3.1 COMPARISON OF COLUMN INTEGRATED WATER VAPOR MEASUREMENTS FROM ATMOSPHERIC INFRARED SOUNDER (AIRS) AND SURFACE-BASED GLOBAL POSITIONING SYSTEM RECEIVERS

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Abstract
Integrated Precipitable Water (IPW) vapor estimates derived from a network of ground-based GPS receivers provide an accurate, convenient, and statistically robust means to assess the quality of AIRS water vapor retrievals over the contiguous United States (CONUS). For a period from April to October 2004, GPS IPW estimates were paired with AIRS data nearly coincident in time and space. The matched data pairs exhibit small monthly mean and rms differences, giving confidence in both the AIRS observations and the humidity retrieval. Monthly rms differences were reduced using stricter horizontal matching, indicating that part of the observed differences are attributable to sampling. IPW biases were found to be proportional to surface pressure differences reported for the GPS and AIRS retrievals. IPW match-up pairs for which the surface pressure differences are small (less than 0.5 mb) show smaller biases. Moreover, adjusting the AIRS IPW values to account for the reported surface pressure differences resulted in significant reductions of both bias and rms differences. The AIRS IPW estimates tend to be relatively dry in moist atmospheres (IPW values > 40 mm) and wet in dry cases (IPW values < 10 mm). This is consistent with previously documented tendency of satellite retrievals to be biased towards initial guess used for the retrievals. Additional investigation is necessary to verify and quantify the effect of the bias of AIRS water vapor retrievals towards initial guess on AIRS IPW estimates and their validation. Finally, it is shown that the IPW bias and rms differences appear to have a seasonal dependency.

1. Introduction

An objective for the 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 a 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 minutes. The satellite is equipped with several passive sensors that are responsive to variations in atmospheric water vapor, most notably the Atmospheric InfraRed Sounder (AIRS).

The project includes a component to validate the AIRS data and products, to clear the way for their effective use in NWP, atmospheric and climate research, and to guide refinements in the retrieval processes (Fetzer et al., 2003). This paper describes the methodology and results of validating the AIRS moisture product for a period of almost 6 months using Global Positioning System (GPS) IPW retrievals.

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.

2.1 The Atmospheric Infra-Red Sounder (AIRS)

Three of the six Aqua sensors are designed to be responsive to variations in atmospheric water vapor. These are AIRS, the Advanced Microwave Sounding Unit-A (AMSU-A), and the Humidity Sounder of Brazil (HSB). Among these cross-track scanning sounders, AIRS may be regarded as the centerpiece, with the microwave sounders AMSU-A and HSB contributing significantly when clouds or heavy precipitation occlude the lower troposphere from AIRS. As it scans, AIRS collects radiances in 2378 IR channels with wavelengths ranging from 3.7 μm – 15.4 μm, and 4 visible channels with wavelength ranging from 0.4 μm – 0.94 μm (Parkinson 2003). Many of these channels respond to the concentration of water vapor at various heights in the atmosphere, so that the instrument suite is capable of providing more accurate, higher vertical resolution humidity measurements than past satellites.

The AIRS hardware instrumentation and moisture retrieval methodology are briefly described by McMillin et al. (2005). More specific details of the AIRS instrumentation and retrieval methodologies can be found in the special issue of *IEEE Transactions on Geoscience and Remote Sensing* devoted to the EOS Aqua Mission (Vol.41, No.2, 2003).

2.2 Global Positioning System (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, and 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 excess delays in the Global Positioning System radio signals caused by the refractivity of the neutral (non-dispersive) 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 (as opposed to azimuth) since the former 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 over-determined 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 GPS signal delays are parsed into their wet and dry components using the technique described by Bevis et al. (1992) and the wet component is mapped into IPW using slightly modified parameters described by Bevis et al. (1994). The accuracy of these IPW retrievals is about 1 mm, or about 3 % of typical IPW values (Mattioli et al., 2005).

During the past decade, NOAA/ESRL has established a network of more than 375 GPS IPW stations (see Figure 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 (NOAA/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 (especially SuomiNet at http://www.suominet.ucar.edu/), and the private sector.

