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Radiosonde humidity corrections and potential Atmospheric Infrared Sounder moisture accuracy

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[1] Although there are a number of sources of radiosonde data for validation of observations from other atmospheric sensors, routine operational sondes remain the main source for a large volume of data. In this study radiosonde moisture profiles are renormalized using Global Positioning System (GPS) Integrated Precipitable Water (IPW) vapor. The GPS-adjusted radiosonde humidity profiles are then compared to the Atmospheric Infrared Sounder (AIRS) measurements. As a check, AIRS measurements are also compared with unadjusted radiosonde moisture profiles. It is shown that the GPS-adjusted values are in better agreement with the AIRS measurements. On the basis of this result, the GPS-adjusted radiosondes are used to assess the AIRS potential accuracy. This is valid because the errors in the AIRS measurements and the adjustments are independent. The GPS-based renormalization of radiosonde humidity measurements produced a significant improvement in the agreement between AIRS and Vaisala RS 57 H type radiosondes in the lower troposphere, where much of the atmospheric water vapor resides. The adjustment also resulted in improved agreement between AIRS and radiosonde IPW estimates. The results showed a day/night bias in the radiosonde values as compared to the GPS and the AIRS values, demonstrating the potential use of the technique for evaluating and correcting this bias. Established corrections for humidity errors also have been applied to some operational radiosonde observations, specifically the published temperature correction developed for the Vaisala RS80 H type radiosonde. This correction produced a much smaller effect than the GPS adjustment.

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1. Introduction

[2] The water vapor content of the terrestrial atmosphere plays a significant role in Earth's weather and climate phenomena. Water vapor is a known greenhouse gas and thus important for global warming studies. This central role is a requirements driver for accurate water vapor observations with high temporal and spatial resolution. The main source for atmospheric water vapor measurement data is the radiosonde soundings performed on an operational basis (twice daily at 00 GMT and 12 GMT) at fixed stations around the globe. However, these are limited generally to accessible land regions. Satellite-based water vapor retrievals form a complementary source of data for operational weather/climate prediction or research applications. Satellite-based humidity sensors provide measurements over the vast ocean regions and also over the inaccessible land regions. Several satellite-based water vapor instruments currently provide high-resolution humidity measurements for the Earth's atmosphere. The Atmospheric Infrared Sounder (AIRS) is one such sensor. Satellite-based humidity measurements must be validated and quality checked to permit their use for operational or research purposes. In general the meteorological science community has accepted as reference standard the in situ radiosonde humidity measurements. Therefore the majority of the validation studies of satellite-based humidity retrievals over the years have focused on investigating the comparative characteristics of space based humidity measurements with respect to the corresponding measurements from colocated radiosondes [e.g., see *Kleespies and McMillin*, 1990; *Divakarla et al.*, 2006]. However, some recent studies have identified important problems which adversely impact the accuracy of radiosonde humidity measurements, and also proposed ways to correct these deficiencies [*Jeannet et al.*, 2002; *Wang et al.*, 2002; *Turner et al.*, 2003; *Miloshevich et al.*, 2004]. The problems associated with the radiosonde humidity measurements as shown by these researchers are sensor-type-dependent and therefore have unique characteristics and correction

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procedures. In a recent study of three-way intercomparison of humidity measurements from GOES, GPS and radiosondes, *Birkenheuer and Gutman* [2005] have argued that the errors in radiosonde humidity data may obscure the quality of remotely sensed data when they are compared.

[3] This paper has several purposes. First it describes results based on using the GPS IPW to scale the radiosonde moisture observations to provide the same total IPW. The original and GPS-adjusted profiles of Layered Precipitable Water (LPW) are then compared to the corresponding profiles derived from AIRS water vapor molecular density observations. It is demonstrated that the GPS-adjusted values provide a better fit to the AIRS data. Since the adjustment and the AIRS data are completely independent, this better fit justifies using the adjusted values to assess the AIRS potential accuracy. The accuracy is called ''potential'' because the AIRS quality control procedures in use when the analysis was performed remained in an early stage of development. A screening method that used radiosonde temperatures to identify bad soundings was applied. These studies were initially performed using the water vapor product from version 3.0.8 of the AIRS retrieval algorithm, but have been repeated for this paper using the products from version 4.0.9, because the latter is considered more accurate and provides better spatial coverage [*Tobin et al.*, 2006; *Divakarla et al.*, 2006; *Susskind et al.*, 2006].

[4] The GPS-based adjustments to the radiosonde humidity measurements are also compared to the published radiosonde humidity correction based on temperature dependence by *Wang et al.* [2002]. It needs to be noted that the comparisons in this study are based on the radiosonde humidity measurements as they are made available to the operational numerical weather prediction centers. These are limited to a small number of ''mandatory'' and ''significant'' atmospheric pressure levels, meaning that much of the original temporal and vertical resolution is lost. Certain published corrections for radiosonde humidity measurements require high temporal resolution (6 s) radiosonde data, for example to apply the time lag correction developed by *Miloshevich et al.* [2001, 2003, 2004]. The 6 s time lag correction cannot be applied to the operational radiosonde measurements received by the forecast centers. Only those corrections that can be applied to the operational radiosonde reports are considered in this study. The Layer Precipitable Water (LPW) derived from the radiosonde water vapor profiles, both as initially reported and temperature corrected, then are compared to the corresponding LPW values derived from AIRS retrievals. Finally, a similar comparison is performed for the radiosonde humidity correction using the GPS derived IPW to renormalize the radiosonde LPW before comparing to AIRS.

2. Instrument Descriptions

[5] Each of the three sensors used for this study employs a unique measurement principle and sampling procedure. Brief descriptions of each instrument and corresponding retrieval methodology are provided in the following subsections.

2.1. GPS IPW

[6] Retrieving IPW from GPS observations involves the collection of dual frequency carrier phase measurements from one or more fixed GPS receivers. From these measurements, the zenith tropospheric delay is estimated at each site by mapping the line-of-sight delays measured to all (typically 6–10) GPS satellites in view to zenith using elevation-dependent mapping functions [*Niell*, 1996] and averaging the results. In the NOAA implementation of this technique, zenith delays are estimated in an absolute sense using the method described by *Duan et al.* [1996]. The hydrostatic component caused by the mass of the atmosphere can be estimated directly from a surface pressure measurement [*Saastamoinen*, 1972] then subtracted from the zenith tropospheric delay, leaving a zenith-scaled ''wet'' delay that is nearly proportional to the IPW [*Bevis et al.*, 1992]. Numerous comparisons with other water vapor sensing systems including radiosondes and microwave water vapor radiometers give a mean estimate of 1.0 mm for the accuracy of GPS IPW estimates [*Mattioli et al.*, 2007].

2.2. Derivation of Moisture Products From AIRS

[7] For clarity, the derivation of moisture from AIRS is considered in two parts. First, the instrument itself is described. Then the process for retrieving water vapor and other atmospheric characteristics from the AIRS observations is outlined.

2.2.1. AIRS Instrument

[8] The AIRS may be regarded as the primary sensor on the Aqua spacecraft [*Parkinson*, 2003], which was launched on 4 May 2002 as part of NASA's Earth Observing System (EOS). The AIRS is an infrared (IR) instrument with the spectral resolution ($\lambda/\Delta\lambda$) of its 2378 channels set to a nominal value of 1200, providing much better vertical resolution than earlier satellite sounders [*Aumann et al.*, 2003].

[9] AIRS is complemented on Aqua by two microwave instruments, the Advanced Microwave Sounding Unit (AMSU) and the Humidity Sensor for Brazil (HSB). Because IR measurements are adversely affected by clouds, the ''AIRS'' soundings are actually made with the help of measurements from the microwave sensors. The microwave observations are used to drive a cloud-clearing algorithm [*Susskind et al.*, 2003] based on seminal work by *Smith* [1968] and *Chahine* [1974, 1977]. The cloud-cleared IR radiances are then used as input to the moisture retrieval algorithm, which is explained in the following subsection. For the current study, the AIRS soundings are made with help of the AMSU only because the HSB failed after a short time in orbit. The AIRS and AMSU are scanning instruments for which the scanning geometry was arranged so that three AIRS Fields-of-View (FOVs) fit in the width of a single AMSU FOV, and 3 AIRS scan lines fit in one AMSU scan line. This yields 9 AIRS FOVs covering one AMSU 40 km FOV. A single retrieval is made for each group of one AMSU and nine AIRS FOVs. AIRS was designed to provide moisture retrievals with better than 10% uncertainty in 2-km layers [*Fetzer et al.*, 2003]. Early validation studies have shown performance approaching this goal [*Tobin et al.*, 2006; *Divakarla et al.*, 2006].

