The Validation of AIRS Retrievals of Integrated Precipitable Water Vapor Using Measurements from a Network of Ground-Based GPS Receivers over the Contiguous United States

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ABSTRACT

A robust and easily implemented verification procedure based on the column-integrated precipitable water (IPW) vapor estimates derived from a network of ground-based global positioning system (GPS) receivers has been used to assess the quality of the Atmospheric Infrared Sounder (AIRS) IPW retrievals over the contiguous United States. For a period of six months from April to October 2004, excellent agreement has been realized between GPS-derived IPW estimates and those determined from AIRS, showing small monthly bias values ranging from 0.5 to 1.5 mm and root-mean-square (rms) differences of 4 mm or less. When the spatial (latitude–longitude) window for the GPS and AIRS matchup observations is reduced from the initial ½° by ½° to ¼° by ¼°, the rms differences are reduced. Analysis revealed that the observed IPW biases between the instruments are strongly correlated to the reported surface pressure differences between the GPS and AIRS observational points. Adjusting the AIRS IPW values to account for the surface pressure discrepancies resulted in significant reductions of the bias between GPS and AIRS. A similar reduction can be obtained by comparing only (GPS–AIRS) match-up pairs for which the corresponding surface pressure differences are 0.5 mb or less. The comparisons also revealed that the AIRS IPW tends to be relatively dry in moist atmospheres (when IPW values $>$40 mm) but wetter in dry cases (when IPW values $<$10 mm). This is consistent with the documented bias of satellite measurements toward the first guess used in retrieval algorithms. However, additional study is needed to verify whether the AIRS water vapor retrieval process is the source of the discrepancies. It is shown that the IPW bias and rms differences have a seasonal dependency, with a maximum in summer (bias $\sim$ 1.2 mm, rms $\sim$ 4.14 mm) and minimum in winter (bias < -0.5 mm, rms $\sim$ 3 mm).

1. Introduction

Atmospheric water vapor is an important parameter to be considered for a wide range of applications, including studies of the earth's radiation budget, hydrological cycle, atmospheric chemistry, and global warming, and therefore its accurate measurement is of great interest. The task of accurately measuring atmospheric water vapor is challenging, given that moisture field variations are more sporadic in nature than variations in temperature or pressure. Conventional in situ measurements of atmospheric water vapor on a global basis are provided by radiosonde humidity sensors. Routine radiosonde ascents are made twice a day at 0000 and 1200 UTC around the globe but are mainly limited to land regions. In the past few decades operational radiosonde humidity measurements have been augmented

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by satellite-based water vapor retrievals, which extend water vapor measurement over the oceans and sparsely populated land regions.

An objective for the National Aeronautics and Space Administration (NASA) *Aqua* mission is to collect observations that improve knowledge of the global distribution of water vapor (Parkinson 2003). Attainment of this goal is expected to convey benefits ranging from more accurate operational numerical weather prediction (NWP) to improved characterization of the global hydrological cycle. *Aqua* was launched in May 2002 into a sun-synchronous polar orbit with a period of 98.8 min. The satellite is equipped with several passive sensors that are responsive to variations in atmospheric water vapor, most notably the Atmospheric Infrared Sounder (AIRS).

In the past, satellite-based water vapor retrievals most commonly were validated using spatially and temporally collocated radiosonde measurements over the land. Radiosondes provide estimates of integrated precipitable water (IPW) as well as vertical profiles of moisture. Thus radiosondes may be used as the basis for validation studies of satellite-derived moisture products including IPW, layered precipitable water (LPW), or height-resolved water vapor mixing ratio profiles (Kleespies and McMillin 1990; McMillin et al. 2005, 2007; Birkenheuer and Gutman 2005; Divakarla et al. 2006). The in situ water vapor measurements from radiosondes are often taken as the standard of reference to which all others are held. However, recent investigations of the accuracy of radiosonde humidity measurements have shown that they exhibit significant biases due to a number of deficiencies in the moisture sensors used in the radiosondes (Jeannet et al. 2002; Turner et al. 2003; Wang et al. 2002, 2003; Miloshevich et al. 2003, 2004; Roy et al. 2004). Birkenheuer and Gutman (2005) have pointed out that errors in radiosonde humidity observations may in fact obscure the quality of remotely sensed moisture data when they are compared and have illustrated that GPS IPW offers a viable alternative to radiosondes as a source of validation data for satellite moisture soundings. Moreover, different types of operational radiosonde moisture sensors are used in various parts of the world (Kuo et al. 2005), and these unique instruments have unique moisture measurement characteristics likely to cause nonuniformity in the uncertainties of the global radiosonde moisture measurements. Accurate IPW measurements from surface microwave radiometers were used by Revercomb et al. (2003) and Turner et al. (2003) as the basis for radiosonde moisture data correction. McMillin et al. (2005) demonstrated the utility of GPS IPW to make corrections to radiosonde humidity measurements.

The National Oceanic and Atmospheric Administration (NOAA) network of ground-based GPS receivers offers a complementary validation tool for satellite-based column-integrated moisture retrievals (Yoe et al. 2003, 2004; McMillin et al. 2005; Birkenheuer and Gutman 2005; Rama Varma Raja et al. 2006). The temporal resolution of the operational GPS data of IPW available for this study is 30 min. Over the contiguous United States (CONUS), the number of GPS receiver sites (~400) is substantially larger than the number of radiosonde observation sites. Therefore, thousands of matchups can be formed of GPS and AIRS IPW data in a month. Although the GPS method does not provide information about the vertical distribution of moisture, the large number of matchups, the all-weather capability, and the measurement accuracy make it useful as a quick, repeatable "sanity" check for AIRS data, and indeed as a validation tool for any satellite-based column-integrated moisture product. This paper describes the methodology and results of validating the AIRS moisture product for a period of almost 6 months using GPS IPW retrievals over CONUS.

2. Instrument descriptions

The two sources of IPW data, GPS and AIRS, are completely independent observing systems based on distinct measurement principles, retrieval methods, and sampling procedures. In this section the most relevant fundamental features of the instruments and measurements are briefly described.

a. *The Atmospheric Infrared Sounder*

The *Aqua* satellite payload consists of six different earth observing instruments (Parkinson 2003): AIRS, the Advanced Microwave Sounding Unit (AMSU-A), the Humidity Sounder of Brazil (HSB), the Advanced Microwave Scanning Radiometer for EOS (AMSR-E), the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Clouds and the Earth's Radiant Energy System (CERES). Three sensors, AIRS, AMSU-A, and HSB, form the "AIRS sounding suite." Among these three cross-track scanning sounders, AIRS may be regarded as the centerpiece, with the microwave sounders AMSU-A and HSB intended mainly for use in cloud clearing.