2.3 Applicability of GPS IPW in moisture validation

Radiosondes provide IPW data, too, and are capable of resolving the vertical distribution of water vapor to validate the AIRS humidity profiles. However, their temporal resolution is only 12 h, and there are less operational radiosonde sites over CONUS than GPS stations. Relatively few pairs of AIRS and radiosondes profiles matched in time and space can be accumulated in a nominal period. It is possible to have thousands of GPS-AIRS IPW match-ups in a month over the CONUS. Although the GPS method does not provide information about the vertical distribution of moisture, the large number of match-ups, the all weather capability, and the measurement accuracy make it useful as a quick, repeatable "sanity" check for AIRS data, and for more detailed investigations, including scaling and weighting of water vapor profiles. GPS can be used as a validation tool for any satellite-based column integrated moisture product. The use of GPS IPW data as a validation tool for AIRS moisture data is discussed by Yoe et al. (2003, 2004) and by McMillin et al. (2005).

Recent studies have documented problems associated with radiosonde moisture measurements (Miloshevich et al., 2003, 2004; Turner et al., 2003; Wang et al., 2002, 2003; Roy et al., 2004; and McMillin et al., 2005). Birkenheuer and Gutman (2005) have pointed out that the errors in radiosonde humidity data may obscure the quality of remotely sensed data when they are compared. Accurate IPW measurements from surface microwave radiometers were used by Revercomb et al. (2003) and Turner et al. (2003) for radiosonde moisture data correction. McMillin et al. (2005) demonstrated the utility of GPS IPW to make corrections to radiosonde humidity measurements.

3. Data Set Preparation

The AIRS data were made available by NASA Jet Propulsion Laboratory (JPL). The GPS IPW and ancillary surface meteorological data were provided by NOAA ESRL/GSD with quality checks and flags. In the course of this study it was noted that IPW observations from some of the GPS stations were not representative of regional conditions. The sites in questions were located near either mountains, where the differences in surface height may prevent good agreement between AIRS and GPS, or near sea coasts where large horizontal variability of moisture over small distances and short time periods may be expected. These unrepresentative soundings have been excluded from the statistical analysis presented in this paper.

The AIRS IPW data are calculated from the retrieved water vapor molecular density profiles from JPL's validation version (V4.0.9) retrieval algorithm. There are two quality flags for moisture product from version V4.0.9. One is a mid-tropospheric temperature flag (QMID) and the other is a lower tropospheric temperature flag (QBOT). These flags are set to zero when the quality check is successful. The AIRS IPW population with QBOT=0 is generally a subset of the population for which QMID=0, as might be expected from the increased difficulty of sounding in the presence of clouds. The specific details regarding AIRS water vapor data quality flags can be found in Susskind et al. (2005). AIRS surface pressure data used in the study are from the NCEP model analysis. The model grid point values are interpolated in space and time to match the ground location and time of the AIRS data. The GPS surface pressure data are from *in situ* barometers.

3.1. GPS – AIRS IPW matching criteria

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

(1) AIRS locations within 0.5 degrees latitude and longitude of the GPS station.

(2) AIRS observations within 30 minutes 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.

(4) Both instruments reporting 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 retrieval confidence flags. The IPW pairs thus obtained were analyzed using statistical methods.

4. Scatter plots, regression, and best-fit lines

The paired IPW data have been examined by conventional statistical methods, calculating the mean and rms differences and the correlation for relevant portions of the dataset. Scatter plots have been used to examine in greater detail how well the data agree and to identify cases in which they conflict so that these may be examined in greater detail as appropriate. Following McMillin et al. (2005) the best-fit lines to the data have been determined by applying linear regression after rotating the data 45 degrees toward the horizontal axis of the scatter plot. The motivation for using "rotated regression" is illustrated in Figure 2a and 2b, for which conventional linear regression has been applied to the data for June 2004. An arbitrary choice of GPS IPW as the predictand (vertical axis) as in Figure 2a, or as the predictor (horizontal axis) as in Figure 2b, results in different slopes and intercepts for the best fit regression lines, indicated in red in the Figure. Note that these best-fit lines are not symmetric with respect to the blue "unity" line that corresponds to perfect agreement. The impact of rotated regression is seen in Figure 2c and 2d, where the effect of the arbitrary choice of predictor and predictand has been eliminated. The intercepts are additive inverses of each other, and the slopes are such that the best-fit lines (red) are symmetric with respect to the unity line (blue). Also, the intercept values are much smaller than those obtained using conventional regression. Rotated regression confers a practical advantage by consistently revealing features of the data set that might not be detected when using conventional regression. For example, the tendency for the AIRS IPW retrievals to be slightly dry relative to the GPS IPW data in the moistest cases is equally evident in Figure 2c and 2d by comparing the best-fit lines to the unity line. Using conventional regression, this aspect of the data set might not be readily apparent. From Figure 2a, the apparent coincidence of the best-fit and unity lines provides little basis to explain the bias difference of 0.77 mm. All subsequent analysis was performed applying the rotated regression with GPS IPW as the predictor and AIRS IPW as the predictand.

