these effects, the availability of various observations including both dynamic and thermodynamic fields is the very first step. Before 1950s, the so-called observations over the plateau were usually obtained by extrapolating from fragmentary meteorological data (Qian and Jiao 1998). Since then, many surface observation stations have been gradually established over the plateau and the surrounding regions. In particular, after two organized scientific experiments on the Tibetan Plateau (Tao et al. 1999), progress in plateau meteorology has been made through both the increase of ground stations and the improvement of observational technologies (Zhang et al. 1988). Since the 1970s, meteorological satellites have become another means to study weather and climate over the Tibetan Plateau and the surrounding areas by supplementing limited, ground-based observations.

The distribution and variation of tropospheric water vapor over the plateau region have been shown to be very important in past studies because of the plateau’s high altitudes and complex orographic features (Zhu 1998; Xu et al. 1996). It was found that there is a “moist pool” (high humidity) over the southeastern portion of the plateau (Zhu 1998). Geostationary Meteorological Satellite-5 (GMS-5) images of water vapor further illustrated that, in general, a dry zone is located over the

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northwestern section and a wet zone is in the southeastern region (Xu et al. 1996). However, detailed analyses of spatial structure and temporal variations of water vapor over the plateau are still not available at this moment, primarily because of the lack of high-quality observations with continuous temporal coverage and good spatial resolution, which hinders our further understanding of the effects of the plateau on the weather, climate, and hydrological cycle over and surrounding the plateau. Compared to other regions in China, ground stations over the Tibetan Plateau are still rare. Therefore, satellite retrievals become extremely important. In the early 1990s, a water vapor product with global coverage from the National Aeronautics and Space Administration’s (NASA) Water Vapor Project (NVAP) became available by merging retrievals from various satellites, such as the Television and Infrared Observation Satellite (TIROS), TIROS Operational Vertical Sounder (TOVS), Special Sensor Microwave Imager (SSM/I), and rawinsondes. However, a temporal inhomogeneity issue in the dataset prevented its further application in climate studies. A follow-up NASA product has been constructed with improved algorithms and merging schemes and will hopefully become available in a couple of years.

The Atmospheric Infrared Sounder (AIRS) on board the *Aqua* satellite, launched in May 2002, provides another means for high-quality vertical profiles of water vapor with good spatial coverage. The AIRS retrieval products have been used in various applications and for a variety of purposes (Aumann et al. 2003; Lambritsens et al. 2004). Water vapor vertical profiles, one of the standard products from AIRS, are widely used for weather forecast improvement (operations and research), climate model validation, and climate process studies. The primary scientific achievements of AIRS have been to improve weather prediction and to study the water and energy cycle (Chahine et al. 2006). Assimilation of thinned AIRS data improves forecasts significantly: less than 1% of AIRS spectra extend the National Oceanic and Atmospheric Administration/National Centers for Environmental Prediction (NOAA/NCEP) global 6-day forecast by 6 h in both hemispheres. AIRS data are now used routinely by major weather forecast centers around the world, including NOAA/NCEP (United States) and the European Centre for Medium-Range Weather Forecasts (ECMWF; Europe) (Le Marshall et al. 2006; McNally et al. 2006; Chahine et al. 2006). Gettelman et al. (2006) examined relative humidity in the troposphere using the AIRS retrievals. Validations of AIRS products have also been made in various areas and with various observations (e.g., Gettelman et al. 2004; Divakarla et al. 2006; Read et al. 2007; Fetzer et al. 2008), including radiosondes, aircraft measurements, and other satellite observations. Divakarla et al. (2006) compared AIRS full retrievals against global operational radiosondes and found that the biases are less than 10% over both land and water. The AIRS retrievals are also found to have very good accuracy for both temperature and water vapor over the tropical ocean with root-mean-square (RMS) errors reaching the theoretical expectation for clear sky, whereas retrievals over a midlatitude land site have a relatively poor performance (Tobin et al. 2006). Thus, the AIRS retrieval data are basically derived from regions of thin or broken partial clouds, certain validations are necessary, especially because the data are to be applied in regions such as the Tibetan Plateau.