AIRS is a hyperspectral instrument based on a grating spectrometer, with a spectral resolution of $(\lambda/\Delta\lambda) = 1200$ in the infrared region (Aumann et al. 2003). As it scans, 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). Many of these channels respond to the concentration of water vapor at various heights in the atmosphere, making the instrument capable of providing more accurate humidity measurements at higher vertical resolution (~1 km) than was possible with past satellite sounders. The AIRS scanning geometry is arranged in such a way that the width of the three AIRS fields-of-view (FOVs) fit in the width of a single AMSU-A FOV, and three AIRS scan lines fit in one AMSU scan line (Aumann et al. 2003; Lambrigtsen and Lee 2003; McMillin et al. 2007). Thus, in a single AMSU FOV of 40 km there are nine AIRS footprints. Since cloud-cleared AIRS radiances are used in retrievals, and AMSU-A is used for generating cloud-cleared datasets, the effective horizontal resolution of AIRS retrievals used in the current study is 40 km. From *Aqua*'s polar orbit, AIRS provides two soundings per day at a given location on the earth.

The AIRS retrieval algorithm is a component of the AIRS product generation software (PGS). The PGS consists of seven major modules for calibration, microwave retrieval, cloud clearing, initial IR retrieval, physical retrieval, bias correction, and radiative transfer calculations. A complete description of the AIRS PGS is given by Aumann et al. (2003).

The AIRS retrieval process uses cloud-cleared radiances in the water vapor absorption channels to determine the amount of radiation absorbed by the atmospheric water vapor molecules along the viewing path. By combining a number of channels with differing sensitivity to the water vapor, and using additional channels that can measure temperature, a water vapor profile and column-integrated water vapor product can be derived. The retrieval algorithm is driven by a first-guess profile in which the atmospheric state variables are assumed to be known. The radiance computed from the first-guess profile for a particular spectral channel is compared with the measured radiance in the same channel, and the differences between the measured and computed radiances for all of the channels are used to derive corrections to the first-guess water vapor profile.

Cloud-clearing is not applied in overcast or nearly overcast conditions; therefore, AIRS IPW retrievals are not available for comparison in these instances. Since the goal of the current study is to assess the AIRS IPW when retrievals are made, this is not a significant limitation. Because cloud-clearing results in soundings made in the relatively dry columns between clouds, a slight dry bias for the AIRS IPW relative to a measurement that samples the atmospheric volume of regard uniformly may result.

Fetzer et al. (2003) pointed out that errors in the AIRS retrievals may originate from a variety of sources, including uncertainties in the radiances used for the retrievals, uncertainties induced by the limitations of the forward model used in the retrieval algorithm, incomplete truth data (e.g., limited observations of surface skin temperature and emissivity or the relatively small number of temperature soundings in the upper atmosphere above 50 hPa), and the uncertainties due to inability to resolve atmospheric structures that exist on spatial scales finer than the resolution of the instrument. There may be computational noise adding to the uncertainties in retrievals due to the numerical solution schemes in the retrieval algorithm.

The AIRS design goal is to provide tropospheric retrievals of temperature with 1-K accuracy in 1-km layers and water vapor retrievals with 10% uncertainty in 2-km layers (Fetzer et al. 2003). The results from a global validation study of AIRS temperature and water vapor retrievals by Divakarla et al. (2006) showed that the accuracies of AIRS retrievals are close to the objective values over land as well as ocean. More specific details of the AIRS instrumentation and retrieval methodology can be found in a number of articles published in a special issue of *IEEE Transactions on Geoscience and Remote Sensing* (2003, Vol. 41, No. 2) devoted to the Earth Observing System (EOS) *Aqua* mission.

The current study is based on water vapor products provided by the AIRS validation team at the NASA Jet Propulsion Laboratory (JPL). These data were generated using the version V4.0.9 AIRS retrieval algorithm and are accompanied by a number of product-specific quality assurance (QA) flags intended to meet the requirements of the diverse AIRS data user community. Two of these QA flags were chosen to help select and stratify the AIRS IPW data evaluated in the current study. These are the flags indicating the quality of the temperature profile of the lower troposphere [Qual_Temp_Profile_Bot (QBOT)] and the quality of the temperature profile in the middle troposphere [Qual_Temp_Profile_Mid (QMID)]. The convention is to assign a value of zero to these flags for the best quality retrievals. Thus, when QBOT = 0, there is the highest confidence in the accuracy of the AIRS IR/microwave (MW) temperature retrievals in the lowest 3 km of the atmosphere. Since accurate temperature sounding to the bottom of the troposphere occurs when the AIRS FOV is clear and the quality of the radiances is high, the requirement for QBOT = 0 is rather stringent and is expected to be associated with the best opportunities for making accurate IPW retrievals, since most water vapor resides in the lower troposphere. This requirement is expected to provide an upper-bound assessment of the AIRS IPW quality. On the other hand, when QMID = 0, there is high confidence in the AIRS

IR/MW temperature retrievals for height levels above 3 km but not necessarily in the generally moister lower troposphere. Thus, requiring QMID = 0 makes another appropriate filter for admitting AIRS IPW to be compared to the GPS data, since the choice effectively removes retrievals that might be based on a generally poor set of input radiances but allows the whole spectrum of quality for the moist lower troposphere.

The number of samples for statistical comparison varies with the QA flag requirement. In general, the QBOT = 0 flag is more stringent than the QMID = 0 flag, because additional and more demanding thresholds are applied to account for the increased sensitivity of temperature retrievals in the lowest atmospheric layers to cloud-clearing errors (Susskind et al. 2006). The more exacting QBOT = 0 data are generally expected to be a subset of the dataset for which QMID = 0. Additional discussion of AIRS quality assurance criteria and corresponding threshold values may be found in Susskind et al. (2003, 2006).

b. GPS IPW sensing

The use of surface-based GPS receivers to measure IPW accurately is well established (Bevis et al. 1992; Rocken et al. 1995; Duan et al. 1996; Wolfe and Gutman 2000; Feng et al. 2001). As described by Gutman et al. (2003), the current implementation of ground-based GPS meteorology (GPS-Met) at the NOAA/Earth System Research Laboratory (ESRL) involves the retrieval of total column precipitable water vapor from delays in the GPS radio signals caused by the refractivity of the neutral (nondispersive) atmosphere, primarily the troposphere.