5. Results and discussion

Figure 2c shows that in a month a statistically significant number of matched AIRS and GPS IPW can be amassed readily, especially if only the less stringent AIRS quality control test, QMID=0 is required. For June 2004, remarkable agreement between GPS IPW and AIRS IPW with a bias difference value of 0.77 mm and rms difference of 4.14 mm has been found. King et al. (2003) compared Terra MODIS and MWR IPW data, and Birkenheuer and Gutman (2005) compared GPS to GOES-11 IPW. These studies found bias and rms differences between satellite and validation data comparable or larger than the GPS and AIRS results for June 2004, as may be seen from the summary presented in Table 1. These various comparisons are based on unique pairs of satellite and validation instruments and represent comparisons made at different times and conditions. They are not identical comparisons and provide only a general idea of the improved satellite moisture sensing capability achieved by AIRS. Increased accuracy is expected of AIRS because it makes use of high spectral resolution radiance measurements.

McMillin et al. (2005) compared GPS AIRS IPW pairs obtained from a three-way match to the radiosonde observations over CONUS, for a period from September through December 2002. The comparison was based on a previous version (V3.0.8) of the AIRS IPW retrieval process, for which the bias and rms differences were 1.5 mm and 4.6 mm, respectively. Using the same version of AIRS IPW data (V3.0.8), Yoe et al. (2004) compared GPS-AIRS IPW for September 2002, for which the bias and rms differences were 1.83 mm and 3.98 mm, respectively. The data in Figure 2c thus seem to indicate that the more recent retrieval version produced smaller bias.

The GPS to AIRS comparison for June 2004 has been refined by applying the stricter AIRS quality flag QBOT=0 and the results presented in Figure 3. The number of match-ups is reduced by a factor of 2/3, and the rms difference between AIRS and GPS IPW reduced to 3.80 mm, although the bias difference increased slightly to 0.87 mm. Since the quality control flags are based on the AIRS radiances, it may be that these best AIRS data are less noisy, resulting in reduced rms differences and suitable to show more clearly effects such as the tendency of the AIRS moisture retrieval to be perhaps too strongly constrained by the first guess value. More effort is needed to confirm a cause and effect relationship, however.

For the month of June 2004, the effect of applying a more stringent spatial match-up by limiting latitude and longitude separation for the GPS and AIRS pairs to 0.25 degrees has also been explored. For this case two scatter plots with AIRS data meeting the strict QBOT=0 (Figure 4a) and the looser QMID=0 (Figure 4b) are presented. The narrower spatial window reduces the number of data pairs by the expected factor 4. Comparison of Figure 2c and Figure 4b, and of Figure 3 and Figure 4a, reveal that spatial tightening of the match-up pairs reduces the rms differences by 0.1 – 0.2 mm, and results in more highly correlated GPS and AIRS IPW values. This is expected since better collocation reduces the contribution of sampling differences to the rms spread of the data. A similar result was reported by Wolfe and Gutman (2000) for

GPS-to-radiosonde moisture data. McMillin et al. (2005) demonstrated the same effect for temporal collocation.

For each month of the study the GPS-AIRS bias differences have been plotted as bar graphs in Figure 5a, with the corresponding rms differences depicted in Figure 5b. For each month four color-coded values are presented. Red indicates half-degree maximum separation and AIRS quality flag QBOT = 0, while light blue indicates half-degree maximum separation and QMID=0. Dark blue and magenta represent quarter-degree 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 mm to 4.4 mm. However, Figure 5 reveals significant monthly variation of both bias and rms differences for all matching criteria. 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 conservative tendency of AIRS moisture retrievals discussed earlier. 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 possible 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 might 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.

