1.3 Validation of AIRS Moisture Products Using Three-way Intercomparisons with Radiosondes and GPS Sensors

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1. INTRODUCTION

As technology advances, new ways of making measurements are developed and made cheaper, and it becomes feasible to make correlative measurements of the same atmospheric properties using multiple independent approaches. In the case of moisture, the availability of observations from conventional radiosondes, surface-based Global Positioning System (GPS) sensors, and the satellite-borne Atmospheric Infrared Sounder (AIRS) instrument suite make possible 3-way comparisons of precipitable water, which permit the AIRS moisture retrievals to be validated more rapidly and confidently than otherwise. For example, it has been noted that certain types of radiosondes exhibit a dry bias due to contamination by the packaging material in which they are stored. The dry tendency increases with time spent in the shipping container, and therefore varies from one radiosonde to another (Turner et al. 2003). Their experience with observations from the Atmospheric Radiation Measurement (ARM) sites has shown that this bias can be removed effectively by adjusting the radiosonde moisture profile to make the total precipitable water agree with an independent value obtained from an upward looking microwave water vapor radiometers (WVRs). Unfortunately, these sensors are few in number so this technique rarely can be applied in practice.

On the other hand, the more widely available surface-based GPS Integrated Precipitable Water (IPW) measurements have many of the same desirable characteristics as WVRs, including accuracy, precision, and temporal resolution. In addition, they are available for areas experiencing heavy precipitation. Of particular interest for this study are a number of sites where the GPS instruments are deployed in close proximity to a conventional radiosonde launching facility. At these locations, 3-way matches between radiosonde, GPS, and AIRS IPW measurements are possible when a satellite overpass occurs. Also, the adjustment technique established using upward-looking microwave measurements can be adopted by substituting the GPS IPW as value used to constrain for correctively scaling the radiosonde profile.

This paper summarizes three-way moisture intercomparisons performed as part of the AIRS validation project, which has been described by Fetzer et al. (2003). The three instruments, measurement principles, and retrieval procedures are outlined in Section 2. A description of the data set and the specific procedures for comparing corresponding IPW measurements and adjusting and comparing AIRS and adjusted radiosonde moisture profiles is presented in Section 3. The results are presented and discussed in Section 4, and conclusions and summary recommendations are in Section 5.

2. Instrument Descriptions

Each of the three sensors used for this study employs a unique measurement principle and sampling procedure. To enable comparisons of the independent water vapor estimates to be understood and interpreted with confidence, brief descriptions of each instrument and corresponding retrieval methodology are provided in the following sub-sections.

2.1 GPS IPW

GPS receivers at fixed positions on the earth’s surface are used to derive IPW based on measurements of the time delay on the arrival of GPS signals imposed by the presence of water vapor in the vertical column at zenith. The technique is described in detail by Wolfe and Gutman (2000) and by Gutman et al. (2003). In practice, the delay is measured at multiple orientations, mapped to zenith, and averaged over appropriate time intervals, typically 30 min. The zenith time delay consists of three contributions, an ionospheric component, a dry atmospheric component, and finally one that depends on the amount of water vapor in the path. Because GPS uses two distinct L-band frequencies for which the dispersion relation is known, the ionospheric delay component is readily determined and removed from the total. Knowledge of the surface pressure and temperature, along with the assumption that the atmosphere is hydrostatic, permit the portion of the delay attributable to the dry atmosphere to also be determined and subtracted. The residual time delay is directly proportional to the column IPW.

2.2 Derivation of moisture products from AIRS

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 The AIRS Instrument

AIRS may be regarded as the primary sensor on the Aqua spacecraft (Parkinson 2003), which was launched on May 4, 2002 as part of NASA's Earth Observing System (EOS). The AIRS (Hartmut et al. 2003) is a high spectral resolution infrared (IR) instrument that provides a much better vertical resolution than earlier satellite sounders. The AIRS is a scanning instrument with 90 spots per scan line. It is arranged so that the width of 3 AIRS Field-of-Views (FOV's) fit in the width of one AMSU FOV and 3 AIRS scan lines fit in one AMSU scan line. This gives 9 AIRS FOV's covering one AMSU 40 km FOV. The spectral resolution ($\lambda / \Delta\lambda$) was set to a nominal value of (1200), a value that allows individual absorption lines of the (bulk and trace) molecular constituents of the atmosphere to be resolved. Once the spectral lines are resolved, higher spectral resolution provides little additional information for sounding temperature, moisture, or trace gases. At the same time, higher spectral resolution decreases the energy and the resulting signal to noise ratio. For these reasons, resolving the spectral lines is desirable, but going beyond this point is not. Thus the large number (2378) of AIRS channels exceeds what is needed for sounding, but overall the AIRS represents a near optimal trade between signal to noise ratio and maximum vertical resolution, and is a significant improvement over earlier sounders such as the High-resolution InfraRed Sounder (HIRS), which is lower in terms of both vertical and spectral resolution than AIRS, despite its name.

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 so-called AIRS soundings in fact are made with the help of measurements from the microwave sensors. For this study, the soundings are made with help of the AMSU only because the HSB failed after a short time in orbit. The microwave observations are used to drive a cloud clearing algorithm (Susskind et al. 2003) that is based on earlier 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 sub-section.

2.2.2 The AIRS Retrieval Algorithm

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 both the profile state variables are known, and the corresponding radiances in the water vapor absorption regions are obtained from radiative transfer calculations. Differences between the measured radiances and those calculated from the guess profile are used to retrieve the corresponding differences in water vapor amount.

To limit the sensitivity to noise, many IR retrieval algorithms use a constraint to limit the ability of the retrieval to depart from the guess. This produces retrievals that are biased toward the guess profile. A sensor with a small number of channels and a limited vertical resolution needs a relatively strong constraint, and the effect of the guess on the retrieval can be large. For a high resolution instrument such as AIRS, the need to constrain the solution is minimized but not totally eliminated, and the guess still affects the final solution to a small extent. Detailed specifics of the AIRS retrieval algorithm can be found in Susskind et al., (2003).

