WVSS-II MOISTURE OBSERVATIONS:
A low-cost tool for validating and monitoring asynoptic satellite data

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1 - Abstract – Knowing the accuracy and representativeness of new observing systems is critical for their optimal use in data assimilation and other applications. One such new system is the laser-diode based Water Vapor Sensing System (WVSS-II) currently being deployed and tested on commercial aircraft in the US and, to a more limited degree, in Europe. The paper discusses the results of three WVSS-II-to-Rawinsonde intercomparison studies, not only in terms of assessing the accuracy of the humidity data, but also for determining how best to use these data as a suppliment to other upper-air moisture measurements and options for using the data as a source of asynoptic observations to validate/calibrate a variety of satellite moisture products.

2 - Background - In the late 1990s, the North American Observing System (NAOS) study group performed an evaluation of the value of automated aircraft reports relative to and as a supplement for rawinsonde observations. The results of that study clearly identified the need to include moisture data in addition to the temperature and wind reports included in the aircraft data and was formalized into an official National Weather Service (NWS) data requirement. In an early attempt to fill this gap, a set of approximately 30 instruments of the first generation Water Vapor Sensing System (WVSS-I) have been operating aboard United Parcel Service (UPS) aircraft for approximately five years. These humidity data were of considerable use in a variety of subjective forecast applications, but never saw wide use in objective forecasting, due both to limited availability and variable accuracy do to engineering limitations.

The prime US objective for obtaining atmospheric moisture profiles from commercial aircraft is to provide sufficient numbers of high-resolution (both spatial and temporal) moisture data to fill the gaps left between the 400km and 12 hr spacing of the national rawinsonde network; the only other source of in-situ moisture observations. Other benefits will include improved the monitoring and prediction of cirrus clouds by obtaining more frequent observations of high-tropospheric moisture and a low-cost means of validating/calibrating satellite sounding moisture profiles and assimilation systems.

In an effort to improve accuracy and reduce maintenance/operations costs noted in the WVSS-I tests, a second generation WVSS-II has been developed and flown on UPS aircraft and have already undergone several tests beginning in 2005. Validation tests pointed to the need for a number of engineering modifications, most importantly improvements to observations during aircraft descent and system reliability.

The accuracy assessments are being accomplished through a systematic and thorough intercomparison of the WVSS-II with other accepted 'standard' observations. Two tests have been performed from 14-24 June 2005 and 7-18 November 2006, during which WVSS-II profiles were compared to spatially and temporally co-located rawinsonde observations. Additional tests of final engineering modifications are scheduled for fall 2009 and spring 2010. Knowing the bias and expected range of observational errors from any new instruments is critical both for developing adequate quality control limits and then for the successful use of the data in objective forecasting application, such as NWP. Additionally, it is important to know whether the aircraft data show different characteristics on ascent, descent and en-route phase of flight.

All non-aircraft validation observations were made from a site adjacent to the Louisville airport. Automated observations were taken from a mobile instrument laboratory continuously throughout the full period. Primary observational systems included a portable surface station reporting temperature, dewpoint temperature and wind, a NWS standard Ceilometer, a GPS receiver for use in calculating total precipitable water (GPS-TPW), an upward looking AERI infrared interferometer to measure boundary layer temperature and moisture at 10 minute temporal resolution. Rawinsonde measurements were taken on weekdays during the experiment using a Vaisala RS-92 GPS rawinsonde system.

3 - Summary of Findings – The most critical surface-based observations for this report were the rawinsonde reports. Three rawinsonde launches were scheduled for each night, one immediately before the majority of the UPS arrivals at about 0400 UTC, another between the rush of descents and ascents at about 0730 UTC and a third after the majority of departures at about 1045 UTC. Exceptions were made on Mondays and Fridays when, due to scheduling of WVSS-II equipped aircraft by UPS, only 2 launches on several occasions. All 28 launches were successful, with no equipment failure. On a typical day, about 5-10 aircraft co-locations were available, but not all fell within the narrow time and space windows used in this assessment.

3.1 - Constraints on assessment due to instrument shortcomings – As a result of the first assessment conducted by CIMSS in 2005, a number of engineering and software modifications were made to the WVSS-II systems and the on-board reporting system to correct deficiencies needed in the earlier tests. Although it had been hoped that all of the WVSS-II sensors and software modifications would have been included on the participating UPS aircraft before the second assessment period began, the complete conversions were not completed until the end of the November 2006 data collection period. As such, the comparisons of the WVSS-II data with the rawinsonde standard were again limited as follows:

1. The engineering changes to correct the erroneous reports in areas of high humidity and clouds during in descent did not alleviate the problem entirely. Since the objective of the experiment was to assess the quality of good quality reports made by both the aircraft and rawinsonde, the intercomparisons focus on rawinsonde co-locations with aircraft ascents.

