FINAL REPORT

Results of the

November 2006 WVSS-II – Rawinsonde Intercomparison Study

Submitted to NOAA/NWS/OST by

Ralph A. Petersen, PI
Wayne Feltz, co-PI
Sarah Bedka
Erik Olson

of the

University of Wisconsin – Madison
Cooperative Institute for Meteorological Satellite Studies (CIMSS)
1225 West Dayton Street
Madison, Wisconsin 53705

15 March 2008

***Background* –** The University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS) conducted a second ground-truth assessment of the WVSS-II systems being flown on UPS aircraft at Louisville KY during weekdays during the period from 7-18 November 2006. This report is intended to provide a general summary of results of the experiment, in terms of the success of the planned observing strategies and intercomparison results.

Observing Systems Available for WVSS-II Validation - All non-aircraft observations were made at 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 AERI infrared interferometer to measure boundary layer temperature and moisture at 10 minute temporal resolution, and a Vaisala GPS rawinsonde system.

It should be noted that special care was given to assure that the rawinsonde moisture data be as accurate as possible. To that end, Model RS92-SGP rawinsondes with dual thin-film capacitive sensors were used for all rawinsonde launches. The rawinsondes were all less than 6 months old and each one was heated to clean the humidity sensors during the ground check procedure. This avoids the possible introduction of errors from sensor contamination that was a problem with some of the earlier RS80 rawinsondes.

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.

All data taken by the UW-CIMSS systems have been archived at UW-CIMSS for future use.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 has also been collected from the FSL MADIS data retrieval system for use in the UW-CIMSS assessment.

Status of Rawinsonde vs. Aircraft Co-location Data - 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. The rawinsonde launch schedule was designed in part to focus on ascents, since there are known problems with descent reports, as discussed later.

All 28 launches were successful, with no equipment failure. Thirteen rawinsondes were launched during the first week and 15 during the second. One of the rawinsonde, which was launched as part of a system tests before the experiment began, was not used in the statistical evaluation. 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 narrow time and space windows used in this assessment.

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. These deficiencies included:

1. An occasional problem was identified in the WVSS-II instrument which produced erroneous reporting in areas of high humidity and clouds while the aircraft where descending. This problem was addressed by incorporating a heater in the air intake to prevent the retention of water on the cold intake pipe.

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 during the 2005 tests and are available for some of the experiment, but was not corrected for all units before the end of the experiment.

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

4. A deficiency was noted 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 erroneously amplified the variability in the co-location results. A revised reporting algorithm was developed by CIMSS to alleviate this issue. (See appendix for details of reporting system).

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. Unfortunately, the complete conversions were not completed until the November 2006 data collection period was completed. As such, the comparisons of the WVSS-II data with the rawinsonde standard were again limited by the following constraints:

1. The engineering changes that were made to correct the erroneous reports in areas of high humidity and clouds during in descent were not sufficient to alleviate the problem entirely. As a result, since the objective of the experiment was to assess the difference in 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. This bias was especially

apparent in areas of extremely low mixing ratio (typically at higher altitude and colder temperatures). As such, the assessments of WVSS-II performance were again limited to regions where the observed mixing ratio was greater than 2 g/kg.

3. Because the improved 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 – increasing toward the end of the test period.

4. 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.

5. As noted from the 2005 assessment, a software changes was needed to correct a deficiency that was noted in the precision of the WVSS-II observations reported to the ground, which could vary as the reported values exceeded 10 g/kg. This software change affected a separate part of the on-board UPS air-to-ground communications systems. Because this software upgrade was not available on all the UPS aircraft during the data collection period, the assessments here are again limited to reports of less than 10 g/kg of moisture - rather than limiting the assessment only to data from small number of aircraft using the new reporting system. It should be noted that for this November period, only a very small number of reports exceeded the 10 g/kg threshold.