Figure 5b also shows that the rms difference is always reduced when more restricted spatial matching is required. To quantify the dependency of (GPS-AIRS) sampling differences on the spatial separation, the match-up data were binned by separation distance and averaged. The standard deviation of these averages were computed and plotted in Figure 6 as a function of mean binned separation, with a different color denoting each month. A tendency can be discerned for the standard deviation to increase in proportion to sample pair separation. The average slope of linear fit is 0.01 mm/km. The seasonal dependency of random differences is also reflected in this plot where the standard deviation increases from April to July then steadily decreases until October.

The estimate of the atmospheric column moisture by GPS or AIRS also depends on the local surface pressure measurements used in their retrieval algorithms. If there is a substantial difference between the two surface pressures, it 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 were binned according to their surface pressure differences and then averaged. These mean (GPS-AIRS) IPW differences are plotted in Figure 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. 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.

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 Figure 7 are used to make this bias adjustment. The linear prediction equation for the bin-averaged IPW differences can be written as:

$$(GPS_{IPW} - AIRS_{IPW}) = (\text{Average slope} * (GPS_{sfp} - AIRS_{sfp})) + \text{Average intercept} \quad (1)$$

Here $(GPS_{IPW} - AIRS_{IPW})$ is the bin averaged IPW difference between GPS and AIRS, and $(GPS_{sfp} - AIRS_{sfp})$ is the bin averaged surface pressure difference between GPS and AIRS. The Average slope refers to the average of all the slope values from all of the linear fit lines to the monthly data in Figure 7, and the Average intercept is the corresponding average value of the y-intercept.

Assuming GPS_{IPW} as truth, the equation for true value of AIRS follows from (1) and can be written as:

$$AIRS_{modified\ IPW} = AIRS_{IPW} + \text{Average slope} * (GPS_{sfp} - AIRS_{sfp})) + \text{Average intercept} \quad (2)$$

Here $AIRS_{modified\ IPW}$ is assumed to be the true value after bias correction.

AIRS IPW data for all pairing criteria have been bias adjusted for surface pressure discrepancies following equation (2) and re-compared to corresponding GPS data. As an additional check pairs of (GPS-AIRS) IPW selected by limiting the magnitude of corresponding surface pressure differences were also compared statistically to determine how this constraint impacts the (GPS-AIRS) bias. Two upper bounds for surface pressure differences were applied. The larger tolerance used was 20 mb, since the majority of the potential GPS and AIRS data pairs had surface pressure differences smaller than this value. A more restrictive upper bound of 0.5 mb was selected to examine the IPW biases when the effect of surface pressure differences was expected to be negligible. The monthly biases of (GPS-AIRS) IPW are presented in Figure 8, where the different colors in the bar chart indicate which set of matching criteria were applied to select the IPW data pairs, and whether or not the surface pressure adjustment procedure has been applied to the AIRS IPW. Red indicates matching using AIRS data with the quality flag QBOT=0 and absolute surface pressure differences of 20 mb or less. Dark blue indicates QBOT=0 for the AIRS data and surface pressure differences of 0.5 mb or less. Yellow indicates AIRS data with quality flag QBOT=0 and the bias adjustment of equation (2) applied. The light blue and magenta are the same as the red and dark blue respectively, except relaxing the AIRS data quality flag to QMID=0. Figure 8 shows that the general seasonal dependence of the biases seen in Figure 5a remains after correcting for surface pressure discrepancies, that is AIRS retrievals still are drier than GPS during the wettest months and wetter during the driest months. However, applying the surface pressure constraint or correction significantly reduced the IPW biases relative to the unadjusted data in Figure 5a. Bias reductions for the wet months ranged from ~ 0.2 to 0.75 mm for July, using either the adjustment or limiting the comparisons to small (0.5 mb) pressure differences. For the moist summer months the bias reduction achieved by adjusting the AIRS data and by considering only small (0.5 mb) pressure differences are similar. However, for the relatively dry months, i.e. April, October and September, which showed negative (GPS-AIRS) bias from original comparisons (Figure 5a), the adjustment actually increased the bias, making the AIRS even more moist relative to GPS. It may be that the averages of slope and intercept on which the correction (equation 2) is based are skewed toward the summer months in the data set since fewer days were included for April and October. Thus the adjustment works very well for summer months where a wetter AIRS result is "desirable" to reduce its dry tendency in moist atmospheres. But this does not seem to work well for relatively dry months for which the AIRS results may be too moist due to the first guess. In the future, when a full year's AIRS IPW data for CONUS are available, it may prove worthwhile to determine coefficients in equation (2) independently for wet and dry months.