2.2.2. AIRS Retrieval Algorithm

[10] To derive a moisture profile, the set of cloud-cleared AIRS radiances for the spectral regions affected by water vapor absorption is examined to determine the amount of

radiation absorbed by the water vapor molecules, from which the amount of water vapor along the viewing path is inferred. By using a number of channels with differing degrees of water vapor absorption sensitivity and additional channels that can measure temperature, a profile of water amount versus height may be obtained. The retrieval algorithms are initiated with a guess profile for which the profile state variables (the temperature and water vapor profiles) are given, and the corresponding radiances in the water vapor absorption regions are obtained from radiative transfer calculations using the state variables. Differences between the measured radiances and those calculated from the guess profile are used to retrieve the corresponding differences in water vapor amount. To reduce sensitivity to noise, the retrieval algorithm uses a constraint to limit the ability of the retrieval to depart from the first guess, at the risk of biasing the retrieval toward the guess profile. Detailed specifics of the AIRS retrieval algorithm are given by *Susskind et al.* [2003].

2.3. Radiosonde Moisture Measurements

[11] Radiosondes provided by various manufacturers use different sensors and techniques to measure moisture. Since the GPS observations used for this study were available only over the continental United States (CONUS), the number of radiosonde varieties to be considered is less than would be required for a global investigation, but even so, current U.S. policy is to procure and use radiosondes from at least two vendors.

[12] In most modern radiosondes, the humidity sensor contains a capacitor containing a plastic element that absorbs or exudes water vapor until it comes to equilibrium with the water vapor in the surrounding air. Because the capacitance varies in a known way as the amount of water vapor contained by the plastic changes, the capacitance serves as the raw measurement from which the water vapor concentration is derived. However, a finite time is required for the water vapor in the plastic to come to equilibrium with the air, so the sensor is subject to a time lag that increases with cold temperatures. The time lag is most important for small-scale fluctuations. At high altitudes, the sensor is in a cold and dry environment, either of which can make the measurement difficult and add to any other errors. Our results, which are discussed later, show a dry bias for these radiosondes in the lower atmosphere when compared to AIRS retrievals. This bias decreases with height and may become a wet bias at the upper levels. Generally IPW is dominated by the lower atmosphere. Errors that affect the upper atmospheric water vapor measurement can be different from those that affect the lower atmospheric values and thus are not necessarily improved by application of a correction based on an IPW that is dominated by the lower atmosphere.

[13] The performance of Vaisala radiosondes is well characterized because of their use at Atmospheric Radiation Measurement (ARM) sites, where numerous other observations are taken simultaneously. A detailed account of the accomplishments of Intensive Water Vapor Observation Periods at ARM sites is given by *Revercomb et al.* [2003]. For the Vaisala sensors it has been found that gases from the packaging material are absorbed by the capacitor element and occupy some of the sites in the plastic that would otherwise be available to absorb water vapor molecules. This results in a dry bias of varying magnitude, because it depends on the time spent in the packaging and other factors [*Wang et al.*, 2002]. This bias can be reduced or eliminated entirely by heating the radiosonde prior to launch. Moreover, new packaging methods are now being used to reduce the effect. For the newer RS90 radiosondes, the error has been reduced [*Turner et al.*, 2003] but significant calibration issues remain. However, the contamination error and some of the other errors in humidity measurements can be reduced by adjusting individual radiosondes to an unbiased measurement, such as that provided by a collocated upward looking Microwave Water Vapor Radiometer (MWVR) or a ground based GPS IPW sensor. Several investigators have demonstrated the usefulness of scaling the individual radiosonde moisture profiles using MWVRs [e.g., *Revercomb et al.*, 2003; *Turner et al.*, 2003; *Ferrare et al.*, 2004; *Soden et al.*, 2004]. In this study we use the GPS derived IPW to scale the individual radiosonde profiles because of its much better spatial coverage.

[14] Another commonly used sensor for measuring water vapor on radiosondes is based on a carbon hygristor. In this device, water vapor changes the resistance of a carbon film and the resistance is measured and used to infer the water vapor amount. Although this type of sensor is not affected by packaging related contamination in the same way, it is subject to other sources of error, and shares the limited ability to respond rapidly to cold, dry conditions [*Jeannet et al.*, 2002]. Although it is being phased out, this type of sensor was widely used in the past.

[15] More recently, radiosonde sensors based on the use of a chilled mirror have been developed. These are used for special studies but not for routine observations, because they are significantly more expensive than the operational varieties. A limited number of moisture comparisons have been made between operational radiosondes and radiosondes using chilled mirrors [*Fujiwara et al.*, 2003; *Wang et al.*, 2003], but the recommended correction varies for each type of radiosonde.

[16] The present study is based on samples drawn from all of the operational radiosondes in the U.S. network. Both the published temperature corrections [*Wang et al.*, 2002] and the rescaling based on the ground based GPS IPW were applied separately and simultaneously in this AIRS validation study. The reliability of the GPS IPW for moisture comparisons has been well established [*Cucurull et al.*, 2000; *Ohtani and Naito*, 2000; *Kopken*, 2001; *Gendt et al.*, 2004].

3. Data Set Preparation and Analysis

[17] The analysis of the data is discussed in this section. The general procedure is to accumulate a subset of AIRS, radiosonde, and GPS water vapor observations that are closely matched in time and location during the period of investigation, which spanned 17 months, between April 2003 and October 2004. There are much larger samples of AIRS and GPS observations available, because the radiosonde launches are the rarest events. A comparison of these AIRS-GPS matches has been made and is discussed by *Rama Varma Raja et al.* [2007].

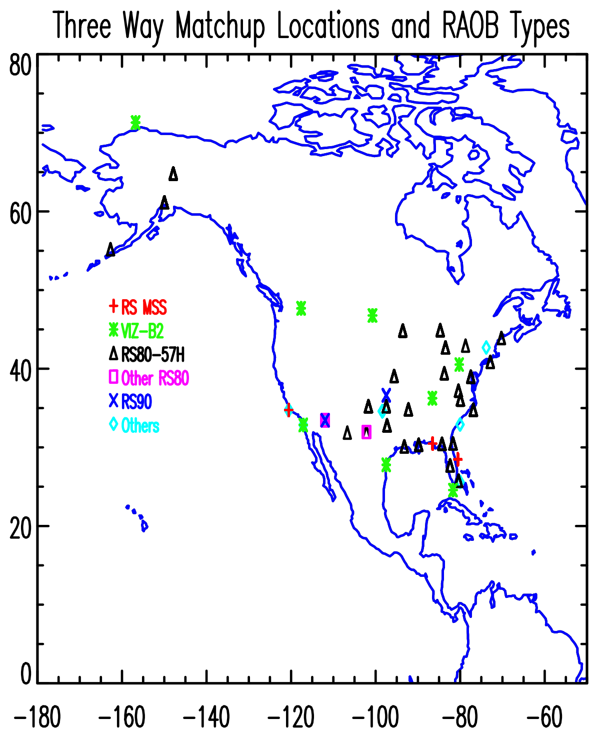

Figure 1. Locations of radiosonde stations that are collocated with a GPS site as well as with AIRS retrievals. The different symbols designate the various radiosonde types.

3.1. Procedure for IPW Comparisons

[18] AIRS and radiosondes provide vertical profiles of water vapor, but the ground-based GPS sensors provide only the total column water vapor which is commonly known as the Integrated Precipitable Water (IPW). Therefore, for the "three-way" comparisons, the radiosonde and AIRS water vapor profiles were converted to IPW to correspond to the GPS measurements. The data were screened using the following procedure.