Conventions for identifying aircraft/rawinsonde co-locations - Based upon experience gained in the 4 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 (3 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. Numerical 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 (See Appendix B). 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. For example, the seven ascents that occurred within the hour before the 1036 UTC rawinsonde launch on 17 November (See Fig. 1) showed excellent agreement between the aircraft data and the rawinsonde profiles. The individual

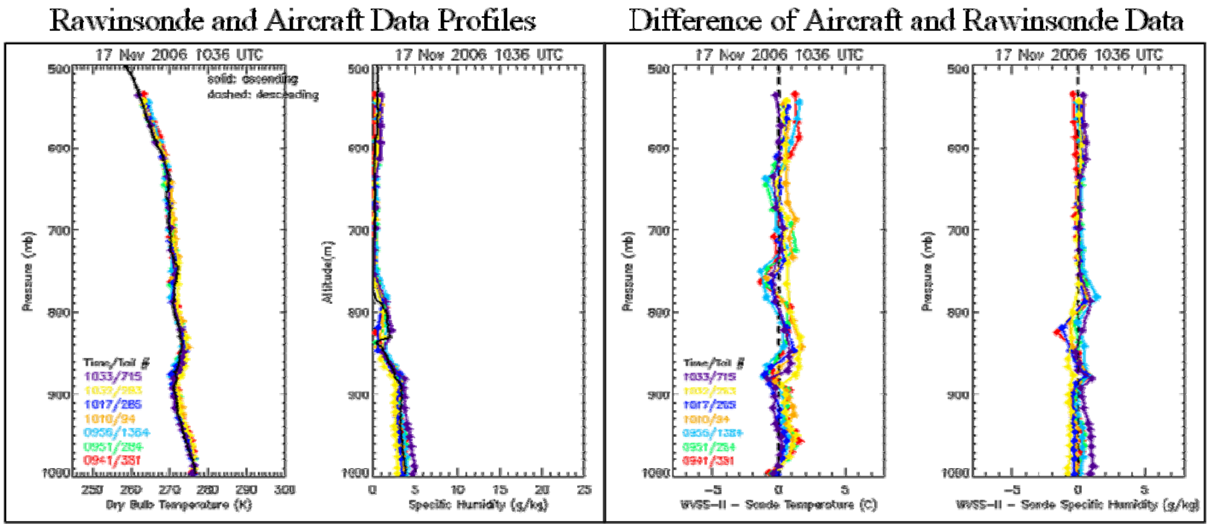


Figure 1: ***Left Panel*** **-** Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from seven different WVSS-II equipped aircraft on 17 November 2006 at Louisville KY. Aircraft observations made within 60 minutes of rawinsonde launch time. Only ascent data available from aircraft for this period. ***Right Panel*** **-** Difference between rawinsonde and individual aircraft profiles for same data.

aircraft reports also showed excellent agreement with one another throughout the period. Although the temperature profiles from some of the aircraft showed differences as large as 2^o at some times, the specific humidity reports made by the WVSS-II systems were within 1 g/kg at all levels. Both data sets captured the inversion between 900 and 850 hPa for both temperature and humidity. In addition, the aircraft data show changes in conditions above and below the inversion during the 52 minute period.

By contrast, the reports taken around the 0400 UTC rawinsonde launch on 16 November (Fig. 2) showed a much greater spread in the WVSS-II moisture data, not only between the individual reporting aircraft (left panels), but also between the aircraft and the rawinsonde report (right