Therefore, our objectives here are (i) to assess to what extent the monthly, gridded (level 3) NASA version 5 operational AIRS water vapor retrieval products can be applied in the Tibetan Plateau and surrounding areas for climate studies by validating against available, well-calibrated radiosonde data; and (ii) to devise schemes to correct or train the AIRS water vapor retrievals using these radiosondes if significant discrepancies exist.

2. Data description

a. AIRS water vapor retrievals

The Atmospheric Infrared Sounder can provide high-quality and high-resolution measurements for the earth’s atmosphere including both temperature and moisture. AIRS collects radiances in 2378 IR channels with wavelengths ranging from 3.7 to 15.4 μm and 4 visible channels with wavelengths ranging from 0.4 to 0.94 μm (Parkinson 2003). Two microwave sounders are also aboard the *Aqua* satellite [i.e., Advanced Microwave Sounding Unit (AMSU) and Humidity Sounder for Brazil (HSB) (Lambritsens 2003)]. Since the HSB instrument failed after a short period, the data used here are a combination of AIRS and AMSU. The AIRS/AMSU data are generated at the 45-km granularity of AMSU, utilizing a single AMSU spectrum and nine spectra of AIRS (Lambritsens and Lee 2003). The monthly AIRS/AMSU water vapor retrievals used here are the version 5, monthly gridded (level 3) product without HSB with a spatial resolution of 1° × 1°, which are derived from the level-2 standard swath data. The original monthly products are simply the arithmetic averages weighted by the counts of the days at each grid and actually include two files for each month, corresponding to the ascending and descending orbits.
of the satellite, respectively. The ascending orbit is from the Southern Hemisphere to Northern Hemisphere with an equatorial crossing time at 1:30 p.m. local time (LT), while the descending orbit is from the Northern Hemisphere to Southern Hemisphere with an equatorial crossing time at 1:30 a.m. LT. Thus, the final monthly data examined here are the averages of these two portions. The AIRS/AMSU retrieval data are available from September 2002 to the present. Here we focus on the period of January 2003–December 2010.

b. Radiosonde observations

The radiosonde data are from 34 ground stations over the Tibetan Plateau and surrounding area, and are archived at the China National Meteorological Information Center. The locations of these stations are shown in Fig. 1. Radiosonde observations were made at these ground stations by launching radiosondes 2 times per day (0000 and 1200 UTC, or 0800 and 2000 LT). Air balloons could ascend up to 30–40 km with an upward speed of about 400 m min$^{-1}$. Each observation could last about 2 h, resulting in an effective horizontal measuring distance of about 200 km. The radiosonde instrument used is a typical one widely used in China, usually called the 59 drum-type radiosonde or the GZZ-2 radiosonde. It includes sensors for temperature, pressure, and humidity in addition to radio transmitters with frequencies of 24.5 and 400 MHz. The regular measurement ranges of radiosonde are supposed to be +50$^\circ$ to about $-90^\circ$C for temperature, 1050–1 hPa for pressure, and 100%–1% for relative humidity. Also, their sensitivities of measuring temperature, pressure, and relative humidity could be 0.4$^\circ$–0.52$^\circ$C, 3.4–4.7 hPa, and 0.9%–2.0%, respectively. Ground observations included windfinding radars as well, commonly called the 701 Doppler Windfinding Radar, which were used to track radiosondes so that wind speed and direction could be determined. The maximal range of the radar detection is about 150–200 km with errors of no more than 80 m. The azimuth angles are unrestricted and the elevations may vary from $-0.3^\circ$ to 90$^\circ$, with errors less than 0.15$^\circ$ when the angles are beyond 8$^\circ$. Continuous working time could last about 6 h and radars can normally work even when wind reaches gale force. Technical details of radiosondes and windfinding radars are provided in Lin (1993) and China Meteorological Administration (2010).