6. Conclusions

Despite the inability of GPS to determine the vertical distribution of atmospheric moisture, this study illustrates that is an excellent tool to validating satellite-based water vapor retrievals because it is accurate and allows large statistically meaningful comparative data sets to be collected quickly and easily, allowing the quality of the satellite data and 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 of April through October 2004 AIRS ad GPS IPW data show remarkable agreement. The absolute (GPS-AIRS) bias values range from 0.5 mm to1.2 mm and rms differences from 3 mm to 4.5 mm even with the loosest tolerance for matching the data in space and the less stringent quality control criteria applied to AIRS data. Monthly correlation coefficients are consistently large, ranging from 0.91 to 0.98. The statistical results are as good or better than those presented for other satellite moisture validation studies, marking the improvements achieved in humidity sensing and retrieval through AIRS.

AIRS data with higher quality 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.

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 0.01mm/km.

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. Large differences of nominal surface pressure between co-located 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.

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Instruments compared	Mean difference (mm)	rms difference (mm)	Number of points
GPS - AIRS	0.77	4.14	19134
GPS-GOES-11 SFOV (IHOP-2002)[1]	-3.75	5.5	34393
GPS-GOES-11 SFOV 2 km (IHOP-2002)[1]	-3.45	5.0	850
MODIS Terra-MWR[2]		4.66	80

[1] Birkenheuer and Gutman (2005)
[2] King et al. (2003)
Table 1: The comparison of different instrument pairs in terms of the IPW agreement between them

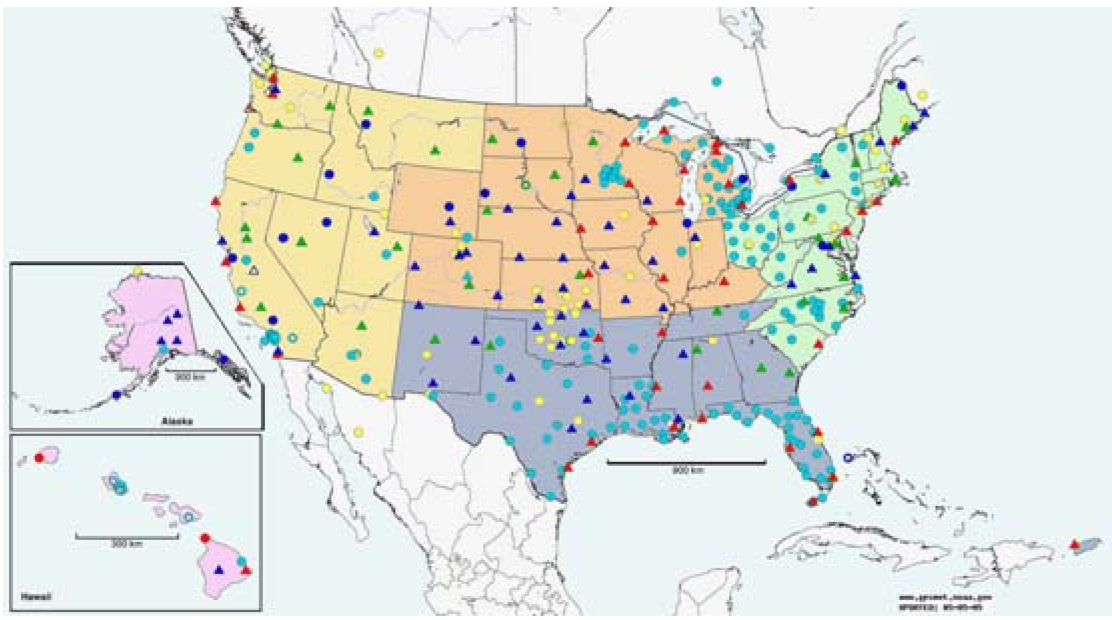

Figure 1. The distribution of GPS IPW stations over the CONUS. These stations are operated by NOAA ESRL/GSD (formerly FSL), Boulder, Colorado, USA.