The first step in estimating the tropospheric signal delay is to form an "ionospheric free" carrier phase observation from a linear combination of the two GPS frequencies, L1 and L2. This eliminates the impact of the ionospheric refractivity. The next step is to form a "double-difference" (defined as the differences in the carrier phase observations of two GPS satellites from two ground stations) to remove receiver and satellite clock biases. It is assumed that tropospherically induced signal delays depend primarily on satellite elevation above the horizon, since the elevation primarily determines the length of the path through the atmosphere. It is also assumed that the total delay has only a wet and dry component. The GPS signal delay along a single path is then modeled in terms of an unknown "zenith tropospheric delay" (ZTD) and known elevation-angle-dependent mapping functions defined by Neill (1996).

Since there are 6–10 GPS satellites at different elevations in view at all times, solutions for ZTD are overdetermined and can be estimated with high accuracy as a nuisance parameter (Mikhail 1976). Duan et al. (1996) describes the technique used by ESRL to estimate ZTD in an absolute sense at each station in a network of continuously operating GPS reference stations.

The zenith-scaled GPS signal delays are parsed into their wet and dry components using the technique described by Bevis et al. (1992, 1994). First, the hydrostatic signal delay is estimated using the relationship defined by Saastamoinen (1972) that depends on atmospheric pressure, station latitude, and elevation. The atmospheric pressure is measured at (or extrapolated to) the elevation of the phase center of the GPS antenna. At the sites identified in Fig. 1, most pressure sensors are either collocated with the GPS receiver or reside in relatively close proximity (defined as a few kilometers horizontally and less than 100 m vertically). Next, the zenith-scaled wet signal delay is computed by simply subtracting the tropospheric delay from the hydrostatic delay. The zenith-scaled wet signal delay is caused by the dipole moments of the water vapor molecules along the respective paths of the GPS signals. Finally, we estimate the amount of column-integrated water vapor responsible for the observed wet signal delay. The magnitude of the wet delay is related to the quantity of path-integrated water vapor through a dimensionless quantity that is a function of the mean weighted temperature (Tm) of the atmosphere. At the time of this experiment, the NOAA GPS-Met network used the modified parameters identified in Bevis et al. (1994) to accomplish this. Surface temperature in this case comes from sensors that are collocated with the GPS receiver or reside in relatively close proximity to the receiver. Although there are limitations (described in Wang et al. 2005) in using a climatological model to estimate Tm, doing so is justified for two reasons. First, IPW retrieval errors caused by using the Bevis mean temperature approximation are always small compared with the errors associated with estimating the zenith tropospheric delay. Second, the investigation is performed to evaluate the errors associated with AIRS water vapor retrievals relative to GPS errors to assess the potential use of the AIRS water vapor retrievals in operational weather forecast models. GPS observation errors have been quantified (Smith et al. 2007), and these observations are currently being assimilated into two operational weather models running at the National Centers for Environmental Prediction (NCEP), the Rapid Update Cycle (RUC) and the North American Mesoscale (NAM) models.

In this investigation, GPS IPW retrievals represent a volume-averaged estimate of IPW over the region of

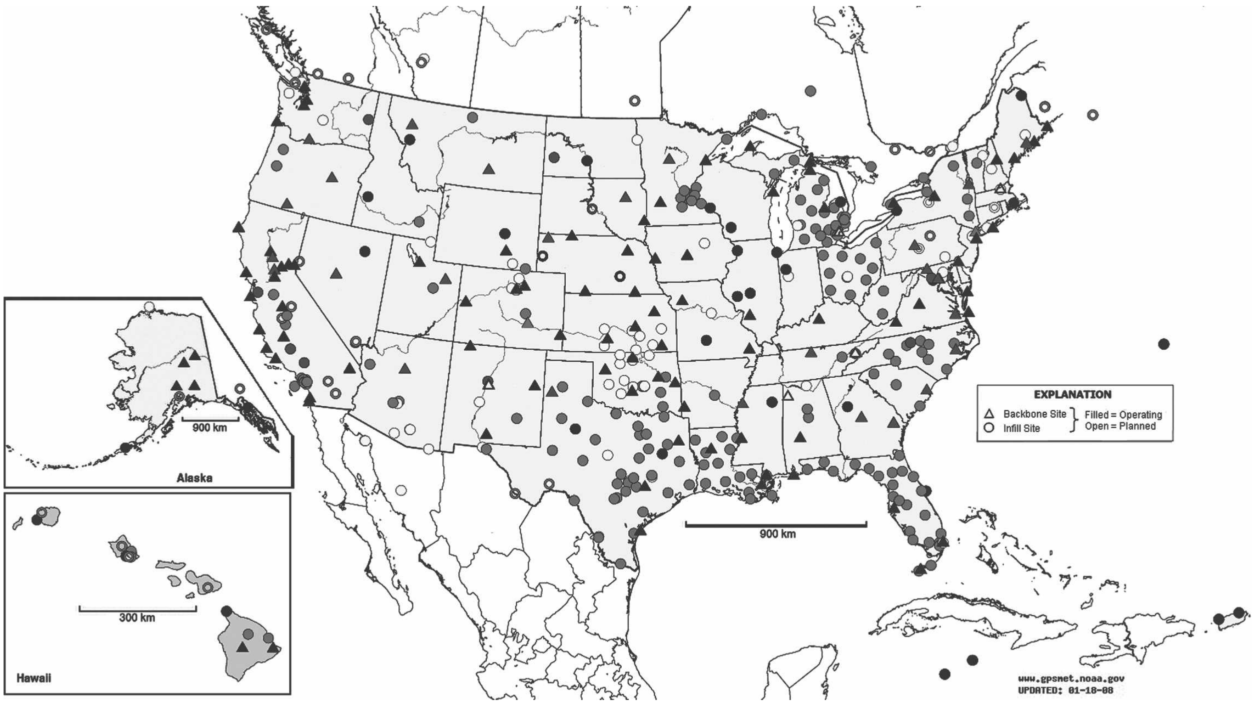

FIG. 1. The distribution of GPS stations operated by NOAA/ESRL to provide IPW in near–real time over CONUS, Alaska, and Hawaii. Backbone sites (triangles) are operated by U.S. federal government agencies, including NOAA, the U.S. Coast Guard/Army Corps of Engineers, and the U.S. Department of Transportation. Infill sites (circles) are operated by state and local government agencies, universities, and the private sector and SuomiNet. Filled triangles and circles represent sites that are already operational while open symbols represent planned sites.

the atmosphere covered by all GPS satellites in view in 30 min. At midlatitudes, the average elevation of the GPS satellites is about 25° above the horizon. Assuming a 5-km depth for the moist layer, the region observed by the GPS antenna is equivalent to an inverted cone with a radius of about 11 km. Viewed from space, this is roughly equivalent to an FOV of about 22 km compared with the 40-km FOV for AIRS measurements.