[19] The quasi-continuous delivery of the GPS observations (one per station every 30 minutes) allows separate time matches to be made to both the AIRS and the radiosonde times, thereby minimizing the time differences. The AIRS and radiosondes observations are only approximately coincident in both time and space; otherwise the sample size would be zero. In practice the GPS data are time interpolated to the AIRS or radiosonde observation time. This yields two GPS observations for each radiosonde/AIRS match up. One is time interpolated to the AIRS value and will be referenced as the AGPS. The GPS observation interpolated to the radiosonde launch time is referred to as RGPS. The corresponding interpolated values were then matched to the appropriate instrument. When a radiosonde moisture profile is adjusted by first using the RGPS and then using the difference between the AGPS and the RGPS to account for the change in moisture which occurred over that time span, the result is identical to that obtained using the AGPS alone to adjust the radiosonde. This is true because the adjustments are linear and the result of applying them in sequence is simply their sum. The effect of the time adjustment is small, but predominately positive.

[20] When the RAOB is matched to AIRS, a time window of ±3 hours and a distance window of 200 km are used. Although the AIRS quality control procedures are now mature and stable [*Susskind et al.*, 2006], they remained in development and subject to frequent changes when the data produced for the current study were delivered. Therefore the following procedure was applied to assure that valid AIRS soundings were used for comparison to the other data. Of the 9 AIRS moisture soundings used for a single retrieval, the 3 closest within the match window were selected. Any of these soundings that did not pass the AIRS quality control were then rejected. Finally, if more than one sounding remained, that with the best temperature match with the RAOB was picked. The best temperature match was determined by calculating the RMS differences at all levels, summing, and selecting the sounding with the smallest value. This screening technique cannot be applied globally for validation purposes, but it does permit the potential accuracy of the AIRS water vapor retrievals to be assessed even before the quality control process was stabilized, after which the true AIRS accuracy can be assessed. Valid moisture values from all three instruments must exist for a match to be included in the comparison data set. AIRS retrievals were limited to those assigned a temperature profile quality flag of zero from the AIRS retrieval version 4.0.9, indicating highest confidence in the accuracy of the temperature profile retrieval [*Susskind et al.*, 2006]. Both the middle troposphere and lower troposphere temperature profile quality flags were considered.

[21] It was discovered that a few GPS locations produced unusually noisy comparisons. The source of the noise appears to be geographic effects that made the stations' observations unrepresentative of the area around them. These stations were either located near mountains, where the differences in surface height between the GPS and the AIRS values can prevent good agreement, or near moist coasts where large fluctuations in moisture often occur over small distances and small time intervals. However, not all coastal stations were excluded; those for which the comparisons did not appear noisy were retained. The three hour time window can result in significant difference in atmospheric moisture in an area where a land or sea breeze develops routinely. Establishing the underlying cause of the anomalous behavior of GPS IPW soundings from these stations is an interesting investigation in its own right. For the time being they have simply been excluded from the comparisons presented in this paper.

[22] Figure 1 shows the locations of the RAOB stations used for this study. Each of the stations used is marked with the corresponding radiosonde type. For the match of the GPS to the radiosondes, GPS observations that are within 50 km of the radiosonde site are used.

3.2. Radiosonde Quality Checks

[23] For a radiosonde report to be used to calculate the total precipitable water, it had to pass a number of quality checks. These are as follows: (1) The first water vapor report must occur within 20 m from ground. (2) The last water vapor report must reach the 350 mbar level or higher. (3) The largest gap between adjacent water vapor levels

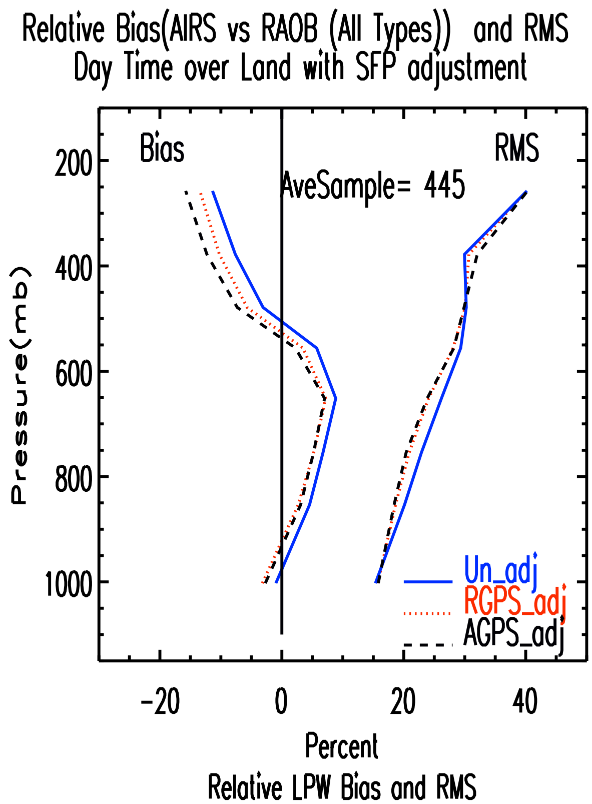

Figure 2. AIRS versus radiosonde observations (RAOB) bias and RMS differences for coincident pairs during day time over land. The midlayer AIRS quality flag was used. All types of RAOB were used to form the coincident pairs in this case. The blue curves show the differences obtained using unadjusted radiosondes. The black curves represent the differences when radiosondes are adjusted using GPS and the time-interpolated to match AIRS. The red curves show the differences when only the GPS adjustment is applied. The legend "AGPS_adj" indicates that the GPS used for adjusting the RAOB is temporally close to AIRS observations while the legend "RGPS_adj" indicates that the GPS used for adjustment is temporally close to RAOB. The legend "AveSample" inside indicates the typical sample size used for generating the differences. See text for details.

must be less than 200 mbar. (4) There must be at least five valid water vapor reports and no more than two reports that are not valid between the ground and the 300 mbar level.

3.3. AIRS Quality Checks

[24] The current version of the AIRS retrieval algorithm has several quality checks as described by *Susskind et al.* [2006]. When the data used in this study were processed, two quality checks were available on the basis of temperature profile estimates. One is a low troposphere temperature quality estimate and the other is a midlevel quality estimate. Since cloud clearing is one of the major sources of error, the low-level test should be the more restrictive and provide better accuracy. Its disadvantage is that the yield in terms of the number of retrievals is too low for many uses.

3.4. GPS Radiosonde Adjustment Procedure

[25] The radiosonde bias adjustment is similar to the one used by investigators in the past, for example, *Turner et al.* [2003], *Revercomb et al.* [2003], and *Ferrare et al.* [2004]. The difference in the current study is that the adjustment is based on a GPS measure of IPW rather than a Microwave Water Vapor Radiometer (MWVR) measurement. The procedure is to take the ratio of the GPS IPW divided by the radiosonde IPW and multiply all the layer amounts by this ratio. The advantage of the GPS over the MWVR is that the equipment is less expensive and therefore more widely available from an extensive operational network, while the number of microwave sites is limited.

4. Comparisons, Results, and Discussion

[26] Statistical comparisons of AIRS LPW to raw and GPS-adjusted radiosonde LPW are presented as functions of pressure (height) level in Figures 2–19. Each comparison is characterized by selection factors including radiosonde type, day/night occurrence, surface type (land or sea), and AIRS quality control requirement. These factors are summarized in Table 1, which also indicates the sample size for each case. The sample size is in fact an average over all levels rounded to a whole number. For most radiosondes, the sample size is the same for all levels, but some have fewer samples at the higher levels because some radiosondes fail before they reach the highest levels.