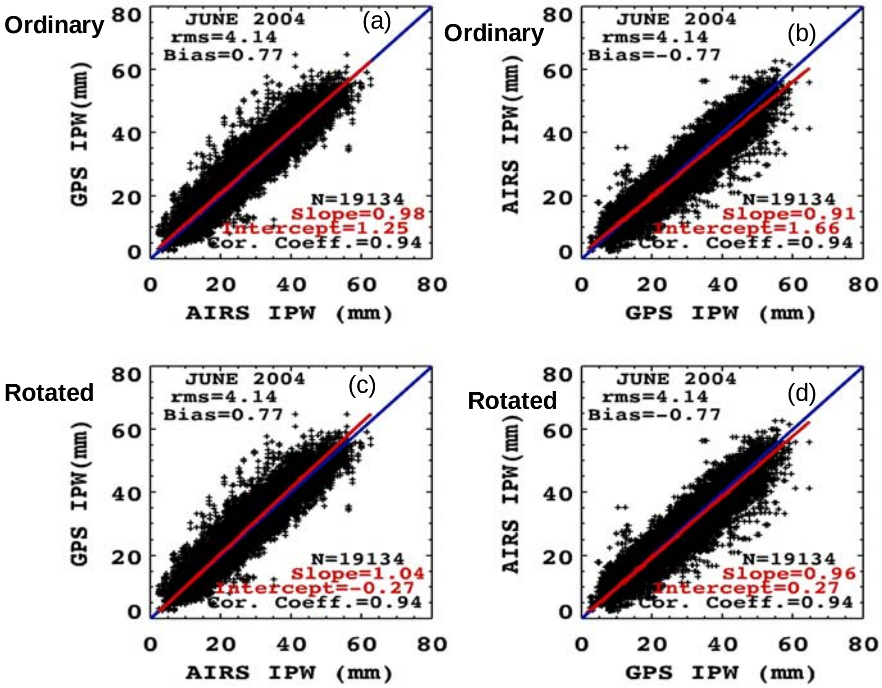

Figure 2. Scatter plots of Integrated Precipitable Water (IPW) from GPS and AIRS for the month of June 2004. These plots compare different linear regression methods such as y on x regression, x on y regression and corresponding regressions in rotated space of data. AIRS IPW data with quality flag QMID=0 is used here. The match-up pairs are within half by half degree latitude-longitude window and within half hour.

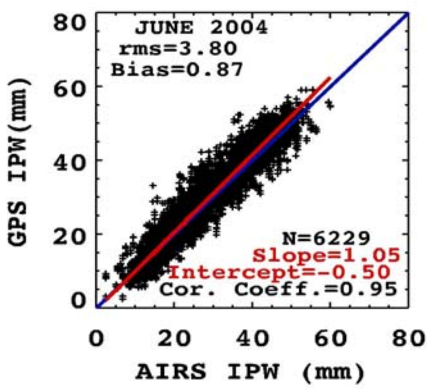

Figure 3. Scatter plot of GPS and AIRS IPW over CONUS for the month June 2004. AIRS IPW data with quality flag QBOT=0 is used in this comparison. All of the GPS-AIRS data pairs shown here are within half degree latitude and longitude and within half hour of each other. The red line is the best fit in the rotated space for the match-up data.

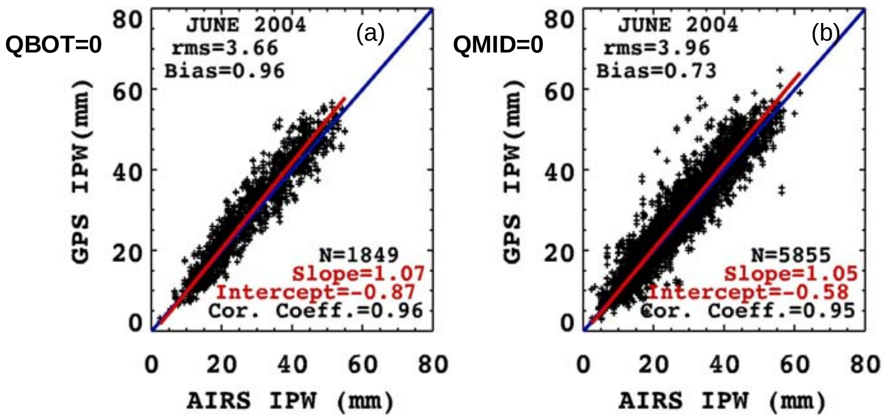

Figure 4. Scatter plot of GPS and AIRS IPW over CONUS for the month June 2004. The maximum spatial separation for the data pairs is 0.25 degree. Panel (a) shows the comparison of AIRS IPW data with quality flag QBOT=0 while Panel (b) shows that with QMID=0 flag. The red lines the best-fit lines determined using rotated regression.