2.3 Radiosonde moisture measurements

Radiosondes provided by various manufacturers use different 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.

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 interval 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 by itself, tends to make these instruments report too much water vapor for higher altitudes, which are relatively cold and dry. This can be counteracted by other effects which can make it too dry, and this is usually the case. Of course if they have an overall dry bias due to packaging, they may be just less dry biased in the upper atmosphere and not actually too wet. In any case our results, which are discussed later, show, compared to AIRS, a dry bias in the lower atmosphere that decreases with height and may become a wet bias at the upper levels.

The performance of Vaisala radiosondes is ell characterized due to their use at Atmospheric Radiation Measurement (ARM) sites, where numerous other observations are taken simultaneously. 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. This bias can be reduced or eliminated entirely by heating the radiosonde prior to launch. Moreover, more inert packaging methods are now being used. For the newer RS90 radiosondes, the error has been reduced (Turner et al., 2003) but significant calibration issues remain. However, these can be reduced by adjusting individual radiosondes to an unbiased measurement, such as that provided by a collocated WVR or GPS IPW sensor.

Another commonly used in situ sensor for measuring water vapor is based on a carbon hygristor. In this device, variable water vapor changes the resistance of a carbon film. Although this type of sensor is not affected by packing 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).

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 number of moisture comparisons have been made between operational radiosondes, chilled mirrors, and radiosondes, but the recommended correction varies for each. The present study is based on samples drawn from all of the operational radiosondes in the U.S. network. In order to treat all of them the same, corrections were limited to the application of collocated GPS IPW to adjust the total moisture for the radiosonde. We are considering using some of the other corrections for a follow on study.

3. Data Set Preparation and Analysis

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 discussed in this section. The general procedure is to accumulate a subset of AIRS, radiosonde, and GPS water vapor observations that are nearly matched in time and location during the period of investigation, which spanned 4 months, September through December, 2002. The resulting set of 137 corresponding moisture observations was examined statistically. We note that there is a much larger sample of AIRS and GPS observations available, because the radiosondes are the rarest events. A comparison of these matches is discussed in a companion paper (Rama Varma Raja et al., 2004).

3.1 Procedure for IPW comparisons

AIRS and radiosondes provide vertical profiles of water vapor, but the GPS sensors offer only the total column water vapor. 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.

The quasi-continuous delivery of the GPS observations (1/station every 30 minutes) allows separate time matches to be made to both the AIRS and the radiosonde times, thereby correcting for the time difference. In each case, the GPS observations were interpolated to the time of the other observation (AIRS or radiosonde) and the corresponding interpolated values were then matched to the appropriate instrument. It should be noted that when both times are matched and the difference in moisture due to the time difference is added to the radiosonde moisture value, the result is the same as would be obtained by using the AIRS time for the GPS that is matched to the radiosonde, since both are linear effects that are added.

When the GPS is matched to AIRS, a time window of +/- 3 hours and a distance window of 200 km is used. Each nominal AIRS retrieval has 9 separate retrievals, one for each of the AIRS locations that covers the AMSU footprint. The AIRS retrieval with the best temperature match with the RAOB is selected. The best temperature match is determined by calculating the rms error over all levels, then selecting the sounding with the smallest value. Valid moisture values from all three instruments must exist for a valid match to be made. AIRS retrievals are limited to those that have a retrieval type of zero from the AIRS retrieval version 3.0.8. to indicate soundings with the best retrieval quality. At the time of this comparison, these high quality retrievals were being produced only over ocean areas so the data set contains only coastal radiosonde

stations. When new retrieval algorithms become available, these matched data are reprocessed . The ocean limitation is temporary and we plan to redo this study as data from new algorithms become available.

It was discovered that a few GPS locations produced unusually noisy comparisons. These stations appear to be “bad” for this purpose because of geographic effects that made the stations unrepresentative of the area around them that was measured by the other sensors. These stations were either located near mountains, where the differences in surface height can prevent good agreement with the AIRS measurements, or near moist coasts where there are large fluctuations in moisture over small distances and small time intervals. Although the reasons just stated are strong suspects, at this time, the exact cause is not known. For this study, these stations were identified and deleted from the sample. Figure 1 shows the locations of the GPS stations used for this study. It turned out that only one of the “noisy” stations also had AIRS matches. This station is denoted by the red X. There were some other stations that were not used because no matches with the AIRS observations were obtained. These stations are shown without a radiosonde indication. All the stations used are marked with the corresponding radiosonde type. For the match of the GPS to the radiosondes, GPS observations that are within 50 kilometers of the radiosonde site are used. The 5 GPS observations closest in time are saved on the match up file to be used for the time interpolation.

3.1.1 Radiosonde quality checks

For a radiosonde report to be used to calculate the total precipitable water, it had to pass a number of quality checks. These are:

1. The first water vapor report must occur within 20 meters from ground.
2. The last water vapor report must reach the 350 mb level or higher.
3. The largest gap between adjacent

water vapor levels must be less than 200mb

4. There must be at least 5 valid water vapor reports and no more than 2 reports that are not valid between the ground and the 300 mb level.

