P2.6 EVALUATION OF THE WVSS-II MOISTURE SENSOR USING CO-LOCATED IN-SITU AND REMOTELY SENSED OBSERVATIONS

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1. BACKGROUND

Various studies over the past decade have shown that additional detailed measurements of the vertical, horizontal and temporal atmospheric moisture structure are necessary to improve forecasts of precipitation location, intensity and timing, as well as the onset and strength of severe convective storms. To meet this need, The Water Vapor Sensing System (WVSS) project was established to develop moisture sensors appropriate for use on commercial aircraft. During the past decade, the WVSS has evolved from using a radiosonde-like thin-film capacitor relative humidity sensor (WVSS-I) to a more precise laser diode mixing ratio measurement system (WVSS-II). The instrument is applicable to all size and speed of aircraft. The WVSS-II data have the potential for filling in the space and time gaps left between other observations by each aircraft providing as many as 10 or more high-resolution tropospheric moisture profiles (along with wind and temperature needed to determine moisture flux) at different sites throughout the day.

The overall objectives of the studies being carried out at the University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS) regarding WVSS-II are:

- To assess the accuracy of the aircraft humidity data by comparing it with radiosonde and ground based remote sensing systems, and

- To provide a basis for determining the optimal spacing and timing of the observations for a variety of weather events.

To address the first goal (the topic of this paper), a ground-truth assessment of the WVSS-II systems being flown on UPS aircraft at Louisville KY was conducted for an approximately 2 week period from 13-24 June 2005. The *accuracy* of WVSS-II humidity data was assessed by comparing it with radiosonde and ground based remote sensing systems. Between 25 and 30 UPS B757 aircraft provided WVSS-II data through MDCRS for assessment during June 2005. In order to avoid the logistical complications of launching radiosondes in areas of congested air traffic near major airports, the tests were conducted at the UPS hub in Louisville – where about 80% of the WVSS-II equipped planes land / take off daily. This initial report of preliminary results only addressees the first of the two project goals and is intended to provide an early look at the general results of the experiment, in terms of the success of the planned observing strategies and some preliminary intercomparison results.

2. OBSERVING SYSTEMS AVAILABLE FOR WVSS-II VALIDATION

All non-aircraft observations were made from a site on the Kentucky Air National Guard (ANG) facility immediately adjacent to the Louisville airport. Observations were taken from the portable “AERIbago” vehicle 24 hours/day during weekdays 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 Atmospheric Emmitted Radiance Interferometer (AERI) infrared interferometer to measure boundary layer temperature and moisture at 10 minute temporal resolution, and a Vaisala RS-92 GPS rawinsonde system, used primarily at night.

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Most of the automated observing systems provided data continuously throughout the two week co-location experiment, with the exception of the GPS-TPW system, which experienced several outages due to temporary power failures at the ANG facilities. These GPS-TPW data are being processed by NOAA FSL. All data taken by the UW-CIMSS systems have been archived at UW-CIMSS for future use. These data are available at: ftp://ftp.ssec.wisc.edu/validation/exper/wvssii/

A full set of aircraft data were also collected from the FSL MADIS data retrieval system for use in the UW-CIMSS assessment.

3. STATUS OF RAWINSONDE VS. AIRCRAFT CO-LOCATION DATA

The most critical observations for this initial report of results were the rawinsonde reports. Three rawinsonde launches were scheduled for each night, one immediately before the majority of the UPS arrivals at about 0240 UTC, another between the rush of descents and ascents at about 0645 UTC[*] and a third after the majority of departures at about 0915 UTC. Exceptions were made on Mondays and Fridays, when scheduling of WVSS-II equipped aircraft by UPS supported only 2 launches on several occasions. The schedule was designed in part to focus on ascents, since there are known problems with descent reports, as discussed later.

A total 27 of the 28 attempted launches were successful, with the one unsuccessful attempt due to equipment failure. Thirteen rawinsondes were launched during the first week and 14 during the second. The rawinsonde data were sent in real time to FSL for display on their ACARS display web site. On a typical day, about 5-10 aircraft co-locations were available, but not all fell within the tightest time window used in this report.