2. The problem of small amounts of moisture entering the laser sensing unit and thereby biasing the moisture reports upward persisted in some units. Because this bias was especially apparent in areas of extremely low mixing, the assessments were again limited to regions where the observed mixing ratio was greater than 2 g/kg.

3. Because a number of the aircraft had biases in their temperature sensors, assessments of moisture were again made in terms of the primary WVSS-II water vapor observation, which is mixing ratio (as reflected in specific humidity), but also transformed in to Relative Humidity using rawinsonde temperatures. A comparison using aircraft temperature reports was also made for reference.

4. Because the software changes developed by CIMSS to correct a deficiency that reduced the precision of the WVSS-II observations exceeding 10 g/k was not available on all the UPS aircraft during the data collection period, the assessment was again limited to reports of less than 10 g/kg.

3.2 - Conventions for identifying aircraft/rawinsonde co-locations - Based upon experience gained in the previous aircraft/rawinsonde co-location tests performed by UW-CIMSS, all co-location data used for the initial assessment were limited to time and space windows of +/- 60 minutes and 50 kilometers. This was done to minimize the impact of transient weather features in the area, such as frontal passages, while assuring that an adequate number of reports were available for statistical calculations.

When the above conditions are applied to the full set of available data, a total of 50 ascending rawinsonde/WVSS-II matches were still available for comparison (from aircraft ascents only). The matches included data from 16 different rawinsonde releases (three of the release times had matches only with descending data and were not included in the assessment) and up to 50% of the approximately 25 aircraft that could have been available in the study any day. Differences between the aircraft and rawinsonde data were calculated at each aircraft reporting level and then 'binned' into 10 hPa deep layers for display and statistical calculations.

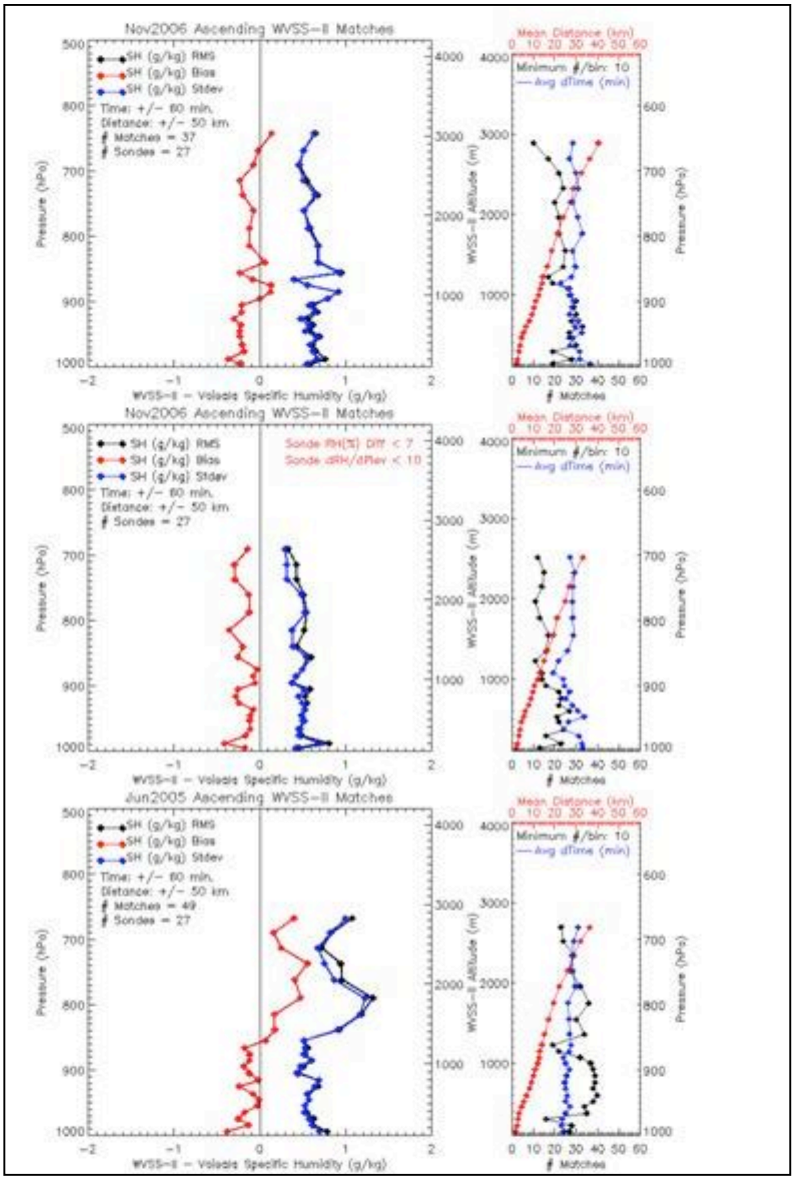
Displays of rawinsonde and aircraft profiles of temperature and specific humidity were made for each of the 13 rawinsonde-aircraft match-up times. Comparison of individual sounding from the two observing systems showed a range of similarity and dissimilarity between the 2 observing systems, related apparently to the specific mix of aircraft reporting and the uniformity of the weather regime present each day. Based upon these findings, data from all aircraft which showed consistently large deviations from the co-located rawinsonde reports were eliminated from the statistical assessments to be discussed next.