During the past decade, NOAA/ESRL has established a network of more than 375 GPS IPW stations (see Fig. 1 and http://gpsmet.noaa.gov) that provide continuous near-real-time IPW estimates for weather forecasting, climate monitoring, and research. These stations utilize the NOAA/National Geodetic Survey (NGS) Continuously Operating Reference Stations (www.ngs.noaa.gov/CORS) that include GPS receivers belonging to NOAA; other federal, state, and local government agencies; universities (in particular the SuomiNet; data available at http://www.suominet.ucar.edu/); and the private sector.

3. Dataset preparation

The AIRS retrievals require surface pressure values at the AIRS footprints, which are obtained from the NCEP Global Forecast System (GFS) model 3- and 6-h forecasts. Complete details of the calculation of the surface pressure values corresponding to AIRS FOVs from the NCEP GFS forecast fields are given in Olsen et al. (2005), but the rudiments are as follows. First, the forecast surface pressure data are bilinearly interpolated in space from the rectangular latitude–longitude grids of the GFS model to the retrieval field of regard (center latitude–longitude of the AMSU FOV). These are then linearly interpolated in time between the GFS 3- and 6-h forecasts. Final values of the AIRS surface pressure fields for the AIRS retrieval are formed by adiabatic extrapolation to the surface as defined by the average topography in the field of regard. The average topography is the mean elevation corresponding to the AIRS footprint, as determined from digital elevation model (DEM) data that are accurate to 20 m. The method of adiabatic extrapolation for AIRS surface pressure values at NASA JPL assumes that throughout the layer depth resulting from the difference between model-predicted surface elevation and average elevation corresponding to the AIRS footprint from the DEM data, the atmosphere is adiabatic, hydrostatic, and polytropic (i.e., the temperature linearly varies as determined by the adiabatic lapse rate). Then the cor-

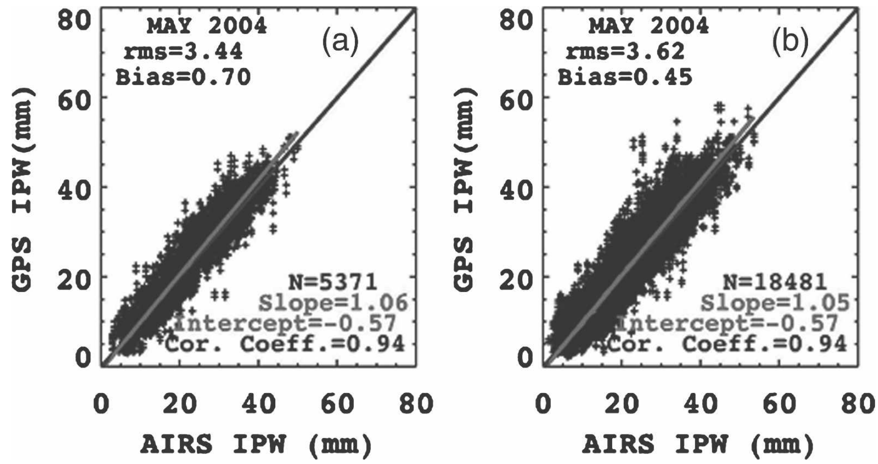

FIG. 2. Scatterplots of GPS and AIRS IPW over CONUS for May 2004 with AIRS data flagged (a) QBOT=0 and (b) QMID=0. Data pairs occur within ½° latitude and longitude and within a half hour of each other. Gray lines denote the best fit to the data determined through rotated linear regression.

rection for model-predicted surface pressure is performed to match the average DEM elevation through the well-known barometric formula and can be expressed as follows:

$$P_{\mathrm{surfairs}} = P_{\mathrm{surfgfs}}\left[1 - \frac{(Z_{\mathrm{DEM}} - Z_{\mathrm{GFS}})}{C_p T_{\mathrm{GFS}}} g\right]^{7/2}, \tag{3.1}$$

where P_{surfairs} is the corrected surface pressure for the AIRS footprint to match the corresponding average DEM topography, P_{surfgfs} is the GFS model-predicted sea level pressure, Z_{DEM} is the surface altitude derived from DEM data, Z_{GFS} is GFS model-predicted surface altitude, and T_{GFS} is the model-predicted surface temperature. The constants g and C_p are gravitational constant and specific heat of air at constant pressure, respectively. The GPS retrieval process requires a surface pressure value as well. These data are provided by surface-based barometric sensors located at each GPS station and thus are expected to contribute negligible error or uncertainty.

GPS–AIRS IPW matching criteria

The initial criteria used to match pairs of AIRS and GPS IPW were the following:

1) AIRS locations within ½° latitude and longitude of the GPS station;
2) AIRS observations within 30 min of the GPS observation time;
3) both instruments reporting realistic IPW values (if either of the instruments reported a flagged or missing value the data pair was excluded); and
4) observations for both instruments include realistic surface pressure values (if either reported a flagged or missing value, the IPW data pair was excluded).

Additional criteria were applied to gain insight as described in subsequent sections. These include sorting the data by month, reducing the horizontal separation tolerance, and categorizing by the AIRS retrieval QA flags. The IPW pairs thus obtained were analyzed using statistical methods.