3.1.3 Best fit lines

When we performed our analysis, we wanted to obtain an estimate of the underlying relationship. This is in contrast to normal regression, which minimizes the least squared error in the direction of the y axis. The difference is that a regression will always give a slope that is biased towards zero unless the predictor is absolutely error free (Crone et al., 1996). One way to obtain an estimate of the true relationship is to predict y from x, then predict x from y and average the result. We will call this result the best fit line. The resulting slope is a function of the relative sizes of the noise, but if the noise values are roughly equal, it provides a reasonable estimate that is, in any case, better than a standard regression. When this is done, it can be shown that the resulting slope is given by

$$S = (2 + S_1 + S_2)/2 \qquad 1.$$

where S is the final result, S_1 is the slope from y predicted from x, and S_2 is the slope from x predicted from y. These are the slopes we predict and show. It should be noted that both regression lines pass through the same point defined by the mean values, so the line with slope S is constrained to pass through the same point. We later did a rotation of the axis and this is probably a better approach. In this approach, the axis are rotated so that the 45 line becomes the new x axis and the regression is done in this coordinate system. In this system, noise constrains the solution to the line that gives y = x or the original 45 degree line and the slope becomes close to zero in the rotated space. The slope derived in rotated space is then rotated back to the original space. The rotations are given by

$$Y_r = (Y - X) \qquad 2.$$

$$X_r = (Y + X) \qquad 3.$$

$$S = (1. + S_r)/(1. - S_r) \qquad 4.$$

where x denotes the dependent variable, y denotes the independent variable, S denotes the slope, and the subscript r denotes the corresponding values in the rotated coordinate system. Since the slopes are so close to the 45 degree line, both the average slope approach and the rotated approach give the same result. The major concern is the difference between this result and the one given by normal regression. In this case, since the true relationship is close to the 45 degree line, both the regression of y on x and x on y gave slopes less than 1.0 when done in the original space. This tended to obscure the fact that the AIRS has a bias toward the mean when the AIRS data were placed on the x axis since the slope was less than 1.0 when the best fit line was actually greater than 1.0. The advantage of the best fit line, whether it is done as an average or in rotated space, is that the reversal of the axis does not affect the result. However, one still has to pay attention to the variable that is placed on the x axis in a particular figure. If AIRS appears as the x axis on one figure and the y axis on another, a slope that is slightly greater than 1.0 becomes slightly less than 1.0 when the axis is switched. But the amount that the slope is greater than or less than 1.0 tends to remain constant as long as the departure from 1.0 is small, and this is the important feature.

3.2 Procedure for moisture profile comparisons – The need for radiosonde adjustments

Radiosonde vertical moisture measurements are subject to a number of errors. The Vaisala radiosondes, in particular, have been extensively studied and a number of corrections have been recommended as discussed in Section 2. The correction we used for this application is to constrain the total moisture to an unbiased value. One of the advantages was that it could be applied to all the U.S. radiosondes. In the future we may apply more of the Vaisala specific corrections. The specific procedures are described in the following section.

3.2.2 The GPS-based radiosonde adjustment

The GPS moisture adjustment is based on the method described by Turner et al., (2003). They used the total water vapor as measured by an upward looking microwave instrument to adjust the radiosonde water vapor measurements. Since the number of such instruments is limited, GPS stations are fairly numerous, and the two measurements share many of the same characteristics, we used the GPS measurements to make the same adjustment. The key to the correction is the fact that the GPS measurements provide relatively unbiased measurements of total water vapor. These are then compared to the total water vapor derived from the radiosonde. We then calculate the ratio of the GPS total water vapor to the radiosonde total water vapor. This ratio is then used as a multiplier to adjust the layer water vapor for each of the retrieved layers, thus forcing the total water vapor amounts to agree. Any other water vapor amounts that are required to be in other units are derived from the adjusted value. Although it might be reasonable to add an estimate for the amount of water vapor above the top of the radiosonde report and we might do this later, for this paper we assume it is zero.

4. Results

The results are described below. As described earlier, we did two comparisons, one for the 3 way match and the other for the adjustment procedure. The results for the 3 way match are described first.

4.1 3-way IPW results

Figure 2 shows the results for the three two-way matches (GPS versus AIRS, GPS versus radiosonde, and AIRS versus radiosonde) as scatter plots; the values in the lower right hand corner are the values that define the best fit line. Four results are presented because the GPS results are separated into RGPS, to designate the GPS value at the radiosonde time, and AGPS, to designate the GPS value at the AIRS time. The results are shown for 4 radiosonde categories, the MSS, the RS80, the VIZ-B2, and miscellaneous others. A fifth category is indicated as “removed”, meaning that these data points were excluded from calculation of best fit lines because they represented instances for which large changes in water vapor occurred with time, as indicated by consecutive GPS observations. It can be seen from the two left hand panels, that these points have significantly different locations in the RGPS and the AGPS plots. This shift is caused by a large change in moisture with time as indicated by the GPS values. This large change with time means that there was a feature such as a front near the station when the data were taken. Since the location of the feature relative to all the sensors at a particular time is not known, a change with time implies a change with location near the station. It is possible that the location of the sensors and the front could be recovered with a lot of work, but the simplest solution is to delete the few cases where these changes occur. The values in the lower right hand corner are the values that define the best fit line.

Since the RGPS versus AIRS inflates the apparent AIRS error, we will concentrate on the other three. We will examine the slope of the fit and the rms accuracy. When comparing slopes, the choice of axis can make the slope greater than or less than 1.0. To remove this ambiguity, we need to look at the difference of the slope from a value of 1.0. In terms of this value, the RGPS versus RAOB has the best fit (0.966), the AGPS versus AIRS is in the middle (1.05), the AIRS versus RAOB has the largest departure (0.912) from unity.

The differences in the slope demonstrate the tendency of the AIRS retrievals to be slightly conservative since the slope for the AGPS versus AIRS is slightly greater than 1.0 and the slope for AIRS versus the RAOB is slightly less than 1.0. This may be an indication that AIRS retrieval process is constrained to the initial guess to some extent. This is a normal expectation of a retrieval system, since even the AIRS, with its high vertical resolution that is one of its major advances over previous instruments, can approach, but not totally resolve all the fine scale features that can be measured by point measurements from a radiosonde.