4. ASSESSMENT PROCEDURES

4.1 Constraints of initial assessment

Comparisons of the WVSS-II data with the rawinsonde standard were limited by the following constraints:

1 – Prior to the experiment, an occasional problem was identified in the WVSS-II instrument. This problem produced erroneous reporting in areas of high humidity and clouds, but only in descent. This problem will be addressed through a future hardware change. However, since the objective of the experiment was to assess the difference in good quality reports made by both the aircraft and rawinsonde, it was decided to focus the rawinsonde launches on co-locations with aircraft ascents.

2 – A second problem was also discovered in some of the early installed WVSS-II units in which a small amount of moisture was entering the laser sensing unit and thereby biasing the moisture reports upward. This bias was especially apparent in areas of extremely low mixing ratio (typically at higher altitude and colder temperatures). This problem was addressed in some of the units that were installed later and are available for some of the experiment, but was not corrected for all units before the end of the experiment. As such, results will may be calculated either by a) excluding data from sensors with known and very large biases and/or 2) limiting assessments of WVSS-II performance to regions where the observed mixing ratio was greater than 2 g/kg. Option 2 was used for this report.

3 – Since WVSS-II sensors continued to be installed on the UPS aircraft throughout the experiment, the number of available matches and mix of reporting units daily varied during the test period.

4 – A number of the aircraft had biases in their temperature sensors, which would cause errors in calculated Relative Humidity. Therefore, initial assessments of moisture profiles were made in terms of the primary WVSS-II water vapor observation - mixing ratio (which is reflected in some figures in this paper as specific humidity).

5 – It should also be noted that a deficiency exists in the way the WVSS-II observations are being reported to the ground. Reports of less than 10 g/kg had precision of at least 0.1 g/kg, while reports greater than 10 g/kg had precisions of only 1 g/kg. As such, the accuracy of the assessments had limits that varied from +/-0.05k/kg for reports between 0 and 10 k/kg to +/-0.5g/kg for values above 10 g/kg. This factor will erroneously amplify the variability in the co-location results. Attempts will be made to stratify the assessments statistics to reflect these differences in the future.

4.2 Conventions used in determining aircraft/rawinsonde co-locations

Based upon experience gained in the 3 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 +/- 30 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 (typically at least 20-25) were available for statistical calculations at each level.

When the above conditions are applied to the full set of available data, a total of 49 ascending rawinsonde/WVSS-II matches were available for comparison (from aircraft ascents only). The matches included data from 13 rawinsonde releases 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 moisture were made for each of the 13 rawinsonde-aircraft match-up times. The individual sounding comparison showed a range of similarity and diversity between the 2 observing systems, related apparently to the specific mix of aircraft reporting and the consistency of the weather regime present each day (see Fig. 1). For example, the two ascents that occurred just before the 0644 UTC rawinsonde launch on 21 June showed excellent agreement between the aircraft data and the rawinsonde data, both for temperature and for moisture. Both data sets captured the change in conditions above and below the inversion near 2300 m for both temperature and humidity. These two sets of aircraft reports, taken 23 minutes apart, also showed excellent agreement with one another.

By contrast, the reports taken around the 0915 UTC rawinsonde launch on 22 June showed a much greater spread between the individual reporting aircraft and between the aircraft and the rawinsonde report. In this case, the majority of the reports reflected the rawinsonde values very closely. However, two of the aircraft reports differed from the rawinsonde data by from 1 to 2 g/kg. It should be noted that one of these 'outlying' reports was taken significantly before the rawinsonde launch.