[27] Initial comparisons have been made using AIRS data that passed the less restrictive midlevel temperature quality control criterion. Differences between AIRS data that have

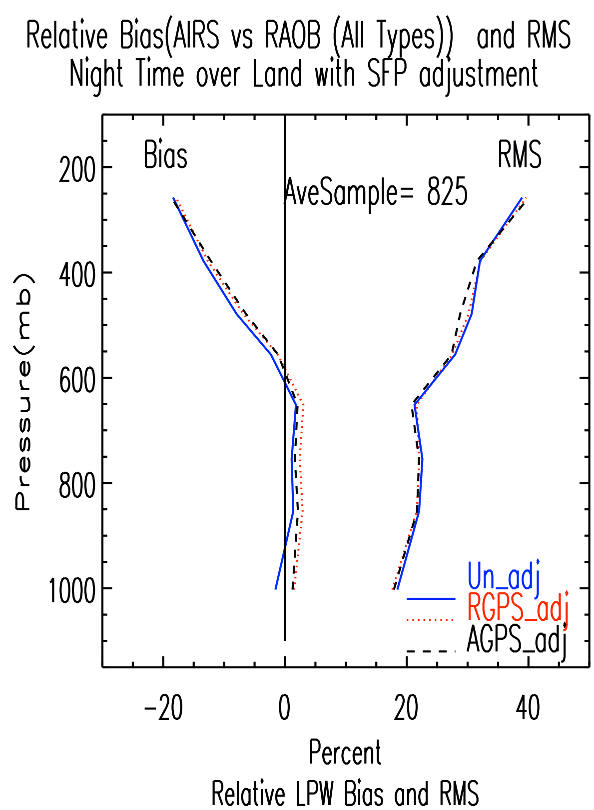

Figure 3. Same as in Figure 2 but for night.

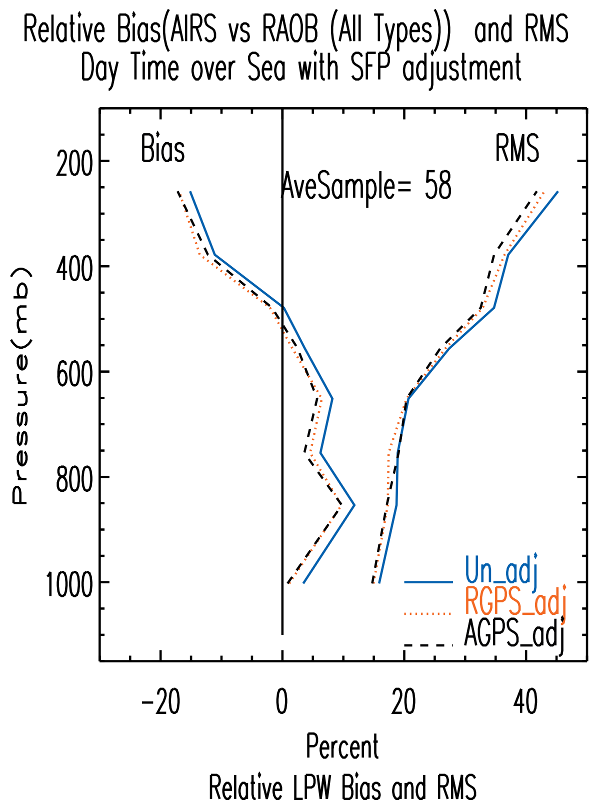

Figure 4. Same as in Figure 2 but for pairs over sea during day.

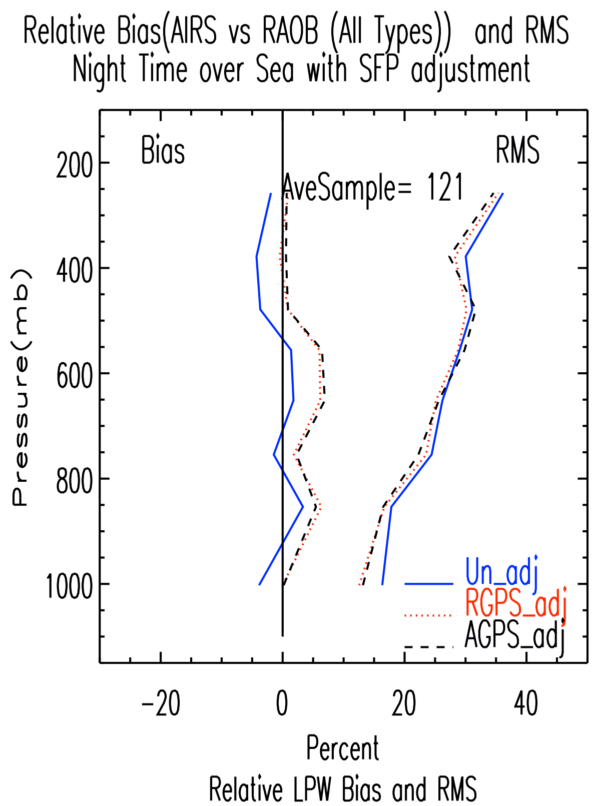

Figure 5. Same as in Figure 2 but for pairs at night over sea.

passed this test and radiosonde data are shown in Figures 2–5, corresponding to daytime land, nighttime land, daytime sea, and nighttime sea soundings, respectively. In each figure six lines are shown, 3 for bias and 3 for RMS differences. The solid blue lines show the differences calculated with respect to the original radiosonde data. The red lines are calculated using the RGPS-adjusted radiosondes, and the black lines are based on the AGPS radiosondes. Since the objective is to compare the adjusted radiosondes to AIRS, the AGPS curves are of particular interest. The retrievals are calculated in absolute water vapor amounts, but soundings over land are drier on the average than soundings over or near the sea. For this reason the results are expressed as percentages, calculated as the standard deviation of the amounts divided by the average amount. This definition retains more of a relationship between the size of the error and the average water vapor amount than a standard deviation of the percentages would. At the same time, it limits large apparent errors when the denominator (average amount) becomes very small.

[28] Operational radiosondes launched twice daily from each CONUS location distribute observations evenly across extended temporal periods. Thus the April 2003 to October 2004 period considered here samples two entire moist summers but only a single complete winter dry season. The intercomparison results presented in this section are effectively biased to moist atmospheres and seasons, for which there is particular benefit to be derived from gaining understanding of and confidence in the satellite moisture soundings.

[29] Comparing Figures 2 and 3, the main differences between day and nighttime performance are the changes in

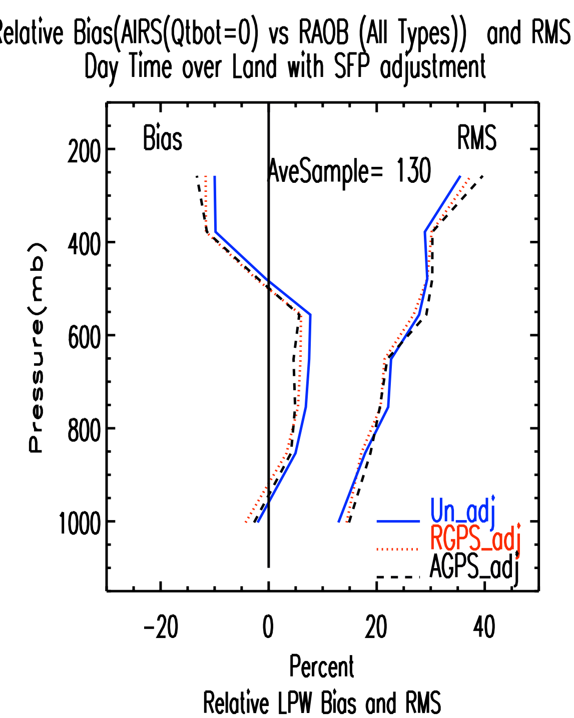

Figure 6. Same as in Figure 2 but applying the AIRS low-level quality control flag.