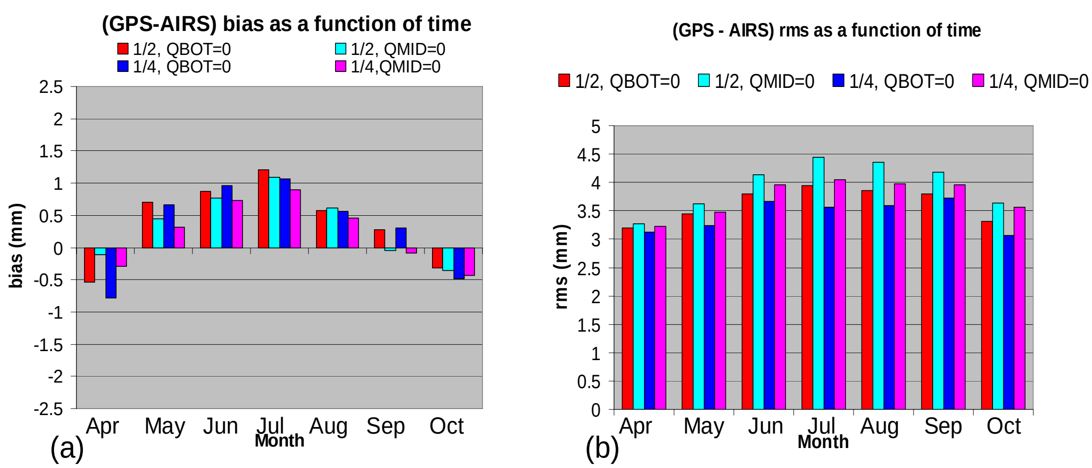

Figure 5. (a) Bar charts of (GPS-AIRS) IPW bias by month from April to October 2004. Corresponding monthly (GPS-AIRS) rms differences are plotted in (b). Different colors indicate different subsets of co-located (GPS-AIRS) pairs used in the comparison. The different subsets were prepared based on two types of AIRS quality flags and two variants of spatial separation used for preparing the match-up data. The label “1/2” indicates that spatial separation between the pairs is half of a degree while “1/4” indicates that it is quarter of a degree. The label “QMID=0” shows that the quality flag of used AIRS data is based on mid-tropospheric layer temperature while QBOT=0 shows that it is based on lower tropospheric layer temperature. The seasonal dependency of (GPS-AIRS) bias or rms differences is clearly evident in these bar diagrams.

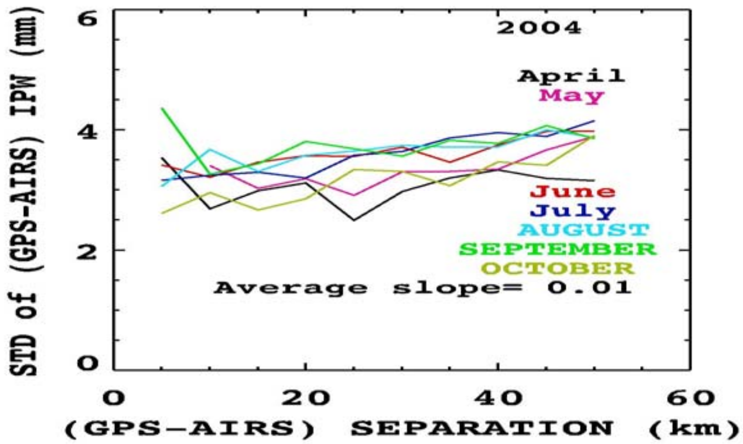

Figure 6. The standard deviation of the mean (GPS-AIRS) IPW is plotted as a function of the separation distance between pairs of observations. There is a nearly linear tendency for the standard deviation to increase with increasing separation. The average slope for the whole period of analysis is 0.01mm/km. The AIRS quality flag used here is QBOT=0 which is the stricter (better) of the two quality flag provided.