2.3 - Results of Rawinsonde/WVSS-II Intercomparisons - Weighted average rawinsonde Intercomparisons were compiled for the full test period according to the number of aircraft matches that occurred for each rawinsonde launch. In this way, an individual sounding during an extreme weather event but with only 1 aircraft match-up would have less influence on the average than a report with many aircraft matches. It should also be noted that because all of the rawinsonde launches were made after sunset and before dawn, corrections of the rawinsondes for the influence of solar radiation were unnecessary. The average temperature profile for the two week assessment period showed a weak temperature inversion in the lowest 50 hPa, capped by a weak lapse rate which becomes nearly adiabatic by 500 hPa. A very weak secondary temperature inversion is also present between 850 and 820 hPa. The moisture profile showed a slight increase in moisture immediately above the surface, with steadily decreasing specific humidity from there to 500 hPa

Statistical fits of the WVSS-II Specific Humidity (SH) data to the rawinsonde reports were obtained for the full observation period using all WVSS-II systems except those that showed consistent erratic behavior. Although a minimum of 20 match-ups were needed to calculate significant statistics at any level, between 30-40 observational matches were made at most levels.

The WVSS-II SH data (Fig. 1 - top) show very small, though generally negative Biases (-0.1 to -0.3 g/kg) from the surface up to nearly 800 hPa. Above that level, the Bias reduces to between 0.0 and -0.1 g/kg. Peaks in the Bias appear at about 850 and 800 hPa. The Root Mean Square (RMS) fits of the full set of aircraft data to the rawinsonde reports showed variability of about 0.7 g/kg from the surface to 800 hPa. Above 800 hPa, RMS values decrease to from 0.5 and 0.3 g/kg. Again, peaks in the RMS appear near 850 and 800 hPa. The fact that the Standard Deviation (StdDev) also shows the unexplained peaks at 850 and 800 hPa indicates that the error is not due entirely to systematic differences between the observing systems (the Bias is very small in this region), but instead must be due to a random factor, possibly related to atmospheric variability near this level.

Inter-comparison amongst the WVSS-II observations themselves showed very good consistency between individual WVSS-II instruments and provides evidence for the source of the peaks in the differences in the 2 data sets near 850 and 800 hPa. For observations taken within 15 minutes of each other, both the Specific Humidity (SH) and Temperature (T) data show similar degrees of consistency from the surface to 500 hPa. The SH RMS ranging from ~0.7 to ~0.4 g/kg with increasing height while the T RMS increasing from ~0.6^o to ~0.8^o. The agreement between independent WVSS-II observations made within 15 minutes was approximately the same as the agreement between WVSS-II and rawinsondes. This fact not only corroborates the WVSS-II-to-rawinsonde statistics, but also provides evidence both of the consistency between individual WVSS-II systems and the reproducibility of the WVSS-II data – a factor important for the future use of these data in NWP based data assimilation systems.