Another measure of agreement is the rms error of the fit. The lowest value is for the RGPS versus the radiosonde (3.746), while the largest is 4.652 for the RGPS versus AIRS. This drops slightly, to 4.630, when the time adjustment is made by using the AGPS. The agreement between AIRS and the radiosonde is almost the same (4.624), but this affected by the fact that AIRS is on the y axis. The slopes give a more unbiased picture. In summary, the GPS results have slightly less variability than the radiosondes, but these effects are slight. The general consensus of these figures is that all three measurements are remarkably consistent. The GPS and RAOB are in slightly better agreement with each other than AIRS is to either, most likely because, as was mentioned in the last paragraph, of the slight tendency of the AIRS data to underestimate large departures from the climatological mean.

4.2 GPS Adjusted Radiosonde Profiles

Figure 3 illustrates the results of adjusting the vertical profiles for the Space Data Corporation Meteorological Sounding System (MSS) radiosondes. The mean (bias) and rms differences between the AIRS and raob water vapor concentrations as functions of pressure are shown. On the average the GPS adjustment makes the MSS soundings wetter leading to a reduced rms in the lower atmosphere up to about 700 mb. Above that level, the adjustment increases the rms error. One possible reason for this is that we have made no attempt to adjust for time lag. This would tend to make the radiosonde too wet at the upper levels. Since most of the total water vapor comes from the lower levels, the adjustment would tend to be dominated by those levels when it changes with height. For this sample, the matches made at the two times (radiosonde-dotted and AIRS-dashed) show little difference. This means that samples with large time changes were not present in the sample.

Corresponding results are presented in Figure 4 for the VIZ-B2 radiosonde. The GPS adjustments make these soundings dryer. The rms is reduced slightly by the GPS adjustment except for the 1000 to 850 mb layer. This effect is probably caused by some initial error that is present at the bottom of the profile, but is not representative of the profile as a whole. As in the previous sample, the time difference illustrated by the difference between two dashed lines is small.

Finally, Figure 5 shows the results for the Vaisala Rs80-57H radiosonde. This radiosonde has been extensively studied and is known to have a dry bias (Turner et al., 2003) and our results show that the GPS adjustment has the effect of making the observations wetter, although the adjustment is small. In addition, the adjustment decreases the rms error between 1000 and 800 mb but makes it slightly larger above that. Again, we suspect the reason for this slightly noisier behavior above this level is the time lag which we have not attempted to correct. A change in error in the same direction is described by (Turner et al., 2003). In this case there is also a larger change with time for the GPS observations used to constrain the raob profiles. This might be due to random sampling error, or it could be a feature of the locations at which this particular radiosonde type is launched. In any case, the AGPS observations that include a compensation for the time difference and is denoted by the dashed line, has the better agreement.

We note that in the upper atmosphere, the adjustment can make the agreement slightly worse. Since most of the water vapor resides in the lower atmosphere, the upper atmospheric water vapor does not affect the total much. We also suspect, but can’t prove, that the result may be due to the time lag. This would cause the radiosondes to become too moist in the upper atmosphere after the combined effects of the dry bias and time lag are considered, and adding moisture would make the fit worse. This is supported by the fact that the bias becomes negative in this region. Another factor to consider is the fact that once a radiosonde is released from its packaging, the contaminant is free to start outgassing. This would have a tendency to make the error decrease with height. However, we have no way of determining the magnitude of this effect and suspect that it is not significant over the time a radiosonde is in the air given typical atmospheric temperatures. We simply note that it is an effect that is present and has the right sign to make it consistent with the results presented in Figures 3, 4, and 5.

We also note that the use of the GPS adjustment validates all three instruments. When the GPS is used to adjust the radiosonde values, there is no *a priori* reason that the agreement with AIRS should get better unless we are making a real improvement. Thus, the AIRS data validates our GPS adjustment approach for the radiosondes because the adjustment reduces the rms error. Then given that the approach is working, the more accurate adjusted moisture values can be used to validate the AIRS instrument.

5. Conclusions and recommendations

The three-way comparisons show excellent agreement among all three methods of determining IPW. For the purposes of validating the AIRS measurements and retrieval process, we note that there is a slight tendency for the AIRS to be more conservative than the other two measurements for the IPW extremes. It has been suggested that the AIRS fails to catch the full extent of the variations measured by the other instruments because of differences between the areas represented by the respective measurements. There is some evidence to support this because the GPS is slightly more conservative than the radiosonde and the GPS can be considered to be between the other two in terms of areal coverage. At the same time, the radiosonde is not a point measurement. It takes some time to reach altitude and drifts with the wind during its ascent. Our impression is that the conservative nature of the AIRS retrievals is mainly, but not entirely, due to the nature of the retrieval algorithm. One of our reasons is that while wet regions can be local, the drier regions cover broader areas. If the aerial coverage were the dominate problem one would expect the effect to dominate the wet cases, but not the dry cases. The effect is present for both extremes. The members of the AIRS team doing the retrieval have the tools to address this question. We want to emphasize, however, that this effect is extremely small. It was only our most sensitive analysis that even showed that it existed. We also note that the AIRS retrieval approach continues to get modified. This effect was typical of the version that was available at the time our study was done and may be resolved in later versions. That is one of the reasons we plan to redo these analysis as newer versions become available.

The results of the adjustment study show that using the GPS water vapor to adjust radiosonde values makes the agreement between vertical moisture profiles derived from the AIRS and the radiosondes more accurate. Although the sample set of three-way match ups is small for statisitics, especially when stratified by radiosonde manufacturer, the logical conclusion from this is that the procedure is actually making the radiosonde moisture values more accurate. Our results validate the use of the procedure for use with radiosondes.