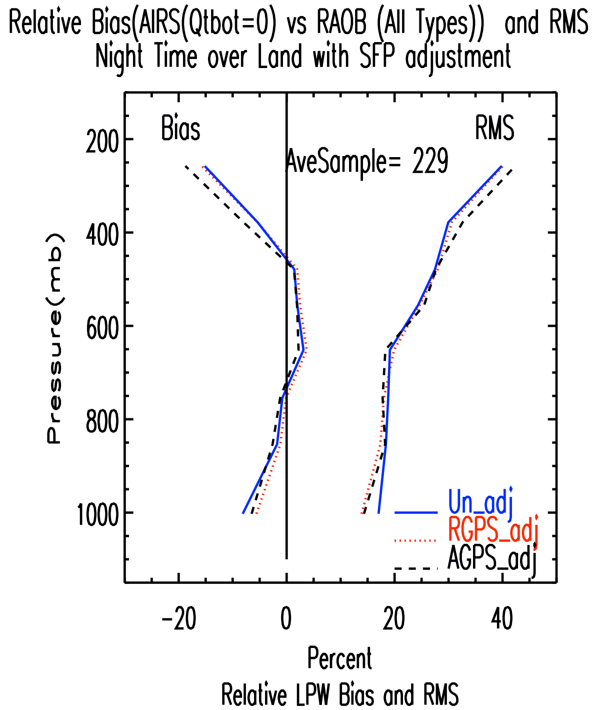

Figure 7. Same as in Figure 2 but for night and applying the AIRS low-level quality control flag.

the bias and the root-mean-square (rms) at the lower levels. During the day (Figure 2) the GPS adjustment moves the black curve to the left of the blue one. This means that the radiosonde was dry at day time and the adjustment makes it wetter. The change in the bias is about 3% and the change in the RMS is about 2.5%. In contrast, Figure 3 shows the black curve move to the right of the blue one, making the radiosonde drier relative to the original one. The changes at night are smaller, 1% or less. In fact the black curves are almost in the same position day and night, while the blue curves (showing the AIRS bias to unadjusted radiosonde water) shift. In both day and night cases, the GPS adjustment increased the agreement between RAOB and AIRS water vapor for most layers.

[30] Figures 4 and 5 present similar comparisons made over sea, including all radiosondes for day and night, respectively. The results are similar to those over land. The same day-to-night difference appears and the same increase in accuracy due to the correction near the surface. The shift is larger at night, nearing 5%.

[31] Figures 6–19 show more of the relative moisture differences between the AIRS and the three (one unadjusted and two GPS-adjusted) radiosonde values. Figures 6 and 7 show the results for all radiosonde types over land for day and night, respectively, but using only AIRS data that pass the low-level temperature quality control test. Compared with Figures 2 and 3, the RMS values in the lower layers are smaller because of the more restrictive quality control. The same day night shift in the bias is observed with the radiosonde being drier during the day. The RMS values

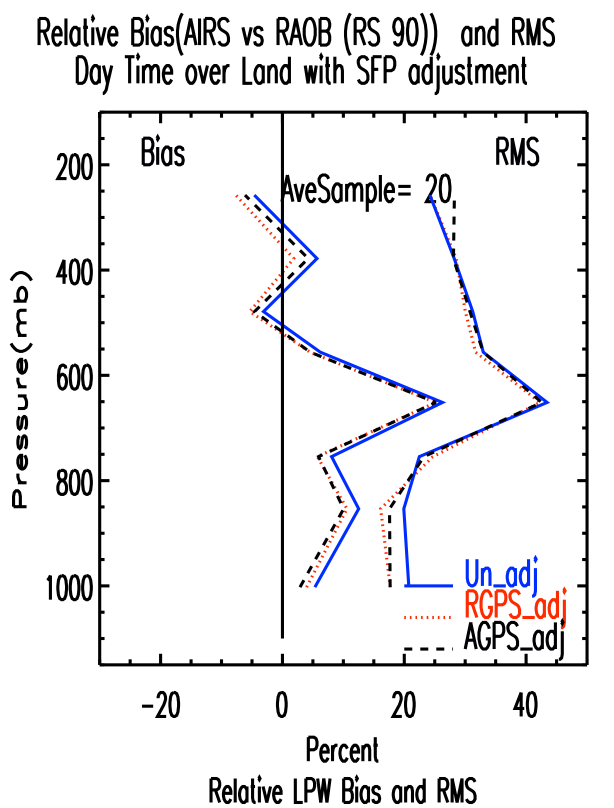

Figure 8. Same as in Figure 2 but including only Vaisala RS 90 type sondes, during the day, over land, and applying the AIRS midlevel temperature quality control flag.

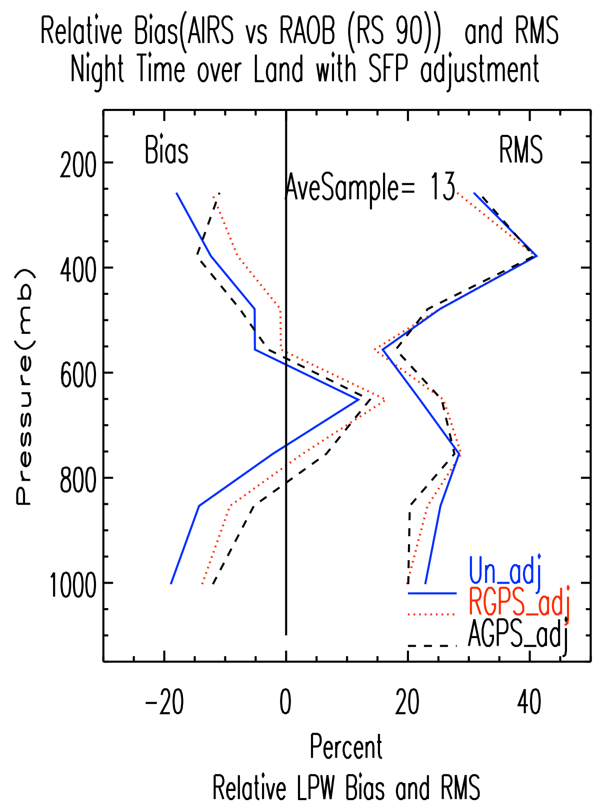

Figure 9. Same as in Figure 8 but for nighttime.

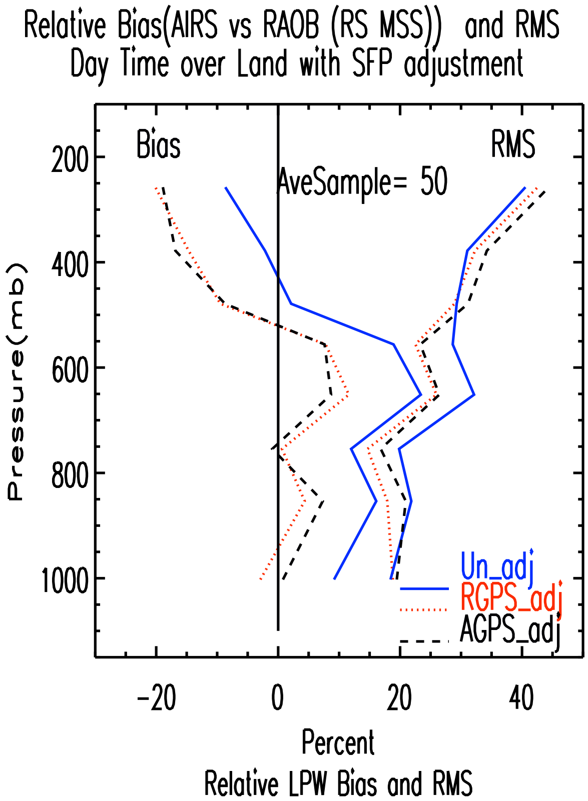

Figure 10. Same as in Figure 8 but including only the MSS radiosondes.

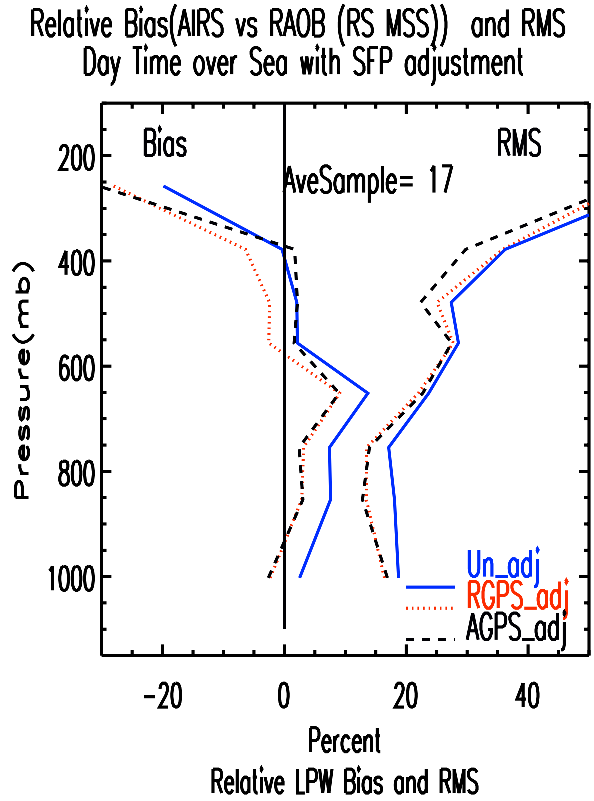

Figure 12. Same as in Figure 8 but including only MSS radiosondes, during day time over sea.