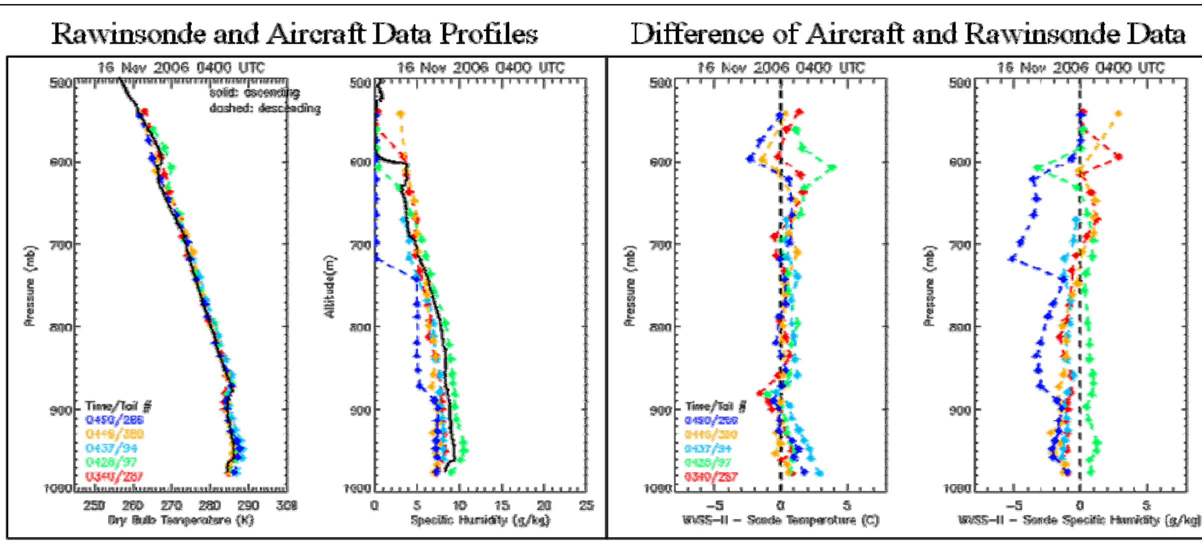


Figure 2: ***Left Panel*** **-** Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from seven different WVSS-II equipped aircraft on 16 November 2006 at Louisville KY. Aircraft observations made within 60 minutes of rawinsonde launch time. Only descent data available from aircraft for this period. ***Right Panel*** **-** Difference between rawinsonde and individual aircraft profiles for same data.

panels). In this case, the reports were all obtained from aircraft while in descent. The agreement between the aircraft and rawinsonde temperature data was similar to that shown in Fig. 1. However, the aircraft moisture reports generally differed from the rawinsonde data by from 1 to 2 g/kg, with one of the reports being 2-4 g/kg drier than the rawinsonde.

Based upon these findings, data from all aircraft which showed consistently large deviations from the co-located rawinsonde reports (see example in Fig. 3) were eliminated from the statistical assessments to be discussed next. Details of aircraft data used and excluded in the assessment are given in Appendices C and D.

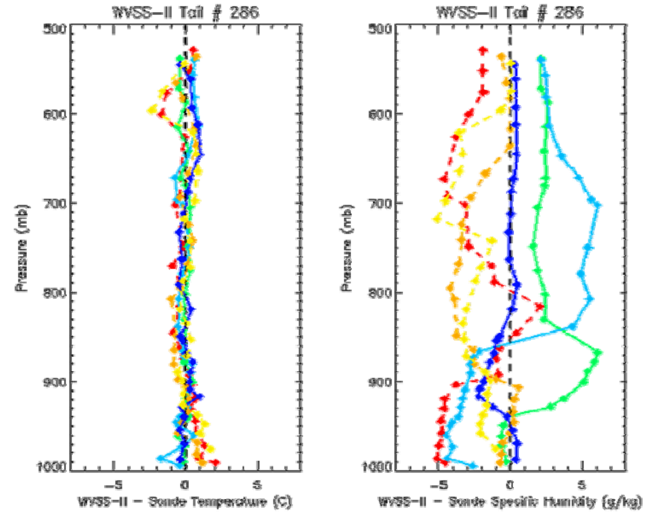


Figure 3. Differences of Temperature (***left***) and Specific Humidity (***right***) between co-located rawinsondes and an individual UPS aircraft (ACARS pseudo-tail # 286) from 8-17 November 2006. All data report were made at night at Louisville KY.