5. STATISTICS FOR THE FULL PERIOD

Weighted average rawinsonde reports were compiled for the full test period (Fig. 2). The averages were weighted 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 will have less influence on the average than a report with many aircraft matches. The temperature profile of these nighttime soundings showed weak temperature inversion in the lowest 50 hPa, capped by a nearly

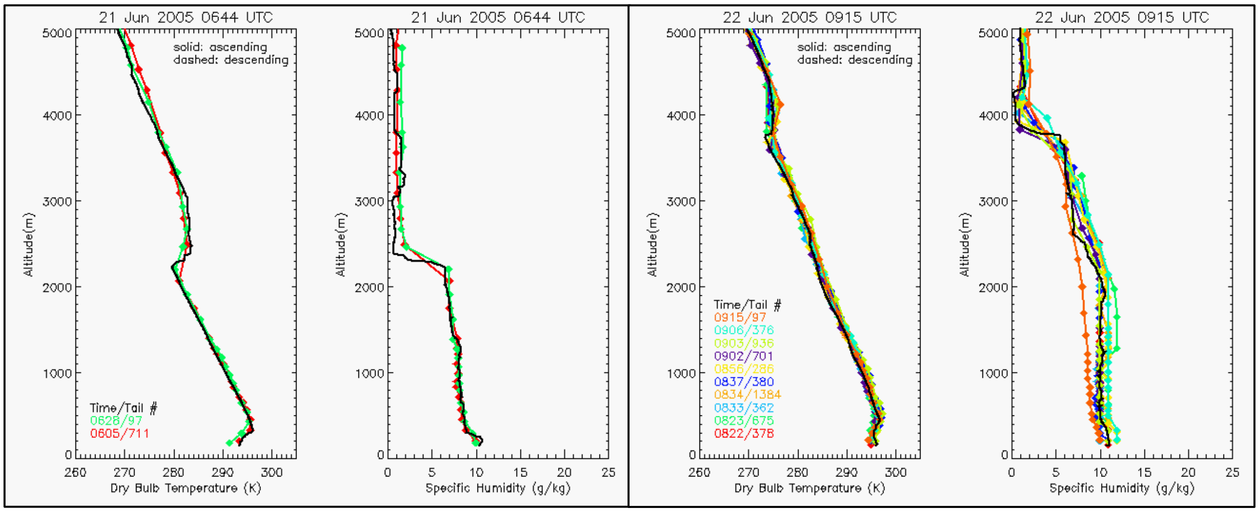

Figure 1 - WVSS-II sounding sets from near 0645 UTC (left) and 0915 UTC (right) on 21 June 2005

adiabatic layer. A weak secondary temperature inversion is also present between 800 and 750 hPa. The moisture profiles showed nearly constant (slightly decreasing) values for the surface to the base of the secondary temperature inversion, a structure consistent with a boundary layer that had been thoroughly mixed during daytime. Above that level, moisture decreases steadily to 500 hPa. The plot of number of matches on the right panel shows increased separation between balloon and aircraft with height as well as the decrease in number of reports used in the intercomparison at upper levels due to the 2 g/kg lower limit which was imposed. It should also be noted that since the average mixing ratio in the lowest 150 hPa was near 10g/kg, truncation error might have affected comparison in this region.