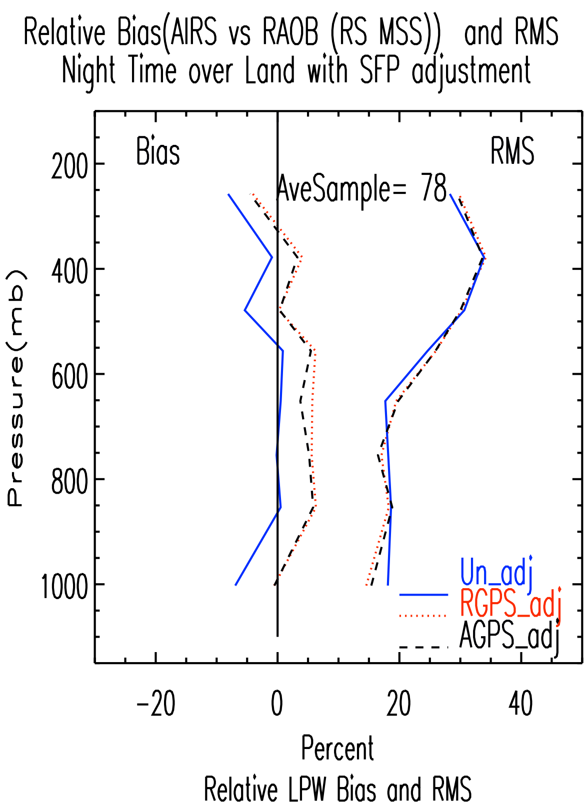

Figure 11. Same as in Figure 10 but for nighttime.

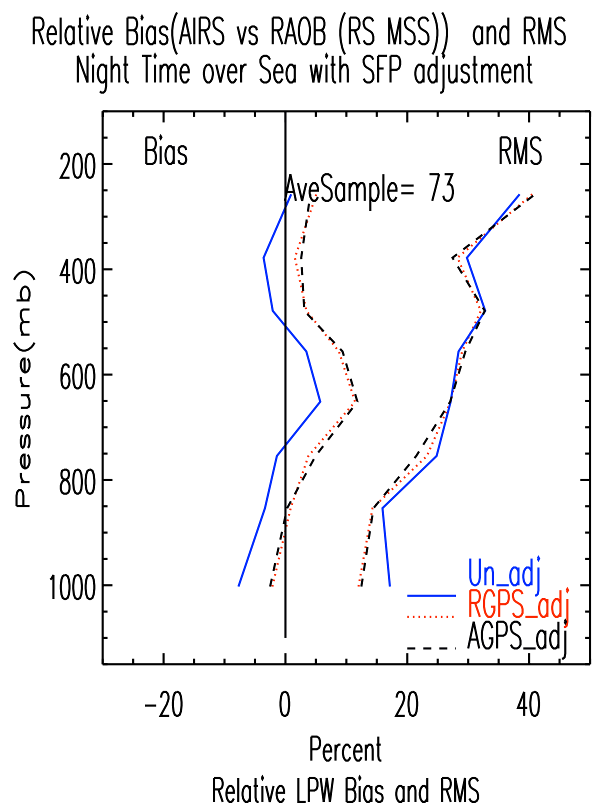

Figure 13. Same as in Figure 12 but for nighttime.

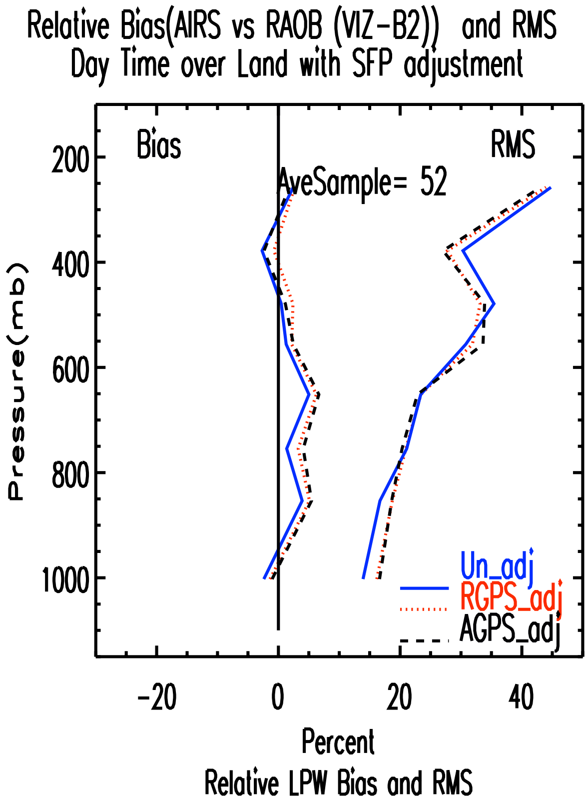

Figure 14. Same as in Figure 8 but including only the VIZ-B2 radiosondes during day over land.

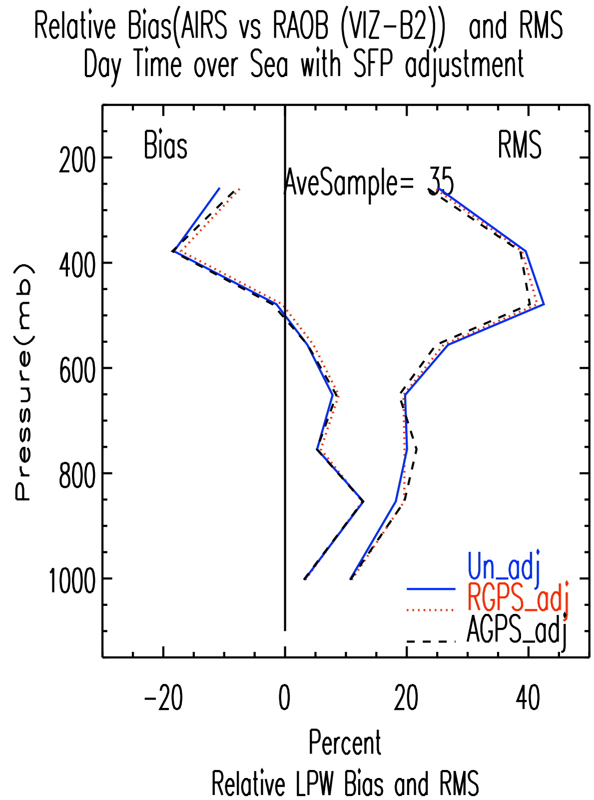

Figure 16. Same as in Figure 14 but for day time over sea.

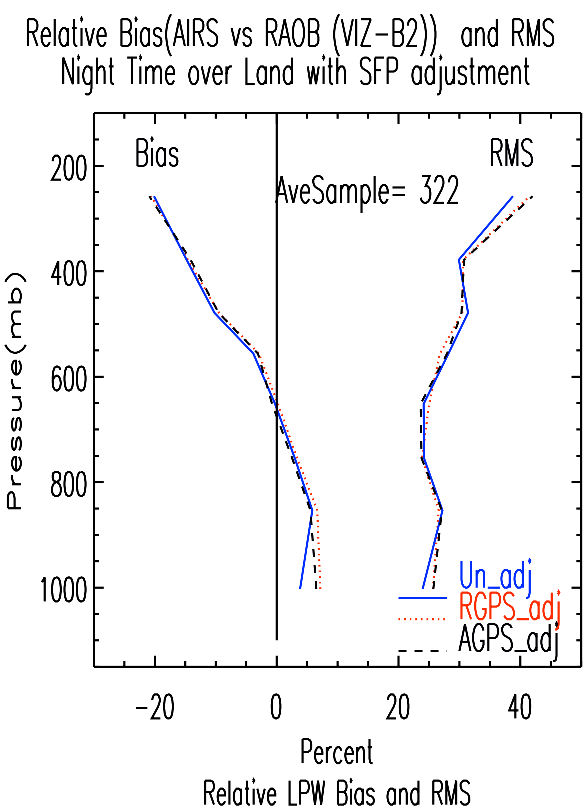

Figure 15. Same as in Figure 14 but for night.