We recommend that efforts be made to expand the GPS network to provide as many GPS values as possible when they are located near radiosonde sites. We also recommend that efforts be made to add GPS measurements to all radiosonde sites. We initially hesitated to do so because we knew that work was being done to eliminate the source of the radiosonde moisture error. Recent results (Turner et al., 2003) have demonstrated that there are calibration and batch differences that are not resolved by the correction. A comparison value is particularly important for the U.S. radiosonde sites where the type of radiosonde can change with time on a rather frequent schedule and where the network uses a mixture of radiosonde types.

GPS surface stations are available at various locations throughout the world. Many of these could be used to derive precipitable water and provide the measurements. However, there are no agreements for their collection and use in the way that radiosonde measurements are shared among countries and readily available on a global distribution network. Given the results we have obtained, we highly encourage efforts to make them available. To be useful, the GPS derived water vapor values would have to be available to the forecast centers at the same time the radiosonde reports are. Such measurements have the potential to make a significant contribution to the global meteorological data. This potential can only be realized if the decisions required to make them available are made.

We also note that for satellite validation purposes, the GPS IPW data can provide a quality assurance role for temperature, if indirectly. One of the advantages of the GPS is the continuous nature of the observations. This means that the GPS can be used to determine when the conditions at the station at a particular moment may not be representative of the area around the station by observing the change of the moisture variable with time. We used this change to determine cases where the atmospheric differences between the satellite and radiosonde soundings were large. It can also be used to detect times when the atmosphere changes near the time of a GPS observation. We note that large changes in moisture are almost always accompanied by large changes in temperature. This is certainly the case near a front. We recommend that this capability be utilized if hourly surface observations are not available.

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REFERENCES

Aumann, H.H, M.T. Chahine, C. Gautier, M.D. Goldberg, E.Kalnay, L.M. McMillin, H. Revercomb, P.W. Rosenkranz, W.L. Smith, D.H. Staelin, L.L. Strow, and J. Susskind, 2003: AIRS/AMSU/HSB on the Aqua Mission, Design, Science Objectives, Data Products, and Processing Systems. *IEEE Trans.Geosci. Remote Sensing*, 41, 253 - 264.

Chahine, M.T., 1974: Remote sensing of cloudy atmospheres. I. The single cloud layer, *J. Atmos. Sci.*, 34, 233-243.

Chahine, M.T., 1977: Remote sensing of cloudy atmospheres. II. Multiple cloud formations. *J. Atmos. Sci.*, 34, 744-757.

Crone, L.J., L.M. McMillin, and D.S. crosby, 1996: Constrained Regression in Satellite Meteorology. *J. Appl. Meteor*., 35, 2023-2035.

Dai, A., and J. wang, 2002:, Diurnal variation in water vapor over North America and its implications for sampling errors. *J. Geophys. Res.*,107, D10, ACL 11-1 - ACL 11-15.

Fetzer, E., L.M. McMillin, D. Tobin, H.H. Aumann, M.R. Gunson, W.W McMillan, D.E. Hagen, M.D. Hofstadter, J. Yoe, D.N. Whitman, J.E. Barnes, R. Bennartz, H. Vomel, V. Walden, M. Newchurch, P.J. Minnett, R. Atlas, F. Schmidlin, E.T. Olsen, M.D. Goldberg, S. Zhou, H. Ding, W.L. Smith, and H. Revercomb., 2003: AIRS/AMSU/HSB, *IEEE Trans. on Geosci. Remote Sensing*, 41, 418-431.

Fujiwara, M., M. Shiotani, F. Hasebe, H. Vomel, S.J. Oltmans, P.W. Ruppert, T. Horinouchi, and T. Tsuda, 2003: *J. Atmos. Oceanic. Technol*., 20, 1534-1542.

Goldberg, M.D., Y. Qu, L. M. McMillin, W. Wolf, L. Zhou and M. Divakarla, 2003: AIRS Near-Real-Time Products and Algorithms in Support of Operational Numerical Weather Prediction. *IEEE Trans. Geosci. Remote Sensing*, 41, 379-389.

Gutman, S.I., S.R. Sahm, J.Q. Stewart, S.G. Benjamin, T.L. Smith, and B.E. Schwartz, 2003: A new composite observing system strategy for ground-based GPS meteorology. *12th Symposium on Meteorological Observations and Instrumentation*, paper 5.2, Long Beach, CA Feb. 9-13.

Haan, S. D., S. Barlag, H. K. Baltink, Fe. Debie and H.van der Marel, 2004: Synergetic Use of GPS Water Vapor and Meteosat Images for Synoptic Weather Forecasting. *J. Appl. Meteor*., 43, 514-518.

Jeannet, P., B. Hoegger, and G. Lavrat, 2002: Comparison of a chilled mirror hygrometer and a carbon hygristor for radiosonde humidity measurements. *Proceedings of the Hampton Radiosonde workshop on CD*.

King, R. W., and Y. Bock, 1996: *Documentation of the GAMIT GPS analysis software, version 9.4, Massachusetts Institute of Technology and Scripps Institution of Oceanography*

King, M.D., W. P. Menzel, Y. J. Kaufman, D. Tanre, B. C. Gao, S. Platnick, S. A. Ackerman, L. A. Remer, R. Pincus and P. A. Hubanks, 2003: Cloud and Aerosol Properties, Precipitable Water, and Profiles of Temperature and Water Vapor from MODIS.

IEEE Trans. Geosci. Remote Sensing,41, 442-458.

Miloshevich, L.M., H. Vomel, S.J. Oltmans, & A. Paukkunen, 2003: In Situ validation of a correction for time-lag and bias errors in Vaisala RS80-H radiosonde humidity measurments. *Thirteenth ARM science team meeting proceedings, Broomfield, CO, March 31-April4*, 2003.