Summary Statistics for the full period - Weighted average rawinsonde reports were compiled for the full test period. 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 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 for the influence of solar radiation of the rawinsondes were unnecessary. The average temperature profile for the two week assessment period (Fig. 4) shows 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 profiles show a slight increase in moisture immediately above the surface, with steadily decreasing specific humidity from there to 500 hPa. The plot of number of matches on the right panel shows the decrease in number

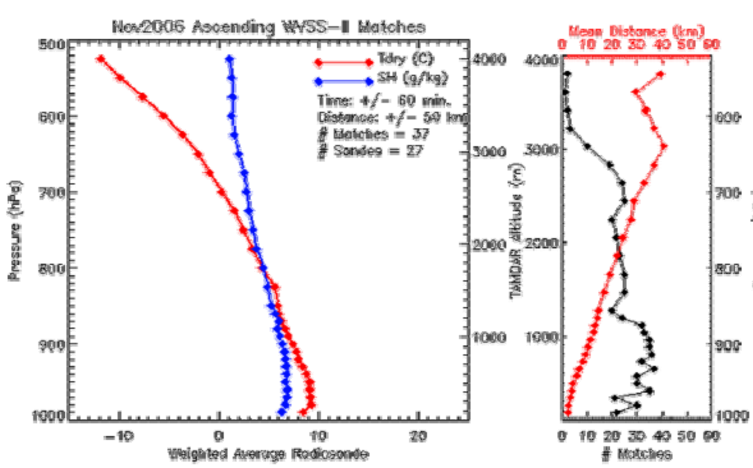


Figure 4. *Left Panel* - Mean Temperature (°C) and Specific Humidity (g/kg) Profiles computed from nighttime rawinsonde observations made between 8-17 November 2006 at Louisville KY.
Right Panel - Number of matches with WVSS-II equipped aircraft (within +/- 60 minutes and +/- 50 km) and mean distance between matched sets of observations.

of reports used in the intercomparison due to the 2 g/kg lower limit that was imposed. It should also be noted that because the average specific humidity in the lowest 100 hPa approached

10g/kg, truncation errors in some of the air-to-ground communication systems may have limited comparison in this region as well.

Figure 5 shows statistical fits of the WVSS-II Specific Humidity (SH) data to the rawinsonde reports for the full observation period excluding WVSS-II systems that showed consistent erratic behavior. All other ascending aircraft data were included in these initial calculations, independent of specific instrument Biases or data transmission software. (See Appendices C and D for plots of differences between each aircraft report and corresponding rawinsonde.) Although a minimum of 10 match-ups were needed to calculate significant statistics at any level, between 30-40 observational matches were found at most levels.

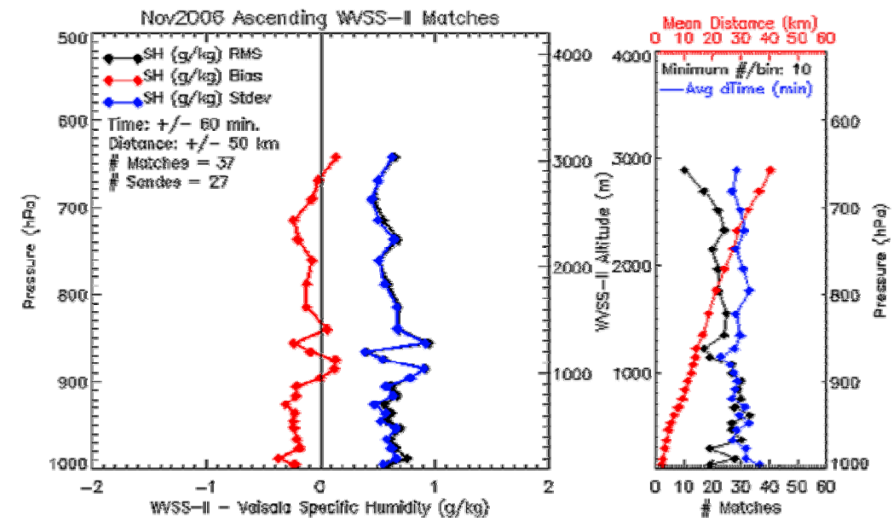


Figure 5: ***Left Panel*** - Statistical comparison of Rawinsonde and WVSS-II moisture observation for the period 7-18 November 2006 at Louisville KY. Bias, Root Mean Square (RMS) and Standard Deviation (Stdev) between data sets (g/kg). ***Right Panel*** - Number of observations used to calculate statistics (matched within +/- 60 minutes and 50 km) and mean distance between observations shown in right panel.