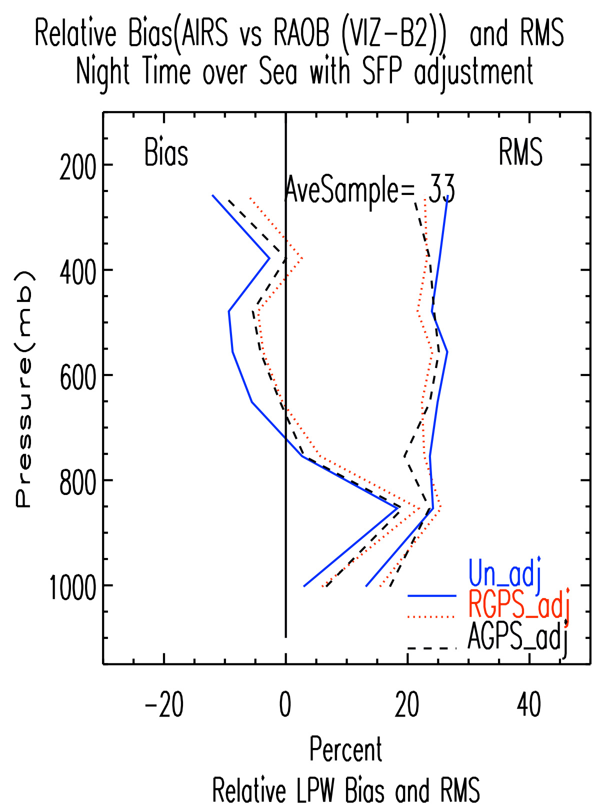

Figure 17. Same as in Figure 14 but for nighttime over sea.

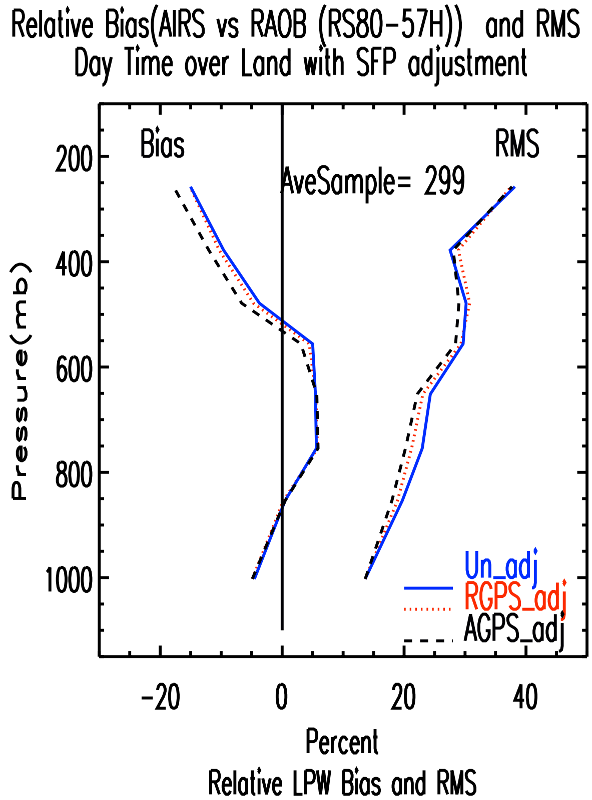

Figure 18. Same as in Figure 8 but including only RS 80-57H radiosondes during day time over land.

show significant improvement for the lower levels at night. No results are shown for all radiosonde types over sea using the "bottom" quality control test because the sample proved too small for both day and night.

[32] The remaining figures present similar statistics of AIRS and radiosonde moisture differences, for day and night over first land and then sea. However, each of these is for an individual radiosonde type while the previous results have been for combined cases.

[33] Figures 8 and 9 are for day and night, respectively, over land, and including the Vaisala RS 90 sondes. Again, a day-to-night shift in the bias is observed, with the radiosonde being relatively drier during the day. In this case, the GPS adjustment improves the relative accuracy for both day and night cases near the surface by as much as 4% to 5%.

[34] Figures 10 and 11 include the MSS radiosondes over land for day and night, respectively. As for the RS 90 sondes, there is a bias change with the day radiosonde being drier than night. However, the change is much larger, approaching 20% in the midlayers. The RMS shows the usual improvement near the surface for the adjustment at night and also shows the improvement during day time. The total day-to-night shift is larger being 15%, with 10% during daylight and 5% at night.

[35] Figures 12 and 13 are for the MSS over sea. The day-to-night bias is observed, but the magnitude is decreased. The RMS shows a significant increase in accuracy near the surface at day and night. The day-to-night shift is slightly smaller, ~12–13%

[36] Figures 14 and 15 are for VIZ-B2 radiosondes over land, and Figures 16 and 17 are for the same instrument over the sea. All results show the GPS adjustment having a relatively minor effect. The case that shows the most change is nighttime over sea. This shows the radiosonde as being slightly wet relative to the GPS, but a constant bias is more noticeable than a day-to-night shift. Comparison of Figures 14–17 to Figures 8–13 shows the VIS-BZ to have overall errors as large or larger than those of the other radiosonde types, consistent with other studies [*Ferrare et al.*, 2004]. Apparently the VIZ-B2 errors are not as readily correctible by the GPS scaling approach. This sensor also shows a negligible day-to-night bias.

[37] Figures 18 and 19 are for the RS80-57H. For this instrument there is a small (2–3%) day-to-night change in the bias. The GPS makes a small improvement in the RMS, mostly in the middle troposphere. At night, the GPS adjustment makes the agreement worse above 400 mbar, but not during the day.

[38] Figure 20 shows the results of a comparison of the temperature based adjustments made by *Wang et al.* [2002] with the GPS adjustments. The temperature based adjustments had a relatively small effect on the mean and RMS values. The GPS adjustment had a significant effect on both the mean and the RMS in the 900 mbar region.

[39] Some of the published corrections are not applicable to routine radiosonde reports because they depend on access to the high-resolution radiosonde reports that are sent to National Climatic Data Center (NCDC), Asheville, NC, USA, but not distributed to the forecast centers. The time

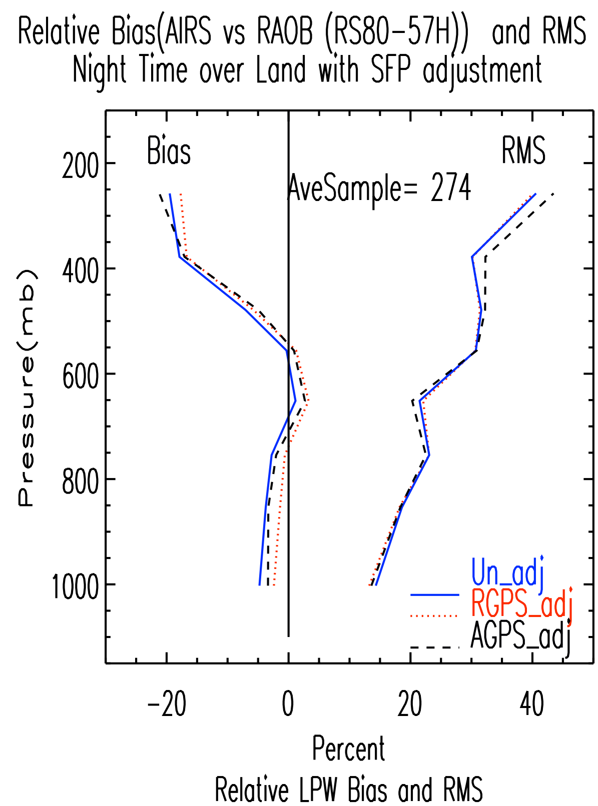

Figure 19. Same as in Figure 18 but for nighttime over land.