At longer time intervals, however, the variability between observations at lower levels increased markedly. The source of this increased variability was traced to a combination of frontal passages and the progressive subsidence of a layer of dry air into the region of lower-level moisture during several periods of the test. Though gradual, the intrusion of the dry air from aloft into the lower levels was rapid enough so that one or more of the 10 hPa deep layers used to generate statistics could be affected. In several cases, WVSS-II reports showed an area of extremely dry air capping a substantial moist layer extending from the surface to about 800-850 hPa. For example, if the WVSS-II reported nearly an hour before the rawinsonde data (which showed the impact of the subsequent downward intrusion of dry air into top-most portion of the moist layer), the statistic would indicated a disagreement – but resulting from time mismatching in a rapidly changing environment rather than an instrumentation errors.

Figure 1: Top: Left - Statistical comparison of Rawinsondes and all WVSS-II moisture observation for the period 7-18 November 2006 at Louisville KY. Bias, Root Mean Square (RMS) and Standard Deviation (StdDev) between data sets (g/kg). Top Right - Number of observations used to calculate statistics (matched within +/- 60 minutes and 50km) and mean distance between observations evaluated in left panel. Middle: Same as top panel but with limitations imposed on WVSS-II observation range and vertical and temporal changes in rawinsonde data. See text for details. Bottom: Same as middle panel but from June 2005 tests and with limitations only on WVSS-II observation range.

In an effort to reduce the impact of the rapid environmental changes in moisture observed between very thin layers on the co-location process, three additional constraints were placed on the statistical calculation. First, the 2 g/kg lower limit and 10 g/kg upper limits using in the 2005 tests were reintroduced – thereby eliminating the possible influences of WVSS-II Biases due to mechanical leaks in the sensor housings and errors due to air-to-ground transmission deficiencies remaining on some aircraft. The second was to eliminate individual cases in which successive rawinsonde reports showed that the variability in moisture in individual 10 hPa layers exceed a threshold – in this case 7% per hour. Lastly, cases where the rawinsonde reports showed vertical changes in Relative Humidity greater than 10% between successive 10 hPa levels were eliminated.

Results using the additional restrictions (Fig. 1 – middle) show that the additional processing constraints showed very little impact on the either the number of rawinsonde-aircraft matches or the statistical evaluation below 900 hPa, where the WVSS-II data show a slight dry systematic error (Bias) of approximately -0.3 g/kg and random error component (Standard Deviation - StdDev) of about 0.6-0.7 g/kg, well within WMO requirements. Above 880 hPa, the number of rawinsonde-aircraft matches was reduced at the uppermost levels (nearly all reports were eliminated above 700 hPa) and the magnitude of the Bias increased slightly to about -0.2 g/kg, both due to the elimination of reports less than 2 g/kg, which tended to have a moist (+) Bias. Additionally, the random error (StdDev) was reduced to between 0.2-0.4 g/kg in the entire region above 900 hPa. Although the peaks in Bias and StdDev which were present before the tests for large atmospheric temporal changes were added have been eliminated, small peaks in the random error are still present near and above 900 hPa. This is likely due to the fact that the number of rawinsonde-aircraft matches has become very low here, in this case due to the additional check for large vertical and temporal moisture changes. Not only has the sample size been reduce by over 30% in this region, but the probability that large environmental variations could still be affecting the remaining data and the fact that the sample size is becoming sub-critical can reduce the reliability of the statistics in this region.

When contrasted with results obtained from the Spring 2005 assessment (Fig. 1 – bottom) , it appears that the engineering changes made after the 2005 test were at least partially successful in removing error in data taken during ascent. First, the positive Biases that were present above 850 hPa in the 2005 data sets have been essentially eliminated. In addition, the unexplained bi-modal character of ‘systematic’ error (negative Biases below 850 hPa and positive above) has been eliminated. Instead, the re-engineered systems are now producing a small negative Bias which appears to be consistent at all levels. The random error component has also improved. Although the StdDev (and RMS) below 900 hPa show very similar results form the two different tests (StdDev values averaging between 0.6-0.7 g/kg across the region), the performance above 900 hPa is greatly improved, with random errors in this region on the order of 0.4 g/kg, a 50-65% reduction from the 2005 tests.

Although not part of the WVSS-II system itself, statistics were also obtained for the aircraft temperature data. These data show a clear warm Bias at all levels above the immediate boundary layer. Values range from about 0.0 to 0.5°C. Random errors (StdDev) range from about 0.5°C in 500 hPa to ~1.0°C down to 950 hPa to 1.5°C near the surface. When the WVSS-II Specific Humidity and aircraft Temperature are used to determine Relative Humidity (RH) as a further means of comparing the WVSS-II and Rawinsonde observations, the warm Bias shown in the temperature data makes the derived Relative Humidity data appear excessively dry. The Relative Humidity data derived by combining aircraft temperature and WVSS-II data has a dry Bias of about 2-3% at almost all levels. Although this comparison does not provide a valid approximation of the error in the WVSS-II instrument, it does provide important information about the types of observational errors that should be used in Data Assimilation systems that plan to use the WVSS-II data.