Comparison or WVSS-II SH to rawinsonde data shows 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 (Stdev) 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 of the WVSS-II observations themselves (Fig. 6) 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 (left-most, red lines), both the SH (top panel) and Temperature (T - bottom panel) 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}. At longer time differences (right-most, blue line) however, the variability between observations at lower levels increases 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.

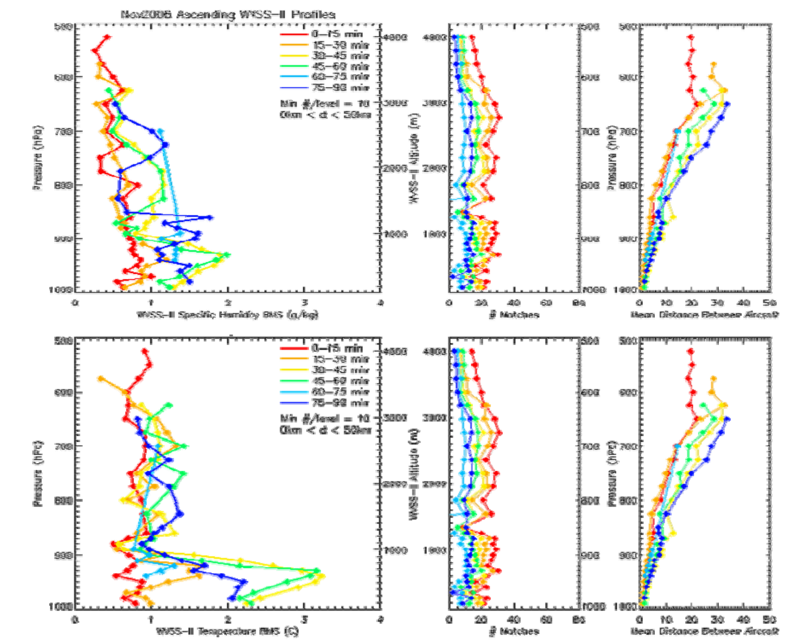


Figure 6: Statistical inter-comparisons of moisture (*top*) and temperature (*bottom*) observations made by multiple WVSS-II equipped aircraft for successive 15-minute time intervals. RMS statistics (*left*), number of aircraft matches used for each time interval (*center*) and distance between matched aircraft pairs (*right*).

It should also be noted that the agreement between multiple 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.

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 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

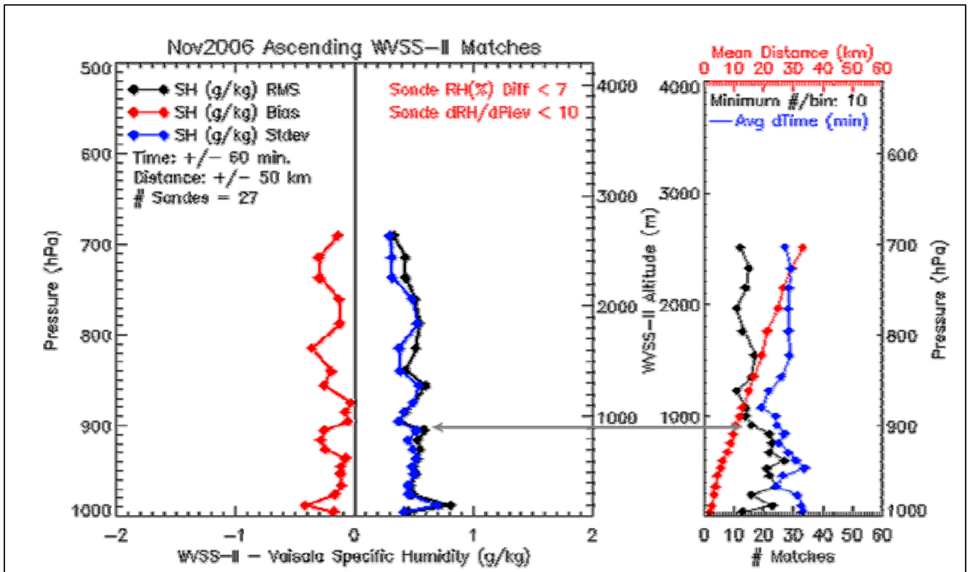


Figure 7. Same as figure 5, except excluding WVSS-II observations <2 g/kg or > 10 g/kg and cases where Relative Humidity (RH) between successive rawinsonde reports in distinct 10 hPa layers varied by more than 7%/hr and where rawinsondes showed extreme vertical moisture gradients (Relative Humidity changes greater than 10 % between adjacent 10 hPa).