1) Estimation of water vapor mixing ratio

To compute the water vapor mixing ratio $q$ (g kg$^{-1}$), vapor partial pressure $E$ (hPa) is first estimated with respect to liquid water ($E_w$) and ice ($E_i$), according to the ranges of dewpoint temperature $T_d$ ($^\circ$C) at each pressure level [Eqs. (1), (2), and (3)], and $q$ is then computed using Eq. (4). The formulas used here are from Dong and Tian (1986), which details a variety of methods to compute various meteorological variables from observations:

$$E_w = 6.1078 \exp[17.26T_d/(273.16 + T_d - 35.86)],$$  (1)

$$E_i = 6.1078 \exp[21.8746T_d/(273.16 + T_d - 7.66)].$$  (2)
Adjustment of spatial resolution

The drift calculation function provided in Liu et al. (2005) includes estimations of both zonal and meridional deviations for each vertical level (Table 1). Drifting corrections are hence made by means of the level-3 AIRS/AMSU retrieval products with 1 km horizontal and vertical resolution. AIRS/AMSU retrievals are interpolated to the exact location (latitude and longitude) of each ground station. To make the comparisons at the same vertical resolution and for the same layers, we further calculate water vapor mixing ratios of radiosondes using values at one pressure level and those immediately above it (Fishbein et al. 2007). Horizontally, they are incorporated from an area with a diameter of 45 km. For comparison, the AIRS/AMSU retrieval data and radiosonde observations need to be adjusted roughly to the same spatial (both horizontal and vertical) location and resolution. AIRS/AMSU retrievals are interpolated to the exact location (latitude and longitude) of each ground station. To make the comparisons at the same vertical resolution and for the same layers, we further calculate water vapor mixing ratios of radiosondes

\[ q = \frac{622E}{P - E} \]  

Here \( P \) (hPa) denotes atmospheric pressure.

2) CORRECTION OF RADIOSONDE DATA

Since radiosonde observations are considered “true” in validating satellite measurements, it is essential to make them as accurate as possible. Several procedures are usually applied including defining a range of parameters, setting rules of internal relevance, determining the climate extreme values, testing for time consistency, and performing comprehensive static quality control (CHQC) (Zhai 1997). The first and most critical step here is to process all the radiosonde data records following these procedures (Wang et al. 2011). Another possible error source that needs to be examined and corrected is air balloon drifting. Air balloons can gradually drift away from their ground launching sites as they ascend. The drifting becomes serious above 500 hPa, and balloons could be 0.5° away from their launching sites when they reach the level of 150 hPa (Liu et al. 2005). Because some regions over the Tibetan Plateau could even be above 600 hPa, air balloon drifting might certainly impact the accuracy of radiosonde data. This could induce even more uncertainties in matching radiosondes with the level-3 AIRS/AMSU retrieval products with 1° spatial resolution. Drifting corrections are hence made by means of the drift calculation function provided in Liu et al. (2005). The corrections include estimations of both zonal and meridional deviations for each vertical level (Table 1).

c. Adjustment of spatial resolution

AIRS water vapor retrieval data are layered averages using values at one pressure level and those immediately above it (Fishbein et al. 2007). Horizontally, they are incorporated from an area with a diameter of 45 km. For comparison, the AIRS/AMSU retrieval data and radiosonde observations need to be adjusted roughly to the same spatial (both horizontal and vertical) location and resolution. AIRS/AMSU retrievals are interpolated to the exact location (latitude and longitude) of each ground station. To make the comparisons at the same vertical resolution and for the same layers, we further calculate water vapor mixing ratios of radiosondes

\[ E = \begin{cases} E_w, \\ 0.22[(80 + 2T_d)E_w - (30 + 2T_d)E_i], \end{cases} \]

\[ q = \frac{622E}{P - E}. \]  

for each standard (AIRS) pressure level based on the AIRS layer definition.