4. Results and discussion

Representative comparisons of GPS IPW and AIRS IPW for a single month are presented in Fig. 2. Figure 2a includes matchups compiled subject to the restriction that AIRS temperature-retrieval QA flag QBOT = 0 was satisfied, while Fig. 2b includes matching pairs accumulated when AIRS QA flag QMID = 0 was provided. In each plot the gray line indicates the best-fit line to the data, determined through the application of linear regression in a coordinate space rotated 45° with respect to the axes depicted in the figure. This method of rotated linear regression (RLR), developed by McMillin et al. (1989), provides a significant advantage over conventional linear regression, in that the resulting best-fit line parameters do not depend upon an arbitrary choice of axis for the predictand or predictor (McMillin et al. 2005; Rama Varma Raja et al. 2006). In RLR the intercepts resulting from swapping the variable axes are additive inverses of each other, and the slopes are such that the best-fit lines are symmetric with respect to the unity line (the line passing through the origin with slope = 1). Moreover, the intercept values resulting from RLR are much smaller than those obtained using conventional regression. Problems associated with conventional linear regression when comparing two noisy datasets have been investigated by Rodgers (1990) and Press et al. (1992).

It is readily apparent from Fig. 2a that a statistically significant number of coincident pairs of AIRS and GPS IPW can be collected over CONUS in a month, even when the more stringent QBOT = 0 QA flag is required. The number of coincident pairs becomes even greater, as expected, if the less stringent AIRS QA flag QMID = 0 is chosen. This is due to the availability of half-hourly GPS data from more than 400 CONUS locations. Remarkably close agreement has been realized between the GPS IPW and AIRS IPW for May 2004, regardless of the required AIRS QA flag, with bias differences of 0.70 mm or less and rms differences under 3.62 mm. The large correlation coefficients (0.94), the best-fit line slopes close to unity, and the small intercepts (−0.6 mm) emphasize the agreement between the AIRS and GPS datasets. These results are testimony to the improved satellite-based moisture-sensing capability achieved by AIRS based on its high spectral resolution radiance measurements.

Using moisture values derived with an earlier version (V3.0.8) of the AIRS retrieval algorithm, Yoe et al. (2004) compared GPS and AIRS IPW for September 2002 and determined that bias and rms differences were 1.83 and 3.98 mm, respectively. These values are considerably larger than those found for any of the 6 months presented in the current work. Using the same V3.0.8 AIRS IPW for September through December 2002 but matching only with those GPS nearly coincident with radiosonde launches, McMillin et al. (2005) found similar bias and rms differences of 1.5 and 4.6 mm, respectively. The smaller biases found in the current work provide a measure of confidence that the revised AIRS retrieval algorithm is more accurate than the preceding version.

The rms IPW difference for May 2004 is smaller (3.44 mm) when the AIRS data admitted for comparison are subject to the restriction that the QA flag QBOT = 0 than that for the same period when the less restrictive QA flag QMID = 0 is required (3.62 mm). This result is to be expected in the sense that the QBOT = 0 flag is likely to be satisfied when the AIRS radiance data are relatively noise free and confidence in the accuracy of the AIRS retrieval accuracy is high. However, the bias difference is considerably larger (0.70 mm) when the presumably more accurate QBOT = 0 QA flag is required than when the less stringent QMID = 0 is specified (0.45 mm). Examination of the best-fit lines in Fig. 2 reveals that in both cases the AIRS data are drier than the GPS observation in moist atmospheres (IPW exceeding ~40 mm) but slightly moister than GPS data in dry atmospheres (IPW less than ~10 mm). It is possible that these results are evidence of a conservative tendency built into the AIRS retrieval algorithm, which may moderate "extremely" wet or dry results if they conflict with the initial guess profile from the meteorological analysis. The reduction of rms scatter produced when the QBOT = 0 QA flag is used effectively removes outliers that mask this conservative tendency, which is more readily observed in this case. Since May is a relatively moist month, a conservative tendency in the AIRS retrieval process would be expected to result in a dry bias, as evident in Fig. 2. Additional investigation is needed to confirm the conservative tendency of the AIRS retrieval algorithm as the explanation of the observed bias and rms difference tendencies.

For the month of May 2004, the effect of applying a more stringent spatial matchup by limiting latitude and longitude separation for the GPS and AIRS pairs to ¼° also has been explored. Scatterplots of the resulting comparisons are presented in Fig. 3, with AIRS data QA flagged QBOT = 0 in Fig. 3a and those flagged QMID = 0 in Fig. 3b. Comparison of Fig. 2a to Fig. 3a and of Fig. 2b to Fig. 3b reveals that reducing the spatial tolerance reduces the number of matchups as expected by a factor of ~4. It also reduces the rms differences by 0.1–0.2 mm and results in even more highly correlated GPS and AIRS IPW values. This is expected, since closer collocation reduces the contribution of spatial sampling differences to the rms spread of the data. The enhanced correlation also renders this. More readily apparent in Fig. 3 is the conservative tendency of AIRS retrievals. The bias values are also reduced when the spatial "tightening" is applied for the coincident pairs of May 2004.

To quantify the dependence of (GPS–AIRS) sampling differences on the spatial separation, the matchup data have been binned by separation distance and averaged. The standard deviation of these averages has been computed and plotted in Fig. 4 as a function of mean binned separation, with a different color denoting each month. A seasonal dependency of the random differences is reflected in Fig. 4, which shows that the standard deviation increases from April to July and then steadily decreases until October, regardless of horizontal separation. For every month the standard deviation appears to increase in linear proportion to the sample pair separation. For all of the months, the average slope of a linear fit to the data is 0.01 mm km^{-1}. A similar result was reported by Wolfe and Gutman (2000) for GPS-to-radiosonde moisture. McMillin et al.

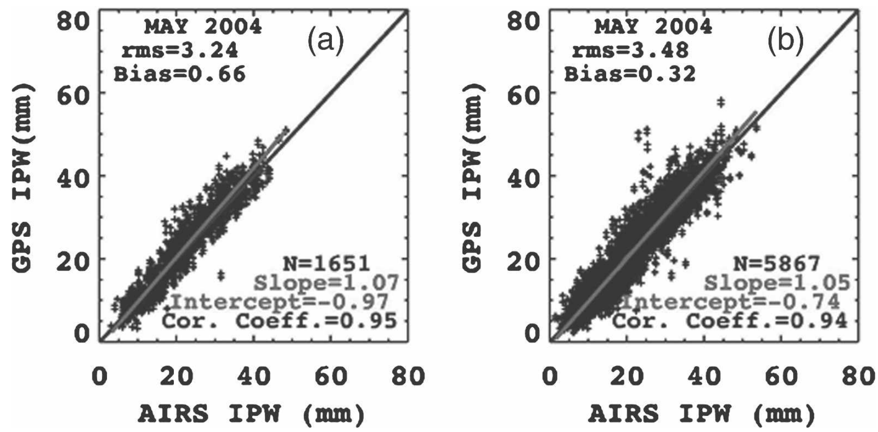

FIG. 3. Scatterplots of GPS and AIRS IPW over CONUS for May 2004 with AIRS data flagged (a) QBOT = 0 and (b) QMID = 0. Data pairs occur within ¼° latitude and longitude and within 30 min of each other. Gray lines are the best fit to the data determined through rotated linear regression.