A better representation of the RH error expected from the WVSS-II system itself was obtained by comparing calculations of RH obtained by combining the Specific Humidity measured by the WMSS-II and Rawinsondes with the Temperature measured by the rawinsonde. In doing so, the RH statistics will represent *only* the effects of differences in the moisture observations between the two observing systems, independent of the effect Temperature differences. The results (FIG. 2 – left) reflect only the Biases noted in the SH results (FIG. 2 - right), with a very slight systematic dry Bias averaging between -1 and -2% from the surface through 700 hPa. Similarly, the random errors of 0.6-0.7 g/kg below 900 hPa and 0.2-0.4 g/kg above 900 hPa translate into RH errors of approximately 9% throughout the column. The uniformity in the calculated RH error relative to the decreases in SH error from lower to upper levels is the result of the decrease temperature with height observed in this region of the atmosphere. These levels of data quality meet or exceed all WMO observational requirements.

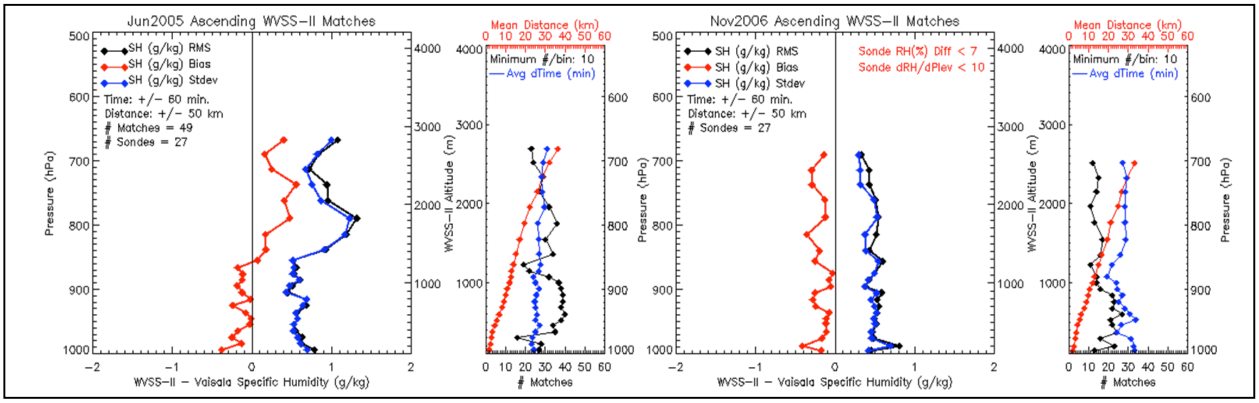


Figure 2 - Comparison of WVSS-II performance statistics by vertical level for 2 week periods in Spring 2005 (left) and Fall 2006 (right). Display content similar to Figure 1.

An additional study was conducted to determine if significant differences were observed in any particular relative humidity range. As with our other results, we again only used WVSS-II data from the high-quality instruments and from the Specific Humidity range of >2 and <10 g/kg, due to leakage and encoding issues. It should be noted that the >2 g/kg restriction limits the number of data points in the lower RH bands.

The results are very consistent across all RH ranges. Biases are near zero across all reports. The results are slightly positive for low RH and slightly negative for higher RH, but that again could be the result of the WVSS-II cutoffs (e.g., the rawinsondes could have reported values both slightly above or below 10 g/kg, but the WVSS-II could only report values <10 g/kg - and visa versa for the lower limits). The RMS and StdDev show very consistent numbers, with slightly better reports nearer to saturation. This leads to the conclusion that the instrument provides consistent measurements across all humidity ranges available.