3. Comparisons between monthly AIRS water vapor retrievals and radiosonde data

a. Correlation and relative deviation analyses

Correlation analysis is usually applied to verify the consistency of two time sequences’ variation tendencies, although it cannot give any information about the absolute differences. Deviation analysis, on the other hand, can determine how much difference exists between the two time series. Both methods are applied here to evaluate the differences between monthly AIRS/AMSU retrieval data and radiosonde data.

Monthly averages of radiosonde are first constructed for each station and for each month of the period focused on here (i.e., January 2003–December 2010). Because tropospheric water vapor decreases dramatically with altitude, relative deviation \( D \) is a function of the AIRS water vapor mass mixing ratio \( q_A \) (g kg\(^{-1}\)), radiosonde water vapor mass mixing ratio \( q_r \) (g kg\(^{-1}\)) and its time average \( \overline{q}_r \) (g kg\(^{-1}\)), and the length of the time series \( N \). Here, \( N \) equals 96 (i.e., the total number of months from January 2003 to December 2010), and \( D \) is expressed as the square root of relative bias between these two data normalized by the standard deviation of radiosonde observations:

\[
D = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \frac{q_A - q_r}{\overline{q}_r} \right)^2}.
\]  

Therefore, in general, if \( D \) is smaller than 1, we would claim that the AIRS/AMSU retrieval data are consistent with radiosondes and are considered credible.

1) HORIZONTAL COMPARISON

Correlation coefficients and relative deviations between monthly AIRS/AMSU water vapor retrievals and radiosondes are estimated at each station and for each standard (AIRS) vertical level during the period from 2003 to 2010. They are then averaged vertically at each
ground station and are, respectively, illustrated in Figs. 2 and 3.

In Fig. 2, high correlations are readily seen, particularly in the southeastern, eastern, and middle portions of the Tibetan Plateau with the maximum reaching 0.9. While the correlations are relatively weak in the northwestern and northern portions, they can still reach the 99% significance level based on the Student’s t test if the autocorrelations in both time series are neglected. Therefore, overall high consistency exists between AIRS/AMSU retrievals and radiosonde data, or at least we can say that they manifest similar seasonal cycles that tend to dominate their correlation relations.

As stated above, correlation analyses can provide a good description of temporal relations between two time series, but not their absolute differences. Direct deviations between them are thus estimated. Figure 3 shows the results of relative deviation at each ground station. The magnitude of relative deviation is denoted by the size of the dots. It is clear that relative deviations at over more than 90% of the ground stations are less than 1, indicating that the monthly AIRS/AMSU retrieval data are credible at these locations. Only one station shows a relative deviation larger than 1, but it is still close to 1. Locations with smaller dots are mostly located at higher altitudes. The stations with large red dots tend to be located at the edge of the Tibetan Plateau. The large yellow dot indicating a relatively large bias is found at a station located at lower altitude. This station is near the downstream of Yarlung Zangbo River, a channel of water vapor from the Bay of Bengal. The complex orographic effect there could be a reason.

2) VERTICAL COMPARISON

Based on the correlations and relative deviations estimated at each station and each level, vertical profiles are then computed for the entire domain for both datasets (Fig. 4). It is obvious that the correlation coefficient can easily reach the 99% significance level (0.26) at the levels below 200 hPa. The relative deviation is less than 1 below 250 hPa. Hence the monthly AIRS/AMSU retrievals are generally consistent with radiosonde observations at the levels below 250 hPa. Moreover, there is a layer between 300 and 600 hPa with very high consistency, with a maximum at 500 hPa. AIRS/AMSU retrieval data at lower levels such as 850