(2005) demonstrated a comparable effect for temporal collocation.

To investigate whether the bias difference depends on the spatial separation between the coincident pairs, the matchup data were binned by separation distance and averaged for each month of the study. The monthly mean differences between GPS and AIRS IPW are plotted as functions of mean binned sample separation in Fig. 5, with a unique color denoting each month. It is apparent from Fig. 5 that the spatial separation between the coincident pairs is not the main source of bias differences between the GPS and AIRS. However, the bias differences do display a seasonal dependency, with the mean (GPS–AIRS) difference increasing from April to July, then steadily decreasing until October.

For each month of the study the GPS–AIRS bias differences have been plotted as bar graphs in Fig. 6a, with the corresponding rms differences depicted in Fig. 6b for four combinations of the major matching criteria. Thus, for each month four color-coded values are presented. Red indicates ½° maximum separation and AIRS QA flag QBOT = 0, while light blue indicates ½°

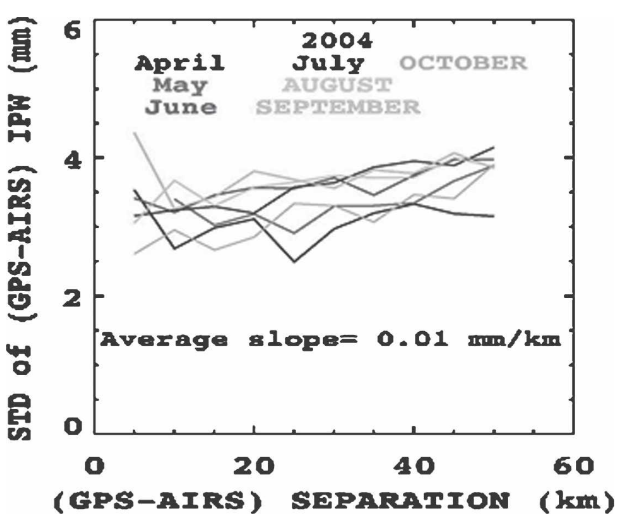

FIG. 4. The standard deviation of the mean (GPS–AIRS) IPW is plotted as a function of the separation distance between pairs of observations. There is a nearly linear tendency for the standard deviation to increase with increasing separation. The average slope for the period of analysis is 0.01 mm km^{-1}. The AIRS quality flag used here is QBOT = 0, which is the stricter of the two quality flags considered.

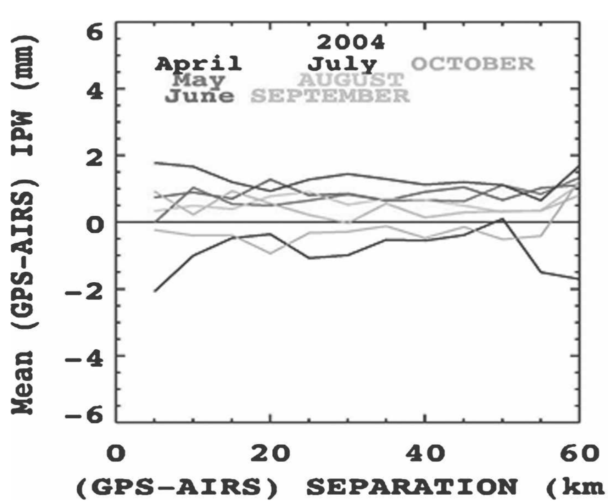

FIG. 5. The mean (GPS–AIRS) IPW plotted as a function of the separation distance between pairs of observations. There is no apparent dependency of the mean difference on the separation distance between the coincident pairs. The AIRS quality flag used here is QBOT = 0, which is the stricter of the two quality flags considered.

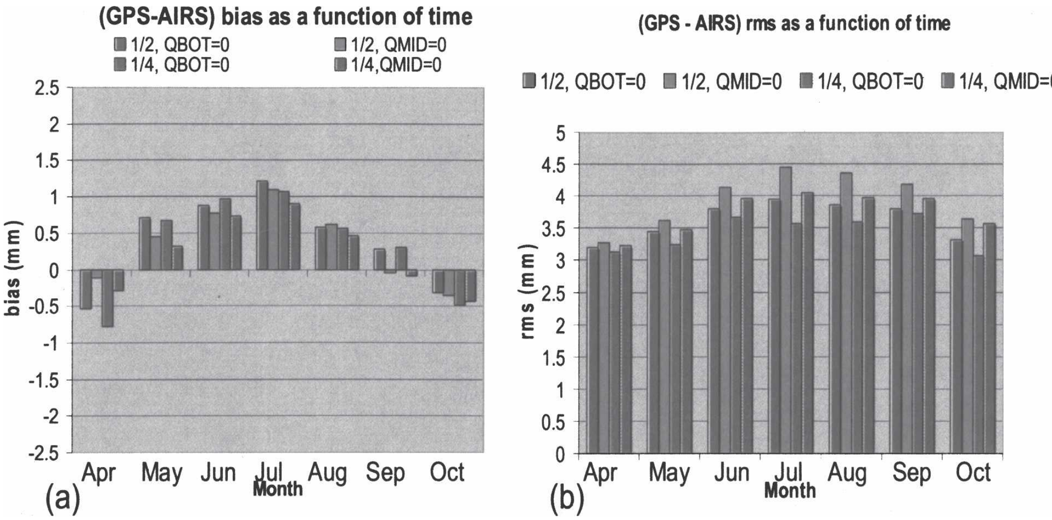

FIG. 6. (a) Bar charts of the (GPS–AIRS) IPW bias by month from April to October 2004. (b) Corresponding monthly (GPS–AIRS) rms differences. Different colors indicate different subsets of collocated (GPS–AIRS) pairs used in the comparison. The different subsets were prepared based on two types of AIRS quality flags and two variants of spatial separation used for preparing the matchup data. The label "½" indicates that spatial separation between the pairs is within ½°, while "¼" indicates it is within ¼°. The labels "QMID = 0" and "QBOT = 0" indicate which of the AIRS QA flags was used.