Table 1. Radiosonde Types, AIRS or Radiosonde Observational Timings, AIRS Data Retrieval Location Surface Type, AIRS Data Quality Control Test Applied, and the Sample Size Used in the Investigations for Results Presented in Figures 2–19[a]

Figure	Radiosonde Type	Time (Day or Night)	Surface Type (Land or Sea)	Quality Control Test (Midlayer or Bottom Layer)	Sample Size
2	all types	day	land	midlayer	445
3	all types	night	land	midlayer	825
4	all types	day	sea	midlayer	58
5	all types	night	sea	midlayer	121
6	all types	day	land	bottom layer	130
7	all types	night	land	bottom layer	229
8	Vaisala RS 90	day	land	midlayer	20
9	Vaisala RS 90	night	land	midlayer	13
10	MSS	day	land	midlayer	50
11	MSS	night	land	midlayer	78
12	MSS	day	sea	midlayer	17
13	MSS	night	sea	midlayer	73
14	VIZ-B2	day	land	midlayer	52
15	VIZ-B2	night	land	midlayer	322
16	VIZ-B2	day	sea	midlayer	35
17	VIZ-B2	night	sea	midlayer	33
18	Vaisala RS80-57H	day	land	midlayer	299
19	Vaisala RS80-57H	night	land	midlayer	274

[a]See text for specific details.

lag correction developed by *Miloshevich et al.* [2001, 2003, 2004] is one such example. The other limitation on the corrections occurs because only one adjustment to the entire profile based on IPW can be made. One can make a succession of such changes, but each one simply cancels the effect of the previous one or ones and substitutes itself. The last one applied is the only one that has any effect on the final result. When we make an adjustment to match the GPS, any previous adjustments effectively are removed and become irrelevant.

5. Summary and Conclusions

[40] We have performed studies to support the validation of AIRS moisture profiles. Our approach was based on use of the operational radiosonde data, since these reports are by far the largest data set that is available for AIRS validation and have the advantage of being routinely available over a long time period. Some special validation measurements are expected to be more accurate, and the ARM site data have the advantage of being accurate and routinely made, but the small number of these sites limits the sample size that can be achieved. We have developed and evaluated a procedure for improving the accuracy of the water vapor profiles reported by operational radiosondes by scaling them to match GPS IPW. Both the adjusted and unadjusted radiosonde water vapor profiles were then compared to the AIRS values. The GPS-adjusted radiosondes produced the closer agreement with the AIRS values. Since the adjustment procedures and the AIRS retrieval procedures are entirely independent, we were justified in using the adjusted values to evaluate the AIRS accuracy. The better agreement with the AIRS data provided a measure of confirmation that the adjustment procedure is valid, and it is recommended that the adjustment to the radiosonde moisture be used in any application where accuracy is a consideration. We also used the radiosonde temperature data to help provide quality control of the AIRS data and remove outliers. Since this screen depends on the presence of a radiosonde, our results validate the AIRS water vapor retrieval algorithm, but not the AIRS quality control procedures. A repeat of this study without the radiosonde temperature screening is desirable once the AIRS quality control is fully developed and stable.

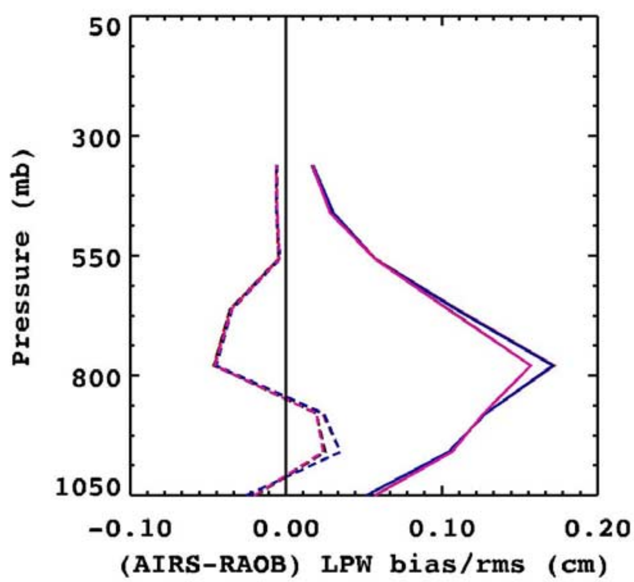

Figure 20. Mean and root mean square differences between AIRS and Vaisala RS 57H Type Radiosonde (RAOB) Layered Precipitable Water (LPW): with uncorrected RAOB (red curves), with *Wang et al.*'s [2002] temperature correction to the RAOB (blue curves) that almost obscures the red curves, with only GPS IPW adjustment to the RAOB (black curves) and with *Wang et al.*'s [2002] temperature correction followed by a GPS adjustment to the RAOB (purple curves) which again almost totally obscures the black curve. The period of observations used in this comparison is September to December 2002.

[41] Analysis of the results revealed several features of interest. These include the difference over land and sea, the day-to-night differences observed for some radiosonde types, the differences based on the AIRS quality control flag chosen, and the differences noticed for each radiosonde type. Because we used only the GPS data available over the United States as the basis for adjusting the radiosonde observations, our results are limited to radiosonde types that are used by the United States. This is an important consideration for the United States, which has a policy of using more than one radiosonde type at one time, and has periodically changed manufacturers. A GPS IPW sensor collocated at each radiosonde site would provide continuity for a data record and allow station and type adjustments to be made and render observations from the various radiosonde types compatible at any given time. Such a program would make a valuable contribution to the network. Although there are regions where the use of the GPS had no effect or made things worse for specific layers in specific cases, the overall effect is that the adjustment is beneficial. The overall agreement between the AIRS and radiosonde LPW observations, particularly when the radiosonde profiles have been rescaled using the GPS IPW, indicates that AIRS is performing very well as a water vapor sounder, consistent with the results published by *Tobin et al.* [2006] and *Divakarla et al.* [2006].

[42] In our comparisons we observed day-to-night biases in the radiosondes. The magnitude varied by type, being the largest for the MSS radiosonde and the smallest for the VIZ. The tendency of the bias was for radiosondes to be drier during the daytime relative to the GPS and AIRS. This suggests that some of the radiosondes are subject to heating effects during daylight. In principle, our GPS-based adjustment technique is capable of determining any day-to-night sensitivity that may exist in present or future radiosonde types. This has implications beyond the United States, since, for example, the Vaisala radiosondes for which a day-to-night bias was detected are being used increasingly in the global network.

[43] Examination of absolute differences (between AIRS and radiosondes) in humidity shows that these differences are smaller over sea than over land. This agrees with the expectation that the AIRS retrievals should be more accurate over water because the high surface reflectivity enhances the sensitivity of the microwave channels to changes in moisture. Coastal radiosonde stations, of course, are actually located on land while a satellite ocean observation must extend far enough over the ocean so that the AMSU FOV is completely over water. This systematically produces a larger collocation error for the sea cases. The ability of these procedures to detect and quantify effects such as the land sea bias for operational radiosondes could be used to improve both forecast accuracy and climate studies that are based on these radiosondes.

[44] The largest effect caused by the different quality control procedures is the sample size. Differences in accuracy are minor but this is partially due to the fact that we screened both for outliers using the AIRS temperature retrievals. There is an improvement (decrease) in the RMS difference near the surface at night. The number of soundings that pass the QC check on the bottom layer is only about $\frac{1}{4}$ of the ones that pass the midlayer check.

[45] Finally, we compared the effect of the GPS IPW correction to radiosonde moisture to that of published radiosonde corrections. Most of the latter are for the Vaisala radiosondes because of their widespread use, and in particular their use at the heavily instrumented ARM sites. Some of these corrections were not useful for our study because they require the 6 s data that are not available in the form used to report radiosonde information to numerical weather prediction centers. The one correction that was applicable was the temperature correction by *Wang et al.* [2002]. We compared this to the GPS adjustment, and found that the temperature correction produced a comparatively small effect.

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