<table>
<thead>
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<th>Pressure (hPa)</th>
<th>Zonal shifting (°)</th>
<th>Meridional shifting (°)</th>
</tr>
</thead>
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<tr>
<td>600</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>500</td>
<td>0.03</td>
<td>0.10</td>
</tr>
<tr>
<td>400</td>
<td>0.05</td>
<td>0.16</td>
</tr>
<tr>
<td>300</td>
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</tr>
<tr>
<td>150</td>
<td>0.14</td>
<td>0.55</td>
</tr>
<tr>
<td>100</td>
<td>0.18</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Fig. 2. Vertically averaged correlation coefficients between monthly AIRS/AMSU water vapor retrievals and radiosonde products during 2003–10.
and 700 hPa are not as good as at the middle levels, but much better than the levels above 250 hPa. This could explain why in higher-altitude regions two kinds of data have higher similarity (Fig. 3). On the other hand, large differences above 250 hPa may be related to the data scarcity of radiosonde observations and (possibly) poor quality of current observation technology. If we are more confident in radiosonde data that are carefully processed through various procedures mentioned above, this result may suggest that monthly AIRS/

**Fig. 3.** Vertically averaged relative deviations at 34 stations on the Tibetan Plateau during 2003–10. The sizes of dots present the magnitudes of $D$. Yellow dot represents $D > 1$, and red dots denote $D \leq 1$.

**Fig. 4.** Vertical profiles of averaged correlation coefficients and relative deviations from the surface to 100 hPa. Dashed lines represent the 99% significance level (0.26) for (left) correlation coefficients and (right) the one standard deviation. The right coordinate denotes the percentage of stations that are used for computation in each level.
AMSU retrieval data could have relatively poor quality at these levels.

b. Comparisons of PDFs and domain averages

In this subsection, comparisons of probably distribution functions (PDFs) at several standard levels between 100 and 850 hPa are shown (Fig. 5). Note that below 250 hPa, where only small disparities between the two datasets are found, overall consistency is occurring, while the distribution shift mainly happens at higher levels. Then, evaluations are further made by comparing the averaged vertical profiles of monthly water vapor content from both AIRS/AMSU retrieval products and radiosonde observations over the entire domain (Fig. 6). Similar results to Fig. 5 could be obtained in Fig. 6. As shown in Figs. 3 and 4, below 250 hPa they are quite close to each other, likely demonstrating a good quality of AIRS/AMSU retrieval data. For high spatial resolutions, AIRS/AMSU water
Vapor retrieval products have great advantages over radiosonde observations from individual ground stations and have evident potential for further applications in this region. Nevertheless, one should be cautious for the levels between 100 and 200 hPa where the deviations become large, as mentioned above (Figs. 4–6). Regarding the high altitudes of the plateau, most ground stations are located above 600 hPa (about 4 km MSL). Some stations can even reach the altitude of about 400 hPa. Hence, water vapor information at the levels above 200 hPa is still very important. However, because the differences between AIRS/AMSU retrievals and radiosondes’ sensors under very cold conditions. There could be issues with sensors of both AIRS/AMSU and radiosondes with very cold temperatures and very low pressures.

4. Spatial corrections of monthly AIRS water vapor retrievals

In this section, we focus on the corrections of the 8-yr averages of monthly AIRS/AMSU retrieval data by validating against averaged radiosonde data. Relations between these two are derived by fitting a binary polynomial, which includes the matrix coefficients $A(i, j)$, AIRS/AMSU water vapor mixing ratio $q_a$ (g kg$^{-1}$), and pressure $P$ (hPa):

$$q_a^* = \sum_{j=1}^{m} \sum_{i=1}^{n} A(i, j) \times q_a^{i-1} \times p^{j-1}. \quad (6)$$

Here $m - 1$ and $n - 1$ are the highest powers for $q_a$ and $P$, respectively. Figure 5 shows that $q_a^*$ is close to $q_r$ at levels lower than 250 hPa for year-means. Comparisons for warm (April–September) and cold (October–March) seasons are also made (Fig. 7). There are some seasonal differences in the relations between $q_a$ and $q_r$. In the warm season, the differences between $q_a$ and $q_r$ tend to be smaller than in the cold season, in particular above 250 hPa. Thus, the fitting relations between $q_r$ and $q_a$ are derived for both the warm and cold seasons.