Parkinson, C. L., 2003: Aqua: An Earth-Observing Satellite Mission to Examine Water and other Climate Variables. IEEE Trans. Geosci. Remote Sensing, 41, 173-183.

Rama Varma Raja, M.K., S.I. Gutman, J. G. Yoe, J.Zhao, and L.M. McMillin: 2004, Comparisons of Column-integrated Water Vapor Measurements from AIRS and Surface-based GPS Receivers. *To be Submitted to J. Atmos. Oceanic Tech*.

Rocken, C., T. van Hove, J. Johnson, F. Solheim, R. H. Ware, C. Alber, M. Bevis, S. Businger, and S. Chiswell, 1995: GPS/STORM-GPS sensing of atmospheric water vapor for meteorology. *J. Atmos. Oceanic Technol*., 12, 468-478.

Smith, W.L., 1968: An improved method for calculating tropospheric temperature and moisture from satellite radiometer measurements, *Mon. Wea. Rev*., 96, 387-396.

Soden, B.J., D.D. Turner, B.M. Lesht, and L.M. Miloshevich, 2004: An analysis of satellite, radiosonde, and lidar observations of upper tropospheric water vapor from the atmospheric radiation measurement program. *J.Geophys.Res*. 109, D04105, 1-19.

Susskind, J., C.D. Barnet, and J.M. Blaisdell, 2003: Retrieval of Atmospheric and Surface Parameters From AIRS/AMSU/HSB Data in the Preseence of Clouds, *IEEE Trans. Geosci. Remote Sensing*, 41, 390 - 409.

Turner, D.D., B.M. Lesht, S.A. Clough, J.C. Liljegren, H.E. Rivercomb, and D.C. Tobin, 2003: Dry Bias Variability in Vaisala RS80-H radiosondes: The ARM experience, *J. Atmos. Oceanic Technol*., 20, 117-132.

Wang, J., D.J. Carlson, D.B. Parsons, T.F. Hock, D. Lauritsen, H.L. Cole, K. Beierle, & e. Chamberlain, 2003: Performance of operational radiosonde humidity sensors in direct comparison with a chilled mirror dew-point hygrometer and its climate implication. *Geophys. Res. Lett*., 30, 16, 1860, ASC 11-1 - ASC 11 - 4.

Wolfe, D. E., and S. I. Gutman, 2000: Developing an Operational, Surface-Based GPS, Water Vapor Observing System for NOAA: Network Design and Results. *J. Atmos. Oceanic Technol*., 17, 426-440.

Figures

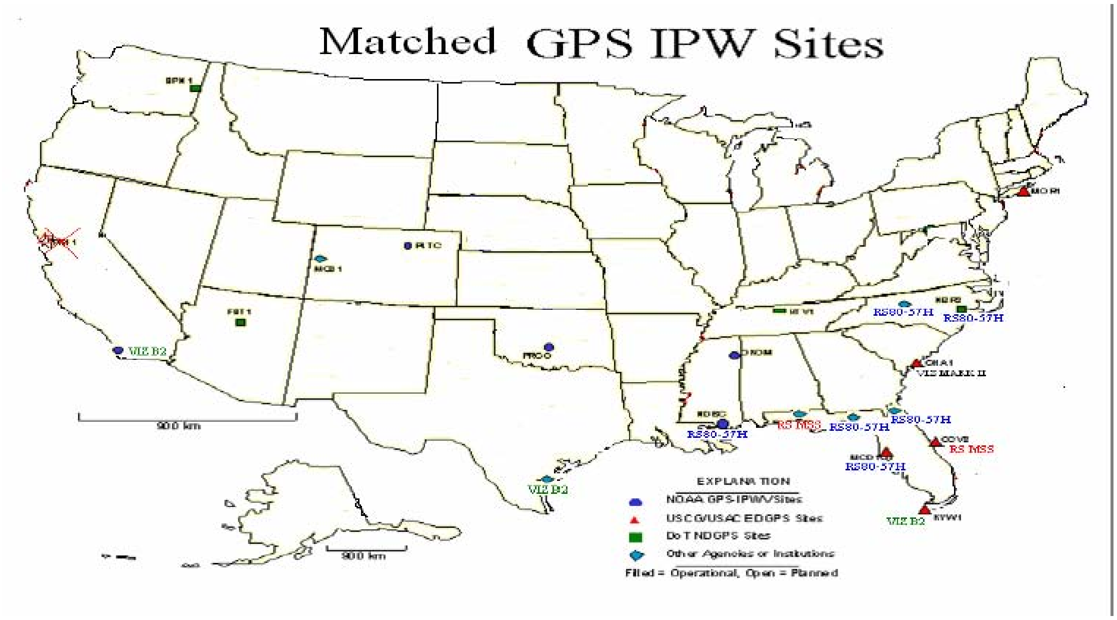

Figure 1. Locations of the GPS stations located near radiosonde stations and used in this study. Stations marked with x's are not used because local terrain conditions made the results differ. Stations without a radiosonde type had no AIRS matches and could not be used.