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.

When comparing the assessment results using the additional restrictions shown in Fig. 7 with the original statistics in Fig. 4, 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 - Stdev) 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 changes due to the elimination of reports less than 2 g/kg, which tended to have a moist (+) Bias. Additionally, the random error (Stdev) was reduced to between 0.2-0.4 g/kg in the entire region above 900 hPa. Although the peaks in Bias and Stdev 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.

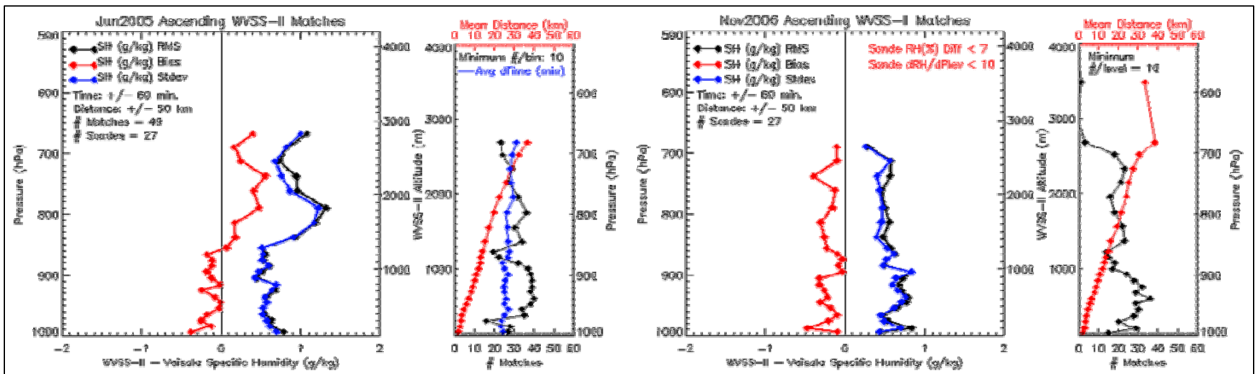


Figure 8: Similar to Figure 5, but comparison of WVSS-II performance statistics for two weeks in Spring 2005 (***left***) and Fall 2006 (***right***).

When contrasted with results obtained from the Spring 2005 assessment shown in Figure 8, 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 Stdev (and RMS) below 900 hPa show very similar results form the two different tests (Stdev 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 (Fig. 9). 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 (Stdev) range from about 0.5 °C in 500 hPa to ~1.0 °C down to 950 hPa to 1.5°C near the surface.