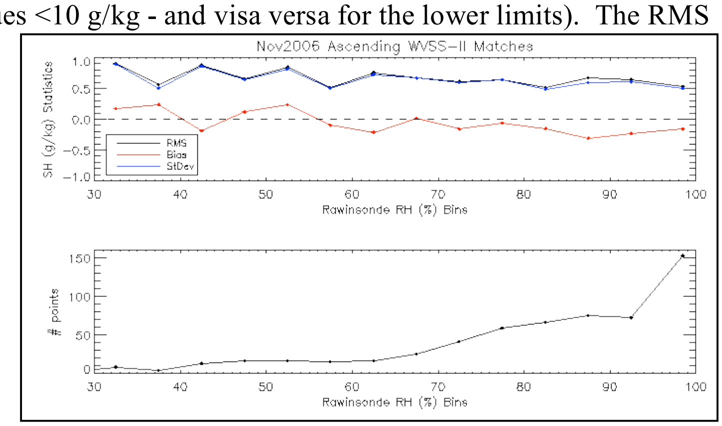


Figure 3 - Distribution of WVSS-II Moisture Observation differences from Rawinsondes by 5% Relative Humidity bands(determined from rawinsonde data).

3.4 - Results of evaluations of alternative assessment methodologies*:* In an attempt to reduce the uncertainty due to the lack of precise time matching between the WVSS-II equipped aircraft and the validating rawinsondes, several additional assessment approaches were investigated conducted using alternative computational approaches. These included 1) time interpolation of the rawinsonde data (which were made immediately before and after the series of WVSS-II ascents and descents) to the time of the aircraft departures and 2) use of data derived from hourly numerical analyses of the Rapid Update Cycle (RUC – available via the web from NOAA's Environmental Systems Research Laboratory) as a means of further reducing the gap in time between the aircraft and validation data sets. Results of using both of these approaches are discussed here.

3.4.1 - Tests of time-interpolated rawinsonde data as an evaluation standard*:* In the first of the alternative assessments technique tests, rawinsonde data acquired before and after each of the WVSS-II profiles were time-interpolated to the beginning time of each aircraft ascent. In doing so, it was anticipated that some of the effects of the rapid moisture changes observed on several days of the test period could be included more fully in the assessment.

When time-interpolation was used as a means of expanding the number of WVSS-II reports that could be used in the assessment by removing the +/-60 minute time matching constraint, the number of matches nearly doubled at most levels, going from near 30 to over 50 below 900 hPa. The Bias and RMS/StdDev statistics, however, became generally worse. Below 900 hPa, the Bias nearly doubled, while the RMS/StdDev increased at all but the upper-most levels. The increased differences between the full set of WVSS-II observations and the time-interpolated rawinsonde data were especially apparent near 900 hPa, where the RMS/StdDev increased by ~50%. Because many of the aircraft that were added in the longer-period tests were the same aircraft that had been shown to be providing high quality data in the +/-60 minute evaluations, the only explanation for the increased differences between the two data sets must be the inability of the linear time-interpolation of the 3-4 hourly rawinsonde data to account for the higher time-frequency variations observed in the WVSS-II moisture data at time separations greater than 1 hour. This conclusion is consistent with the WVSS-II temporal variability analysis discussed earlier. Even when using WVSS-II/Rawinsonde pairs that are time-matched to be within 1 hour, linear interpolation of 4 hourly rawinsonde data can not fully account for local variability seen in the much higher frequency WVSS-II reports (e.g., the miss-matches observed around the quickly changing moisture inversion). As such, the approach of eliminating areas of large temporal/vertical gradients was used instead of a time-interpolation approach.

3.4.2 - Tests of utility of RUC analysis data as an evaluation standard: In the second alternative assessments technique tests, hourly Rapid update Cycle (RUC) analyses made immediately before and after each of the WVSS-II ascents were tested as the evaluation standard Again, it was anticipated that some of the effects of the rapid moisture changes observed on several days of the test period might be included more fully in the assessment using the higher time-resolution of the hourly RUC analyses instead of the 3-4 hourly rawinsonde data. Again, evaluations were made for both temperature and water vapor.

A total of 3 different comparisons were made for both the temperature and moisture data. These included using 1) all aircraft observations that passed Quality Control within +/-60 minutes of the rawinsonde launch compared with the rawinsonde report nearest in time without any time-interpolation , 2) all observations that passed Quality Control compared with the closest hourly RUC analysis data taken from the model grid point nearest the Louisville airport, and 3) comparison for rawinsonde data with hourly RUC analysis data taken from the model grid point nearest the Louisville airport. It should be noted both 1) that the rawinsonde data used in the earlier for comparison discussed in this report were not used in the RUC analyses and 2) that aircraft temperature data were available for use in the RUC temperature analyses.