maximum separation and QMID = 0. Dark blue and magenta represent ¼° maximum separation with QBOT = 0 and QMID = 0, respectively. For the entire period there is overall good agreement between GPS and AIRS IPW, with the absolute values of the bias between 0.5 and 1.2 mm and rms differences ranging from 3 to 4.4 mm. However, Fig. 6 emphasizes the significant monthly variation of both bias and rms differences. The (GPS–AIRS) bias is negative during the relatively dry months of April and October but positive for the relatively wet summer months from May through August. This is consistent with the expectation for the AIRS moisture retrievals to conservatively discount data significantly moister or drier than the first-guess data. The bias values change in a gradual fashion month by month as the atmosphere over CONUS moistens and dries. Generally, the (GPS–AIRS) bias values derived using AIRS data with quality flag QBOT = 0 are greater than or equal to those for which QMID = 0, regardless of spatial separation. A reasonable explanation is that the higher quality AIRS radiances produce fewer "outlier" moisture retrievals. The rms differences also show a general pattern of monthly variation, gradually increasing from lower values in April, reaching a peak in July, and decreasing toward October. The rms differences range from 3 mm to nearly 4.4 mm. The large rms differences in summer may reflect increased spatial and temporal moisture variability in these months. For all months the rms difference is always less when the stricter constraint QBOT = 0 is required to use the AIRS IPW for comparison.

Since the estimate of the atmospheric column moisture by GPS and AIRS each depends on the local surface pressure estimate used in their retrieval algorithms, a substantial difference between the two reported surface pressures might be expected to cause a discrepancy between the AIRS and GPS IPW retrievals. To explore this possibility the IPW differences between GPS–AIRS pairs have been binned according to their surface pressure differences and then averaged. These mean (GPS–AIRS) IPW differences are plotted in Fig. 7 as a function of the bin-averaged surface pressure differences for each month. The figure reveals a nearly linear dependence of the mean IPW differences on the mean surface pressure differences, with an average slope of 0.05 mm mb^{-1}. Seasonal variation of the mean differences is also reflected in this figure, with the monthly mean differences generally increasing from April to July and then decreasing until October. Because most of the GPS surface pressure values are from the barometer readings at the receiver sites, it is concluded that the source of surface pressure differences lies in the uncertainties in the AIRS surface pressure values derived from the GFS model forecasts. Apart from the model uncertainties in surface pressure values, there may also be errors associated with the interpolation of surface pressure values to the AIRS footprint

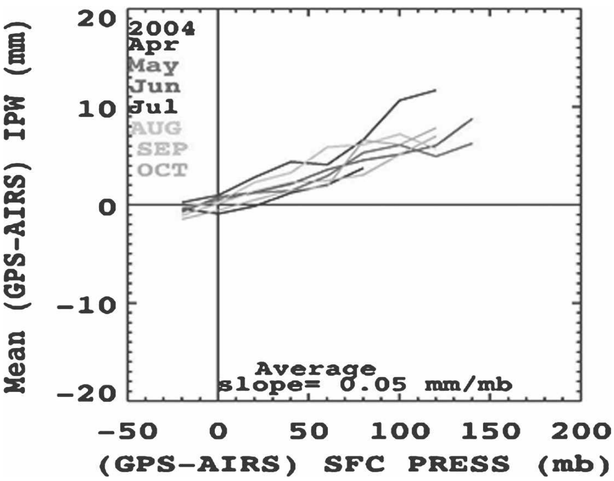

FIG. 7. The mean (GPS–AIRS) IPW difference plotted as a function of the corresponding surface pressure differences. It can be noted that there is a near-linear tendency for the mean IPW difference to increase with increasing surface pressure differences. The average slope for the whole period of analysis is 0.05 mm mb^{-1}. The AIRS quality flag used here is QBOT = 0, which is the stricter of the two quality flags provided.

location. The model-induced uncertainties in forecast values of surface pressure are likely to be greater for elevated regions, where high terrain variability is a common feature. Thus, the largest apparent differences in surface pressure values for corresponding GPS and AIRS may be attributable to differences in surface elevation not properly accounted for in the interpolation of the model forecast surface pressure used for the AIRS retrieval. This idea is supported by the fact that the mean (GPS–AIRS) IPW differences show no general sensitivity to the horizontal separation distance.

The near-linear dependence of IPW differences on surface pressure differences provides a reason to develop a regression-based IPW bias correction to the AIRS IPW data. The goal is to predict the observed differences in IPW (GPS–AIRS) based on the reported surface pressure differences. The average slope and intercept values derived from the linear fit to the data in Fig. 7 are used to make this bias adjustment. The linear prediction equation for the bin-averaged IPW differences can be written as

$$(\mathrm{GPS}_{\mathrm{IPW}} - \mathrm{AIRS}_{\mathrm{IPW}}) = [\text{Average slope}(\mathrm{GPS}_{\mathrm{sfp}} - \mathrm{AIRS}_{\mathrm{sfp}})] + \text{Average intercept}. \tag{4.1}$$

Here $(\mathrm{GPS}_{\mathrm{IPW}} - \mathrm{AIRS}_{\mathrm{IPW}})$ is the bin-averaged IPW difference between GPS and AIRS, and $(\mathrm{GPS}_{\mathrm{sfp}} - \mathrm{AIRS}_{\mathrm{sfp}})$ is the bin-averaged surface pressure difference between GPS and AIRS. The average slope refers to the mean of the slopes of the linear fit lines to the monthly data in Fig. 7, and the average intercept is the mean of the monthly intercept. Assuming $\mathrm{GPS}_{\mathrm{IPW}}$ as truth, the equation for the corrected value of AIRS IPW ($\mathrm{AIRS}_{\text{modified IPW}}$) follows from (4.1) and may be expressed as

$$\mathrm{AIRS}_{\text{modified IPW}} = \mathrm{AIRS}_{\mathrm{IPW}} + \text{Average slope}(\mathrm{GPS}_{\mathrm{sfp}} - \mathrm{AIRS}_{\mathrm{sfp}}) + \text{Average intercept}. \tag{4.2}$$