To evaluate the goodness of fit, a correlation index $R^2$ is used:

$$R^2 = 1 - \frac{\sum (q_r - q_a^*)^2}{\sum (q_r - \bar{q}_r)^2}. \quad (7)$$

Here, $\sum (q_r - q_a^*)^2$ represents error squares sum (ESS) and $\sum (q_r - \bar{q}_r)^2$ denotes total variance. The smaller the

<table>
<thead>
<tr>
<th>$m$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm season</td>
<td>0.9807</td>
<td>0.9850</td>
<td>0.9885</td>
<td>0.9892</td>
</tr>
<tr>
<td>Cold season</td>
<td>0.9591</td>
<td>0.9712</td>
<td>0.9728</td>
<td>0.9746</td>
</tr>
</tbody>
</table>

AIRS/AMSU retrieval data may have to be corrected/trained using limited radiosonde observations. As mentioned above, we know this is essentially based on the belief in the quality of radiosonde data that is especially related to the sensitivities of radiosondes' sensors under very cold conditions. There could be issues with sensors of both AIRS/AMSU and radiosondes with very cold temperatures and very low pressures.

**Fig. 7.** Scatterplots of domain-averaged $q_a$ and $q_r$ for each vertical level during warm and cold seasons, respectively.
ratio between ESS and total variance is, the smaller the difference between the fitting and that observed, and the higher the fitting precision (Chen 1993). In other words, better corrections are obtained when this correlation index becomes closer to 1. For the warm season, we can see that there exists a linear relation (Fig. 7). So we chose \( m = 2 \) to simplify the fitting estimation. However, it is found that there is no linear relation between \( q_a \) and \( q_r \) for the cold season, so \( m = 3 \) is preferred to make the fitting estimation more reliable. We vary \( n \) from 1 to 4 and compare the fitting results of two situations to determine the best for each one. Table 2 summarizes the correlation index for both seasons.

If the correlation index approaches 1, the corresponding fitting precision is higher. However, it is noted that the fitting program would be more complex and the effect of pressure may be weighted too heavily by the increase of \( n \). That is to say, the correlation index that is closest to 1 may not necessarily be the best choice. In other words, the correlation index should be as close to 1 as possible, but \( n \) should be as small as possible. It seems that 0.9885 (\( n = 3 \)) is the very correlation index for the warm season, which is larger than 0.9807 (\( n = 1 \)) and 0.985 (\( n = 2 \)) but only slightly smaller than 0.9892 (\( n = 4 \)). Similarly, 0.9712 (\( n = 2 \)) is chosen as the very correlation index for the cold season. Further comparisons based on actual physical conditions are made below to confirm this.
Figures 7 and 8 illustrate the comparisons of $q_r$ and $q_a^*$ using different fitting programs for the warm and cold season, respectively. In general, $n = 3$ and $n = 4$ lead to quite similar outcomes (Fig. 8). Moreover, $n = 3$ seems more reasonable because fitting points distribute more evenly around the slope line, with a slope rate of 1 specifically at relatively high levels. If both computational efficiency and physical situation are taken into account, the fitting function with $n = 3$ is preferred for warm seasons. Figure 9 indicates that although there is a higher fitting precision as $n = 3$, the results at high levels are close to each other and fitting values are almost the same. To keep horizontal disparity, the fitting function with $n = 2$ is chosen for the cold season.