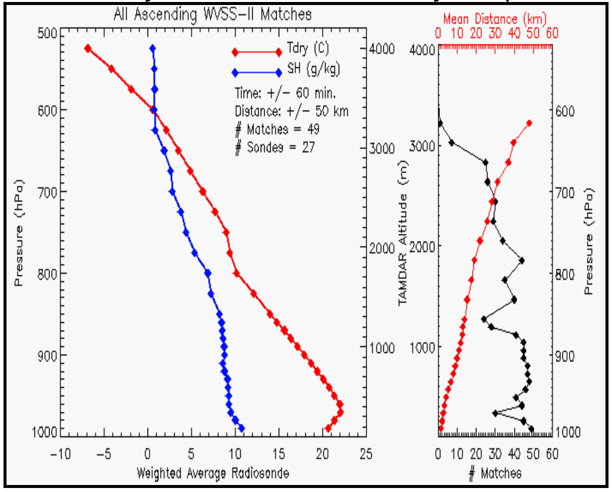

Figure 2 - Mean soundings and co-location counts for full assessment period

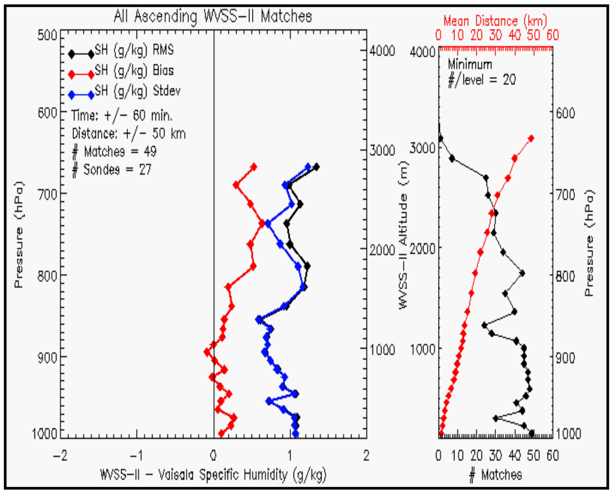

Figure 3 – Bias, RMS and SD co-location statistics between rawinsondes and all ascending WVSS-II aircraft for the full assessment period

Statistical fits of the WVSS-II mixing ratio data to the rawinsonde reports for all of the ascending aircraft were made for the full observation period. Although a minimum of 20 match-ups was needed to calculate significant statistics, most levels used between 30-40 observation matches. All ascending aircraft data with mixing ratio measurements greater than 2 g/kg were included, independent of known specific instrument errors.

Mixing ratio bias results show very small, though generally positive biases (0.1 to 0.2 g/kg) from the surface up to nearly 800 hPa. Above that level, the bias increases to between 0.2 and 0.4 g/kg. Analysis of this bi-modal bias structure has not yet been completed.

The Root Mean Square (RMS) and Standard Deviation (SD) fits of the aircraft data to the rawinsonde reports showed variability of about 1 g/kg from the surface to 800 hPa. Above 800 hPa, RMS values increase to between 1 and 1.5 k/kg, due in large part to the increased biases found in the region.

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^{o}C. RMS measures of variability ranged from about 0.5 to 1.0^{o}C.

If the mixing ratio data had been converted to Relative Humidity as a means of providing comparisons with earlier WVSS-I assessment results, the warm bias shown in the temperature data would have been transferred to the humidity observation misleadingly by making the derived Relative Humidity data appear too dry by about 2-3% at almost all levels. These results indicate that biases in temperature of 0.5^{o}C will produce biases in calculated RH of 3.5 to 4%.

In order to remove the dependency on biased aircraft temperature reports but still provide information in the form of RH accuracy of the WVSS-II sensor alone, the WVSS-II mixing ratio data were combined with the rawinsonde temperature data to produce RH values.

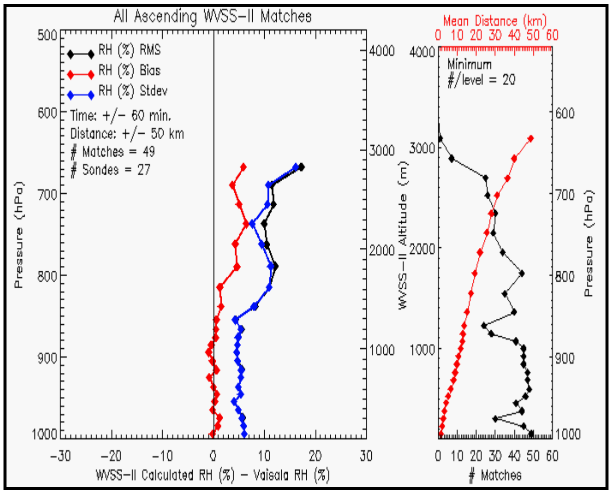

Figure 4 - Bias, RMS and SD calculation for RH derived from WVSS-II mixing ratio and rawinsonde temperatures for all ascending aircraft-rawinsonde matchups.