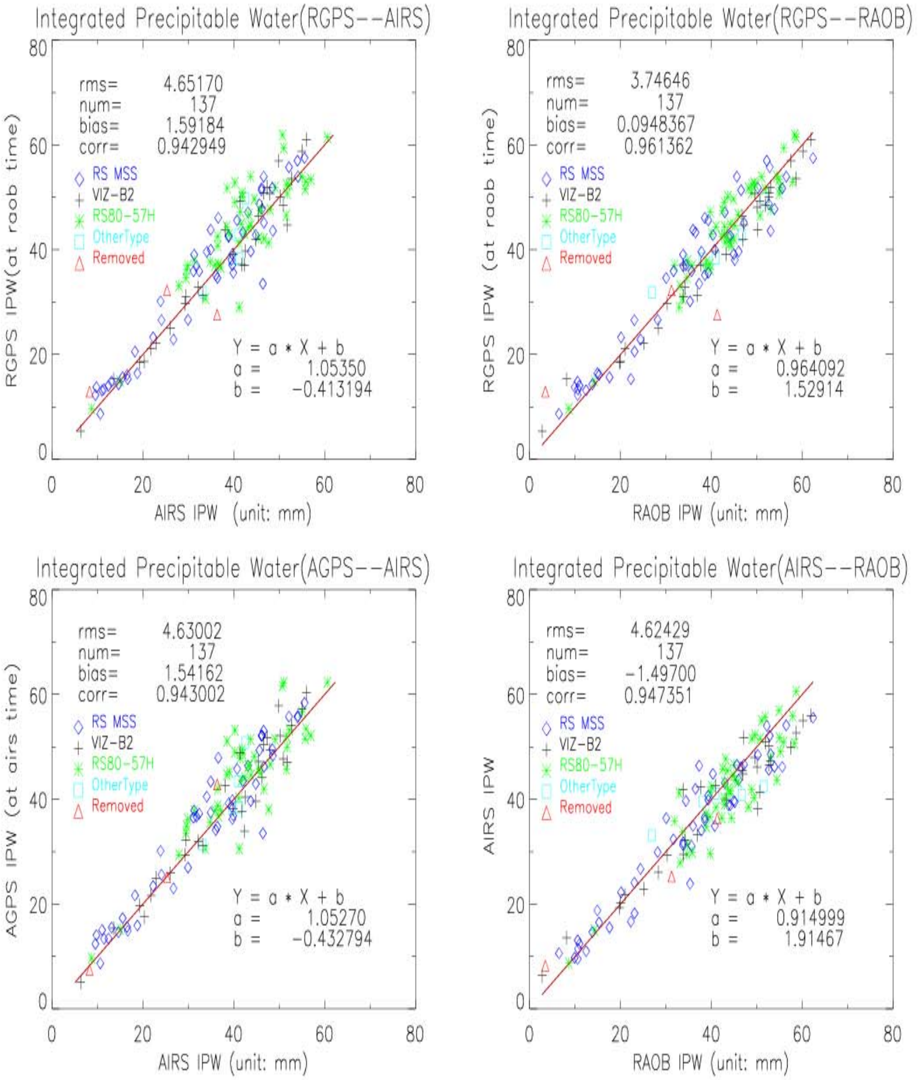

Figure 2. Scatter plots of total precipitable water for three instruments, AIRS, GPS, and radiosondes. Since the GPS is a continuous measurement, it is matched in time to the AIRS (AGPS) and the radiosonde (RGPS) resulting in four comparisons. The values in the upper left hand corner show the usual fit. The values in the bottom right define the best fit line. The line shown in the figures is the 45 degree line.

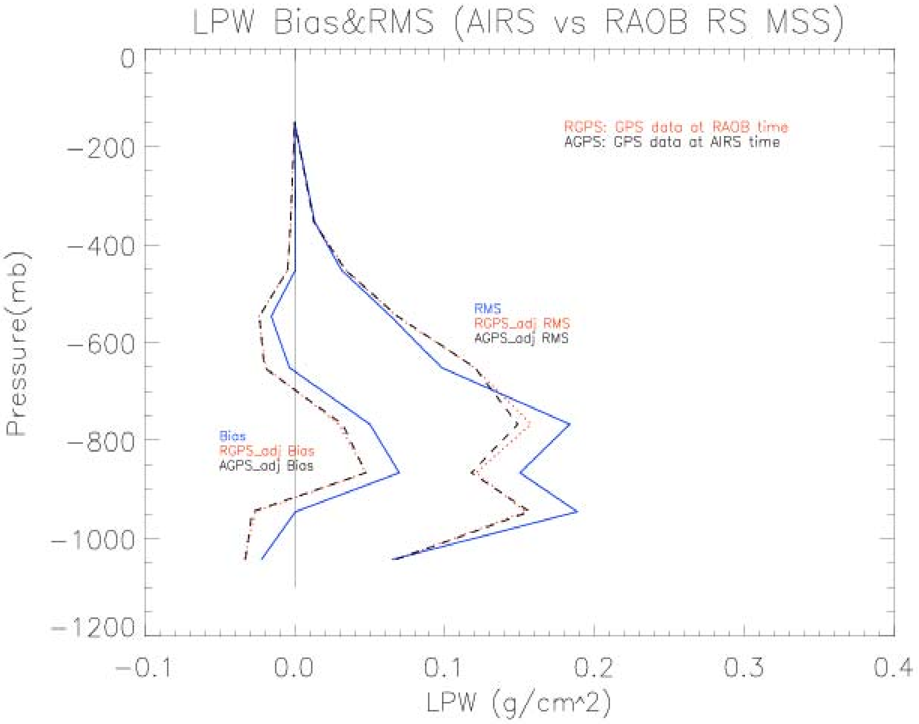

Figure 3 RMS and bias as a function of pressure for the Meteorological Sounding System (MSS) mad by the Space Data Corporation. The lines labeled as RGPS and AGPS show the match with AIRS after the GPS has been used to adjust the radiosonde. The two lines show the results for GPS values at the radiosonde (RGPS) and AIRS (AGPS) times. The AGPS is slightly better as expected.