Although temperature intercomparisons show generally similar results when inter-comparing the three systems, with the RUC analyses having many more matches than the rawinsonde data, as is to be expected, the picture for moisture observations is less promising. In this case, the fit of the RUC moisture analysis to the rawinsonde data taken at Louisville showed both large Biases and large RMS/StdDev values from the surface through 600 hPa. The Biases range from more than -1 g/kg below 800 hPa to more than 0.7 g/kg near and above 700 hPa. These Biases translate to RH differences of about -15% to nearly +20%. The random error is even larger throughout the lowest 400 hPa of the atmosphere, with StdDev values exceeding 1g/kg at almost every level. The maximum value > 1.5 g/kg at 700 hPa, corresponds to a RH difference of nearly 50%. By comparison, the StdDev fit of the WVSS-II data to rawinsondes was generally 0.5 g/kg or less at all levels. The fact that the two independent observational data sets were in close agreement validates the quality of the rawinsonde reports as a comparison standard and points to inaccuracies in the RUC analyses as being the source of the large differences (both systemic and random) between the two data sets. The effects of the large differences between the rawinsonde data and the RUC analyses were also apparent when comparing the RUC and WVSS-II data, with generally positive Biases and RMS/StdDev values between 1 and 1.5 g/kg.

From these data alone, it is unknown whether the large differences are due the inability of the RUC analyses to capture small-scale variation in observed moisture fields, or whether the RUC is adding small-scale features to its moisture analyses which are either unrealistic or out of phase with observations. Additional examination of temporal and spatial moisture variability being carried out under this proposal should help to address that question.

Although these results show that the RUC can be useful as a measure temperature observation accuracy, the fact that the errors in the RUC moisture analyses when compared to independent rawinsonde are much larger than the differences between the rawinsonde and WVSS-II data makes it inappropriate to use the RUC analyses (or short range forecasts) as a validation standard for any moisture observation.

It should also be noted that care was needed to eliminate localized areas of excessive changes between successive rawinsondes and thereby minimize the impact of atmospheric variability in the instrument evaluation. Similar procedures may be needed for future use of these data with NWP data assimilation systems.

3.5 - Preliminary 2009 Validation Results – Based on the results of the previous evaluation, a number of additional engineering changes where made to the entire WVSS-II observing and data processing systems. These included additional safeguards in the WVSS-II laser observing chamber, as well as changes to the data processing hardware to make it fully digital, more stable and less susceptible to temperature variations within the aircraft.

Initial comparison data were provided by Randy Baker of UPS. The data set consisted of more than 200 co-located surface METAR observations made at various airports around the US and WVSS-II data taken upon arrival or aircraft at the airports or immediately before departure. Although these data do not represent the ability of VWSS-II to provide accurate data during flight, the intercomparisons are made using a more accurate moisture measuring system for validation compared to that used in rawinsondes. The observed moisture values ranged from 2 to 20 g/kg, with the majority being fairly uniformly distributed between 5 and 17 g/kg.

The results in the left panel of Fig WVSS-4 indicate that the latest set of engineering changes has notably improved the observations. The WVSS-II data show almost no Bias (systematic error) and have a Standard Deviation (random error) near 0.4 g/kg – a value well within WMO requirements for mesoscale forecasting. By contrast, the aircraft temperature reports showed both a positive bias and a random error greater than that in the derived Dewpoint temperature data. The results in the other 2 panels show that the majority of the derived RH error is caused by aircraft temperature error, and that the WVSS-II moisture observations contributed only about 35% of the total RH error.