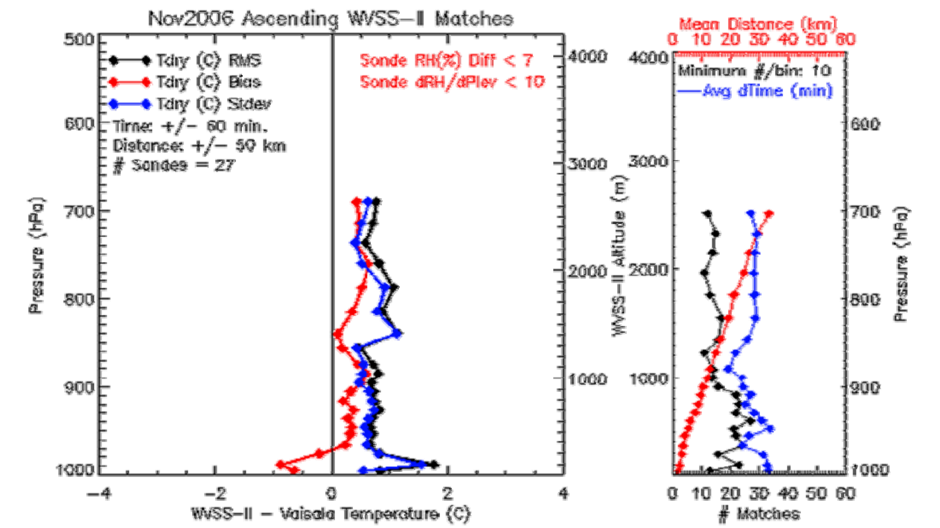


Figure 9: ***Left Panel*** - Statistical comparison of Rawinsonde and WVSS-II Temperature observation for the period 7-18 November 2006 at Louisville KY. Bias, Root Mean Square (RMS) And Standard Deviation (Stdev) between data sets in °C. ***Right Panel*** - Number of observations used to calculate statistics (matched within +/- 60 minutes and 50 km) and mean distance between observations.

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 in Fig. 10 appear too 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.

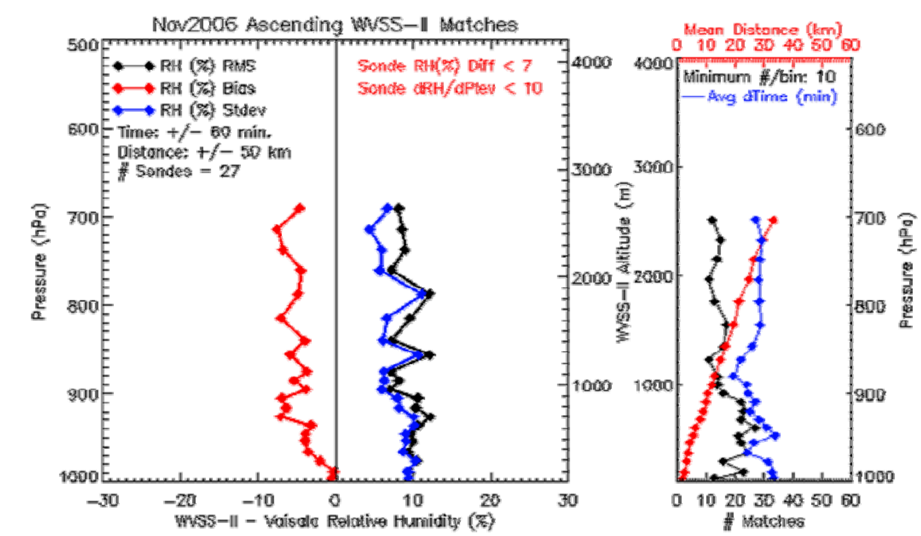


Figure 10: ***Left Panel*** - Statistical comparison of Relative Humidity (RH) derived from Rawinsonde and WVSS-II Specific Humidity and aircraft Temperature observation taken at Louisville KY during the period 7-18 November 2006. Bias, Root Mean Square (RMS) and Standard Deviation (Stdev) between data sets in %. ***Right Panel*** - Number of observations used (matched within +/- 60 minutes and 50 km) and distance between observations at right.

A better representation of the RH error expected from the WVSS-II system itself can be 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 for calculated Relative Humidity shown in Fig. 11 reflect only the Biases noted in the SH results (see Fig. 7), 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 (see Figure 4). These values meet and exceed WMO observational requirements.