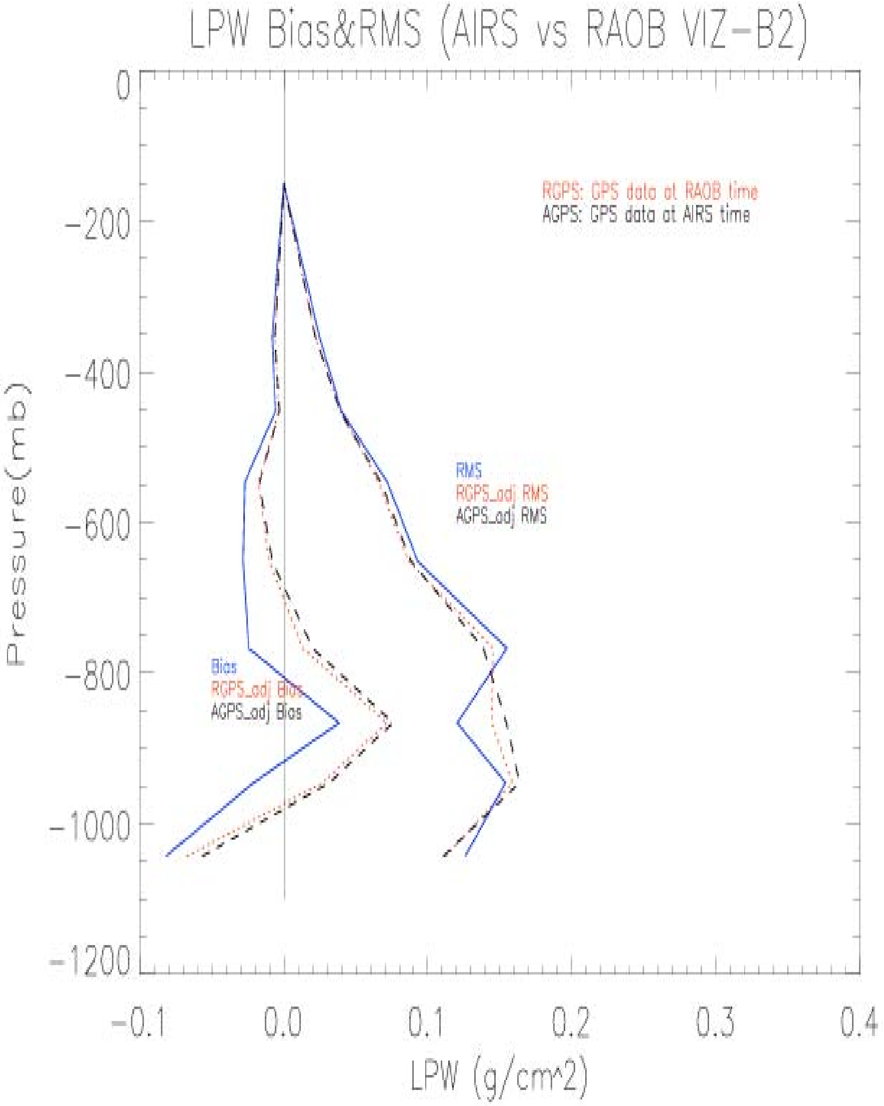

Figure 4 RMS and bias as a function of pressure for the VIZ-B2 radiosonde. The lines labeled as RGPS and AGPS show the match with AIRS after the GPS has been used to adjust the radiosonde. The two lines show the results for GPS values at the radiosonde (RGPS) and AIRS (AGPS) times. The AGPS is slightly better as expected except for the region near 900 mb.

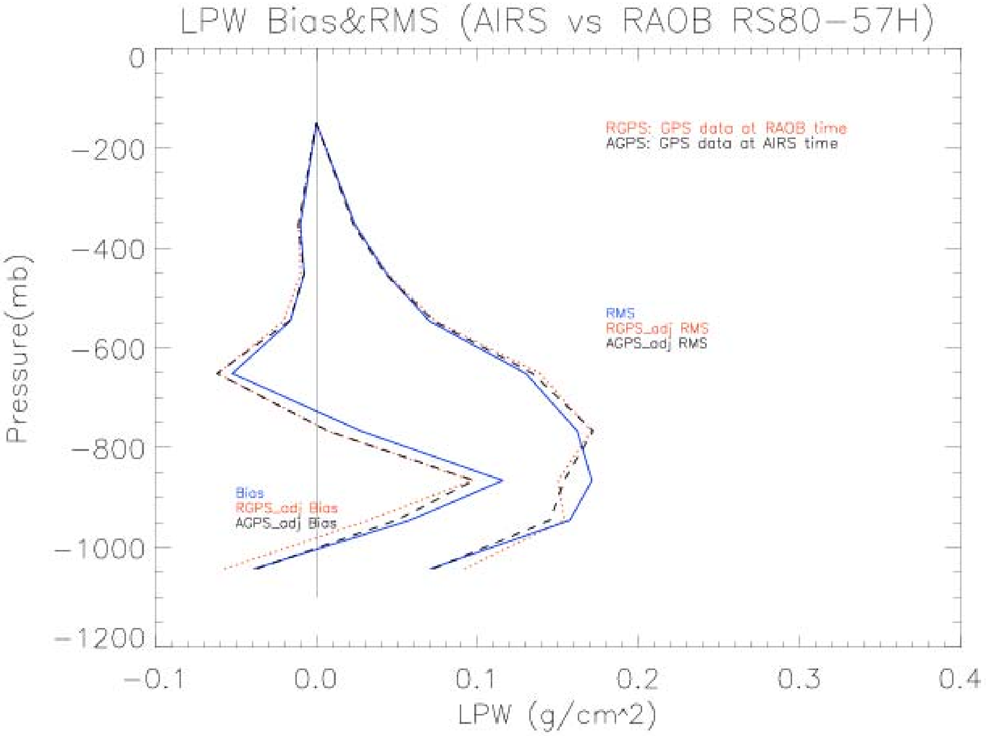

Figure 5 RMS and bias as a function of pressure for the Vaisala RS80-57H radiosonde. The lines labeled as RGPS and AGPS show the match with AIRS after the GPS has been used to adjust the radiosonde. The two lines show the results for GPS values at the radiosonde (RGPS) and AIRS (AGPS) times. The AGPS is slightly better as expected.