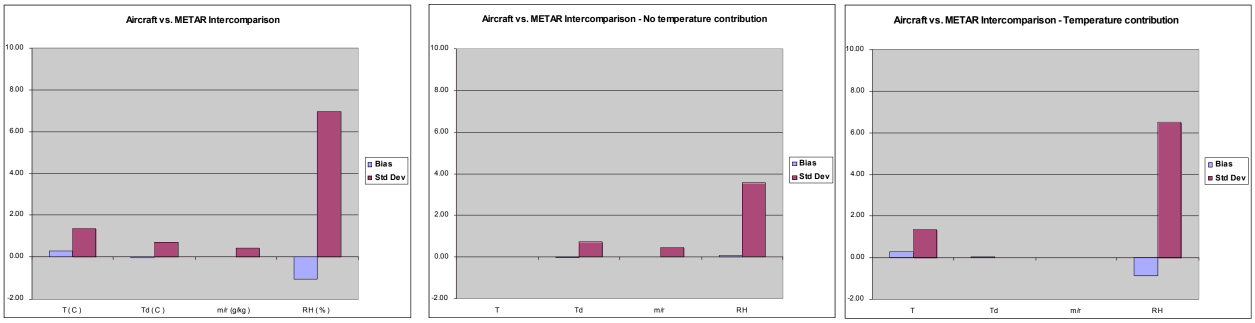


Figure 4 - Intercomparisons of surface METAR and aircraft reports from Sept-Oct. 2009. Left panel shows observed Temperature (^{o}C) and Mixing Ratio (g/kg), along with derived Dewpoint Temperature (^{o}C) and Relative Humidity (%). Center panel shows contribution from WVSS-II Mixing Ratio error on Relative Humidity error. Right panel shows contribution from aircraft Temperature error on Relative Humidity error.

4 - Summary of Co-location Assessments – This report presents a summary of the accuracy of mixing ratio observations made by WVSS-II equipped commercial aircraft during a two-week period in November 2006. Because errors due to engineering deficiencies were again noted in some of the descending data, the evaluation here again focused on data taken during aircraft ascent. The results show small, negative Biases, on the order of -0.1 to -0.3 g/kg, and more vertically uniform than those observed in 2005. RMS fits average around 0.5 g/kg, notably less than that observed in 2005. This accuracy is well within NWS and WMO requirements. Initial results using a production version of the WVSS-II instrument with improve engineering show even higher data quality for the Mixing Ratio observations themselves and indicate that the largest contribution to Relative Humidity errors is now coming from the temperature sensors used on the aircraft.

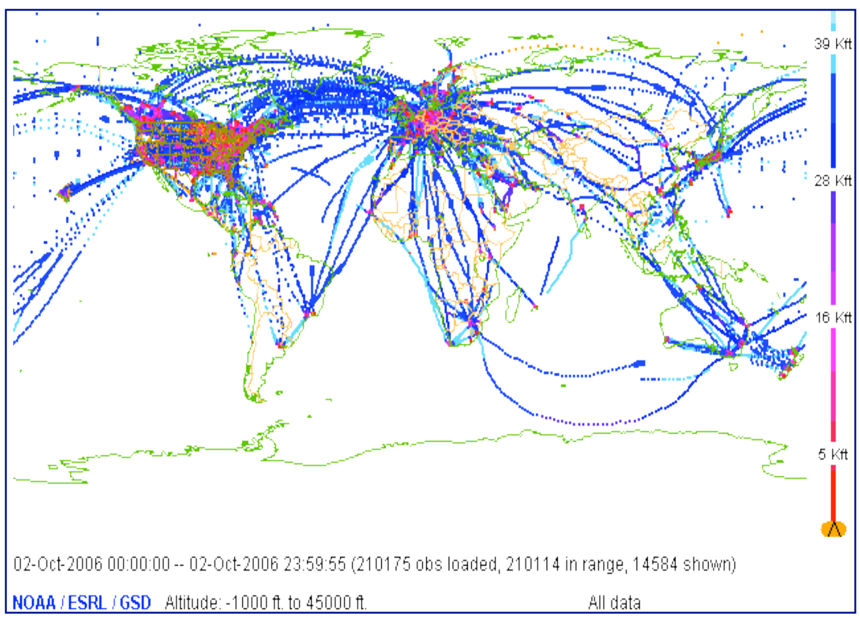


Figure 5 - Plot of locations of automated aircraft reports for 24 hour period in 2006. WVSS-II instruments could be included in many of these observations in the future.

The results indicate that as WVSS-II observations become available from an expanding fleet of in the US and other portions of the globe, the data will provide and excellent validation and calibration standards for a variety of satellite-based atmospheric moisture sensors, both at low and high vertical resolution. In the future, these data could be made available both during ascent/descent and at flight level from a large number of AMDAR equipped aircraft around the world, as shown in Figure 5.

5 - Acknowledgements - The authors thank the large group of people who have been involved in the WVSS-II development and implementation efforts. Special thanks during the co-location tests need to be given to Dave Helms of NOAA/NWS, Randy Baker of UPS, Bill Moninger of NOAA/OAR, Rex Fleming of UCAR, and the graduate students and staff of CIMSS who made this verification exercise possible. The work was supported by the NWS/Office of Climate, Water and Weather Services, Aviation Weather Branch through the NOAA/NESDIS-UW CIMSS agreement.