Matrix coefficients $A(i, j)$ are estimated for the above two fitting functions (Table 3). They are computed by taking the logarithm of $q_r$, $q_a$, and $P$ before fitting, which helps arrange three sequences of data within a factor of 10. The correction functions are expressed as follows:

$$
\log q_a^* = -31.9404 + 24.7223 \log P - 4.7697(\log P)^2 \\
- 5.8061 \log q_a + 4.1636 \log q_a \times \log P \\
- 0.5755 \log q_a \times (\log P)^2
$$

for the warm season, and

$$
\log q_a^* = 1.9113 - 0.6569 \log P + 7.9050 \log q_a \\
- 2.4197 \log q_a \times \log P + 2.0446(\log q_a)^2 \\
- 0.6329(\log q_a)^2 \times \log P
$$

for the cold season.

Figure 10 depicts the distributions of correction functions for both warm and cold seasons. Points are basically scattered around the curve surface (Fig. 10). Below about 300 hPa, it is quite similar to an approximate linear changing tendency during both warm and cold seasons, which further indicates the good quality of AIRS/AMSU water vapor retrievals below about 300 hPa over a whole year.

Finally, we use these two correction functions to correct the monthly AIRS/AMSU water vapor retrieval data from 2003 to 2010. Here function (8) is used for the months from April to September and function (9) from October to March. The results of the domain-averaged $q_a$ and $q_r$ at all standard levels during all seasons are shown in Fig. 11. We can see that AIRS/AMSU retrieval data are adjusted to be evenly distributed around the one-to-one line almost at every level, suggesting the effectiveness of making the monthly AIRS/AMSU retrieval data approach radiosonde observations. To show more detailed results of our corrections, Fig. 12 further
depicts how $q_a$ behaves in relation to $q_r$ before and after correction for all stations over the Tibetan Plateau. It is found that more consistency between two datasets is displayed after the corrections, especially at higher levels.

5. Summary

The availability of the monthly gridded AIRS/AMSU vertical retrievals of water vapor provides a great opportunity for us to examine the distribution and variations of tropospheric water vapor over the Tibetan Plateau region where other longtime, consistent, high-quality observations are not available. Therefore, this study aims to explore the applicability of monthly AIRS/AMSU water vapor retrieval products by validating them against limited radiosonde observations.

Radiosonde data are first carefully processed following comprehensive quality control procedures (Zhai 1997), and are then further adjusted for possible errors caused by air balloon drifting. Adjustments are also made to match the spatial resolutions of AIRS/AMSU retrieval products. Correlation analyses suggest that over the whole plateau region and below 200 hPa, the monthly AIRS/AMSU retrieval data and radiosondes have high consistency in temporal variations, especially in the southeastern part and between 300 and 600 hPa. Relative deviation analyses further indicate that over nearly the entire plateau and below 250 hPa, relative deviations are generally small, particularly in the high-altitude regions and between 300 and 600 hPa. Thus, the monthly AIRS/AMSU water vapor retrievals can be applied in this area, especially for exploring the spatial distribution and temporal variation of tropospheric water vapor, which are essential to further our understanding of the effects of the plateau on weather and climate specifically in East Asia.

Differences between the magnitudes of these two datasets exist, specifically above 250 hPa, which may limit further applications including quantitative analyses of water budget in the atmosphere and of the entire water cycle in the plateau and neighboring areas. Based

![FIG. 11. Scatterplot of domain-averaged, layered AIRS/AMSU retrieval data vs radiosonde observations. Empty and solid circles denote original and corrected AIRS data, respectively.](image1)

![FIG. 12. Scatterplots of $q_a$ and $q_r$ for the standard layers from 850 to 100 hPa of all stations over the Tibetan Plateau, respectively. (left) before and (right) after correction during January 2003–December 2010.](image2)
on our belief in the carefully processed radiosonde data, simple corrections are thus made using the polynomial fitting for both the warm and cold seasons. The corrected monthly AIRS/AMSU retrieval data tend to show more consistency with available radiosonde observations, and hence greater confidence in applying them to this region is established.

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