Following Eq. (4.2), the AIRS IPW data for all pairing criteria have been bias adjusted for surface pressure discrepancies and recompared to corresponding GPS data. The monthly biases of (GPS–AIRS) IPW before and after the correction for the ½° spatial matchup pairs with AIRS QA flag QBOT = 0 are presented in Table 1. Because the results are nearly identical for all other pairing criteria (see Fig. 8 of Rama Varma Raja et al. 2006), they are not presented in Table 1. The second column of the table shows the monthly (GPS–AIRS) IPW biases with no surface pressure correction applied to the AIRS data, while the third column shows the biases determined after the AIRS data have been adjusted to account for the surface pressure discrepancy. The seasonal bias dependence remains after application of the correction; that is, the AIRS retrievals are still drier than GPS during the wettest months and wetter during the driest months. However, the surface pressure difference correction to the AIRS data significantly reduced the IPW biases relative to the unadjusted data. Bias reductions due to the correction for the wet months ranged from ~0.2 to 0.75 mm for July. However, for the relatively dry months (i.e., April, October, and September), which showed negative (GPS–AIRS) biases in the original comparison, the surface pressure discrepancy adjustment actually increased the bias, making the AIRS even moister than the GPS. Because the change in IPW corresponding to a given in change in elevation (or surface pressure) is not constant but rather a function of the amount of water vapor in the portion of the atmosphere that is "removed" or "added" by the adjustment, a given height or surface pressure adjustment results in a larger change in IPW during the moist summer months than during the drier

TABLE 1. The impact of surface pressure difference–based correction to AIRS IPW on the observed bias between GPS and AIRS. The second column of the table shows the (GPS–AIRS) bias values before making adjustment to the AIRS IPW retrievals, while the third column shows the (GPS–AIRS) bias values after the surface pressure difference–based correction. It can be noted that for the summer wet months the correction resulted in significant improvement in terms of reducing the observed (GPS–AIRS) bias. The AIRS quality flag used here is QBOT = 0, which is the stricter of the two quality flags chosen for this study. The spatial separation between the GPS and AIRS matchups is a ½° latitude and longitude.

Month	($GPS–AIRS_{QBOT}$) before adjustment (mm)	($GPS–AIRS_{QBOT}$) after adjustment (mm)
Apr	−0.53	−0.84
May	0.70	0.35
Jun	0.87	0.51
Jul	1.21	0.42
Aug	0.58	0.35
Sep	0.28	−0.06
Oct	−0.32	−0.65

months. It may be that the average slope and intercept on which the correction [Eq. (4.2)] is based are skewed toward the moist months, since fewer days were included for April and October. Thus, the adjustments appear to work well for summer months where a wetter AIRS result is desirable to reduce its dry tendency in moist atmospheres. However, the adjustment does not appear to work well during dry months for which the AIRS results may be too moist due to the first guess. Additional investigations are necessary to arrive at definite conclusions about this behavior. It may prove worthwhile in future work to determine coefficients in Eq. (4.2) independently for wet and dry months. A detailed examination of conditions associated with the occurrence of the larger surface pressure discrepancies, including terrain, season, and synoptic conditions, may prove valuable in understanding when and where AIRS moisture soundings may be especially prone to errors arising from poor surface pressure information. For example, it may prove useful to determine whether most of the largest surface pressure discrepancies occur for a limited number of stations, and whether those stations are in regions for which the actual terrain is not as smooth as that implicit in the Global Forecast System, since such differences would likely result in systematic biases. The effect of replacing the adiabatic lapse rate to extrapolate surface pressure for the AIRS retrievals with a standard atmospheric lapse rate more commonly used in meteorology might be explored, too, but this is beyond the scope of the current investigation. Despite these uncertainties, the current results bear out the remarkable agreement realized between GPS and AIRS IPW estimates, providing confidence in the AIRS water vapor channel radiances and moisture retrieval process, especially when consistent ancillary data are available.

5. Conclusions

Although the measurements are limited to total values of column water vapor, this study illustrates that GPS is an excellent tool for validating satellite-based water vapor retrievals because it is accurate and allows large statistically meaningful comparative datasets to be collected quickly and easily, thus allowing the quality both of the satellite data and of the retrieval algorithms to be assessed, at least indirectly. Conventional instruments such as radiosondes and advanced instruments such as microwave water vapor radiometers are simply too few or operated too infrequently to match the GPS network in this regard. Hence, it is desirable that all the global meteorological organizations take a common initiative for creating a dense GPS receiver network around the world.

For the period April through October 2004, AIRS and GPS IPW data show remarkable agreement. The absolute (GPS–AIRS) bias values range from 0.5 to 1.2 mm and rms differences from 3 to 4.5 mm, even with the loosest tolerance for matching the data in space and the less stringent quality assurance criteria that are required for the AIRS data. Monthly correlation coefficients are consistently large, ranging from 0.91 to 0.98. The statistical results provide confidence in AIRS as a platform for humidity sensing and retrieval.

AIRS IPW data associated with the higher quality temperature QA flag QBOT = 0 produced better agreement with GPS than those with the less demanding QMID = 0 quality flag, especially in the rms sense. This result indicates the effectiveness of the AIRS quality control in identifying sets of radiances that may not produce the most realistic humidity retrieval.

The study revealed seasonal variation of the (GPS–AIRS) bias and rms differences. The largest rms differences are generally observed for the wet summer months. The (GPS–AIRS) bias changed sign by season, increasing from small negative values in April to peak positive values in July and decreasing thereafter. The tendency of AIRS to estimate less moisture than GPS during the wettest months is thought to be an indication of the retrievals being too strongly constrained by first-guess values and may be enhanced by the tendency of cloud clearing to select radiances from drier cloud-free columns as inputs to the retrieval process.

Reducing the spatial separation between the (GPS–AIRS) IPW pairs reduced their rms differences. The standard deviation of the mean (GPS–AIRS) IPW differences exhibits a tendency for linear increase with spatial separation between the samples. The average slope for this linear increase is found to be 0.01 mm km^{-1}.

Mean (GPS–AIRS) IPW differences have shown a nearly linear dependence on the surface pressure differences reported for each instrument, with an average slope of 0.05 mm mb^{-1}. Large differences of nominal surface pressure between collocated GPS–AIRS pairs can cause significant bias in corresponding IPW comparison but can be successfully accounted for to produce accurate IPW retrievals and meaningful comparisons. The surface pressure differences as shown in this study also provide the opportunity of identifying the AIRS retrievals with largest differences over CONUS, where a dense network of GPS receivers is already operational.

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