The statistical RH comparisons shown in Figure 4 are consistent with the Mixing Ratio results shown in Figure 3. Below 800 hPa, the RH matchups show almost no bias and Standard Deviations of about 5% and within the WMO requirements for regional forecasting applications. Above this level, the increase in bias may be an indication of continuation of the problem of seepage of moisture into some of the sensor assemblies described earlier, while the steady increase in SD is again an indication of the increased atmospheric variability above the nocturnal boundary layer and the increased distance between aircraft and rawinsonde at higher elevations.

6. IMPACT OF AIR-TO-GROUND DATA COMMUNICATION COMPRESSION AND SUGGESTIONS FOR IMPROVEMENT

As noted earlier, the convention used to transmit the WVSS-II data from aircraft to ground limits the precision of the moisture reports to only 2 digits. In practice, however, a total of three digits are available for the data transmission, two for the mantissa of the report and 1 for the power of 10 (assumed to always be negative). Part of the reasoning for the decision to use this type of format was probably related to desires both to reduce communication costs by limiting the number of digits added to the weather data messages, and to obtain reports of very low moisture amounts.

Unfortunately, the process of rounding or truncating data to the nearest two digit integer can add substantial error to the moisture reports exceeding 10 k/kg. Additionally, this error varies according to the value of the reported mixing ratio itself. For example, if the data are rounded, observations of both 10.6 and 11.4 g/kg would be reported as 11 g/kg, even though the measurements themselves were separated by 0.8 k/kg. Theoretically, this should add between 0.25 and 0.30 g/kg to the RMS and SD comparisons. Expressed in another way, if the saturation mixing ratio in this case was 12k/kg, the transmitted 11 k/kg data would convert to 91.6%, instead of showing relative humidity values of 88.3% and 95% respectively. This range of values of +/- 3.3% has an effect equivalent to a random temperature error of almost 0.5^{o}C. By contrast, if the report had been 9.5 k/kg with the same saturation value, the range of possible observations would have only varied from 9.45 to 9.55 g/kg or 78.75% to 79.58% - a range of only +/- 0.4%.

The effect of the change in data reporting precision at 10 k/kg are shown in Figure 5, which separates mixing ratio intercomparisons between

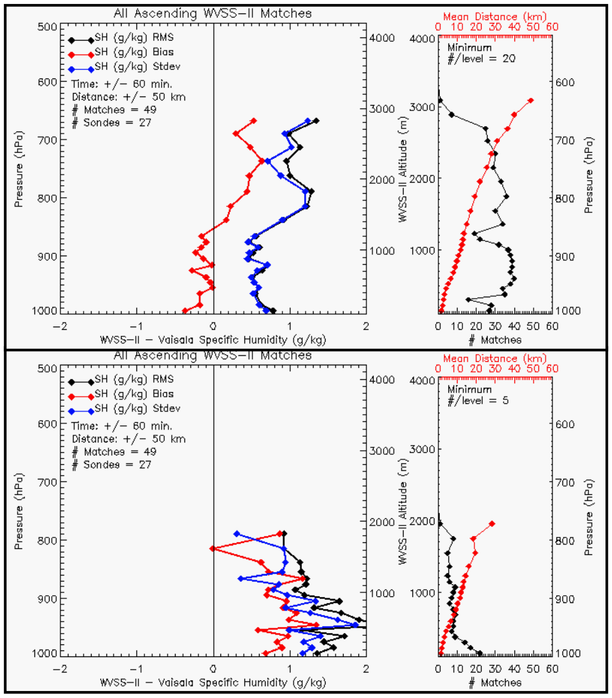

Figure 5 Comparisons of Bias, RMS and SD for Mixing Ratio co-locations divided between observations less than 10 g/kg (top) and greater than 10 g/kg (bottom).

WVSS-II values less than 10 g/kg and those above 10 g/kg. Although only a few reports fall in the larger category and the RMS and SD statistics may therefore not be entirely valid, the jump in bias and the effect of the low-level RMS and SD are readily apparent and consistent with the conceptual analyses presented above. Comparison of the behavior of reports greater than 10 k/kg and those between 8 and 10 g/kg showed similar results, further pointing the error increase to the data discretization conventions.