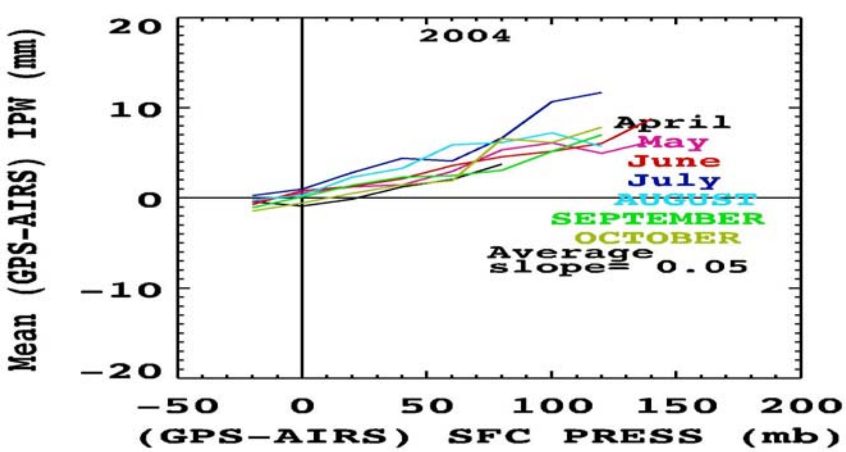

Figure 7. The mean (GPS-AIRS) IPW difference is plotted as a function of the corresponding surface pressure differences. It can be noted that there is a near linear tendency for the mean IPW difference to increase with increasing surface pressure differences. The average slope for the whole period of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

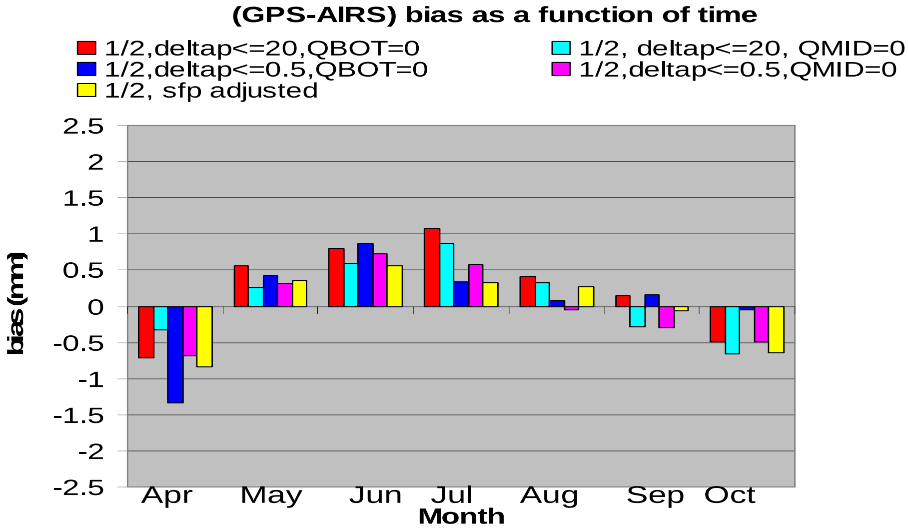

Figure 8. Bar charts showing the impact of surface pressure difference based correction/constraint on (GPS-AIRS) bias in each month from April to October 2004. The maximum spatial separation allowed between the pairs is half degree in this case as represented by the label “1/2”. The different colors of the bars in the chart indicate unique subsets of co-located (GPS-AIRS) pairs based on two AIRS quality flags and the type of correction/constraints applied on the data sets. The label “QMID=0” shows that the quality flag of used AIRS data is based on mid-tropospheric layer temperature while QBOT=0 shows that it is based on lower tropospheric layer temperature. The label “deltap <=20” indicates that the absolute (GPS-AIRS) surface pressure differences allowed for the subset is 20 mb or less while “deltap <=0.5” indicates it is 0.5 mb or less. The label “sfp adjusted” indicates that a bias correction was applied to the AIRS data in the subset based on equation (2) in this paper.