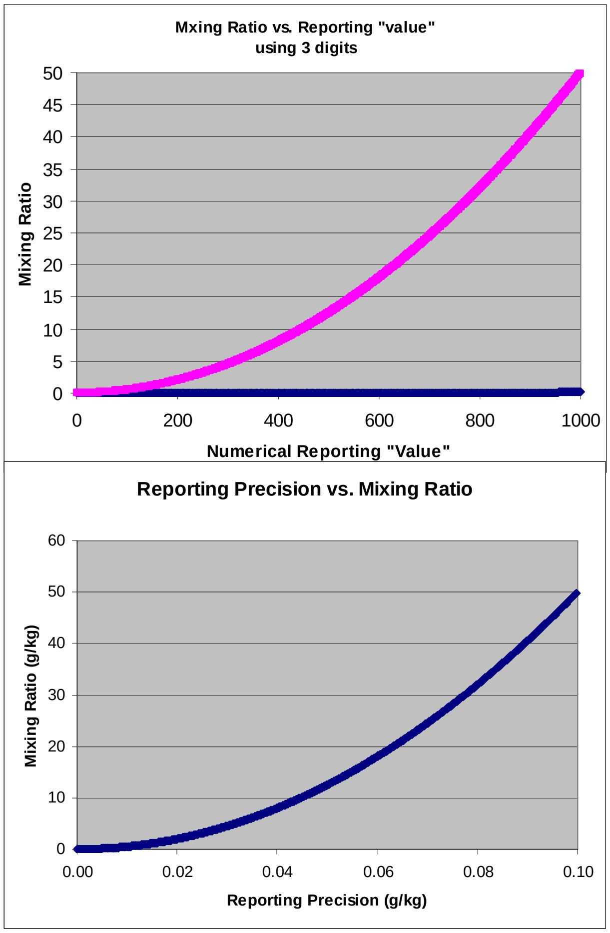

Figure 6 - Suggested alternative discretization schema (top) and associated reporting precision error (bottom) for alternative use of 3-digit reporting procedures for WVSS-II mixing ratio reports.

As an alternative use of the 3 digits that are currently reserved to the coded mixing ratio, a scaled lookup table could be used which would spread the typical range of mixing ratio reports over the full 1000 intervals available as shown in Figure 6. This approach would allow values less than 1 g/kg to be reported at about 0.01 g/kg precision, while improving the precision of observations greater than 10 g/kg to vary smoothly form 0.045 to 0.1 g/kg, a major improvement over the current arbitrary precision reduction for weather forecasting and numerical weather prediction applications.

The major negative aspect of this approach is that the data will not be immediately readable from the report. However, this should not be a major limitation since most, if not all, users of these data will be receiving the data in BURF messages - which already are decoded with computers.

6. Summary

This report presents a preliminary summary of the accuracy of mixing ratio observations made by WVSS-II equipped commercial aircraft. The results show a small, but slightly positive bias in the boundary layer, with slightly larger values above. RMS and SD fits average around 1 g/kg at all. These mixing ratio statistics correspond to RH biases of nearly zero throughout the lowest 200 hPa of the atmosphere and increasing to less than 5% at selected levels aloft. The RH SD results range from 5% in the boundary layer to around 10% aloft. The large values aloft are likely due at least in part to increased atmospheric variability above the nocturnal boundary layer and to the increased separation between the WVSS-II aircraft and the rawinsondes at these elevations. When the observations are categorized according to reporting precision (less than and greater than 10 g/kg), the mixing ratio reports show a slight negative bias below 850 hPa and positive biases above, with the SD only slightly different than for the full sample. However, for mixing ratio values above 10 g/kg, the biases increase dramatically, probably due to a large part to the encoding precision conventions used in constructing the transmitted reports.

7. ACKNOWLEDGMENTS

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