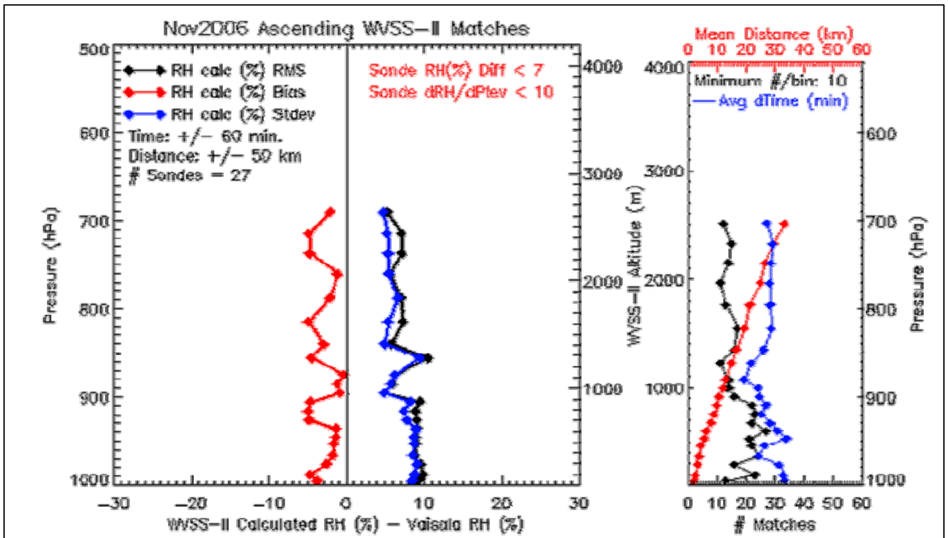


Figure 11: ***Left Panel*** - Statistical comparison of Relative Humidity (RH) calculated by combining Specific Humidity data from Rawinsonde and WVSS-II with Rawinsonde Temperature observation for the period 7-18 November 2006 from Louisville KY. Bias, Root Mean Square (RMS) and Standard Deviation (Stdev) between data sets in %. ***Right Panel*** - Number of observations used to calculate statistics (matched within +/- 60 minutes and 50 km) and mean distance between observations.

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.

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.

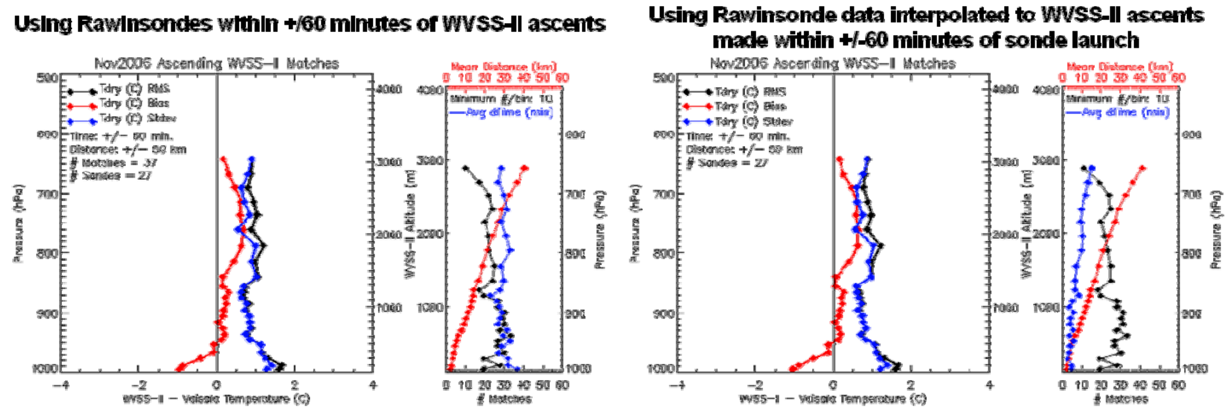


Figure 12: Intercomparisons of ACARS Temperature reports (°C) with data from nearest rawinsonde launched within +/-60 minutes of aircraft ascent (left), and data time-interpolated from rawinsondes bracketing the aircraft to the time of aircraft ascents made within +/-60 minutes of rawinsonde launch (right) at Louisville KY for the period from 7-18 November 2006.

The results for temperature data taken within +/-60 minutes of each other in Fig. 12 show that although the number of aircraft-rawinsonde matches increases slightly at most levels and the time offset between the data interpolated the overall statistical comparisons showed only small impact, with a slight reduction in Bias, RMS and to the aircraft take-off time and the subsequent in-flight reports was reduced substantially, Stdev at some levels above 900 hPa when compared with basic comparisons shown in Figure 5.

For the moisture data (Fig.13), a total of 4 options were compared. These included using 1) all WVSS-II observations that passed Quality Control within +/-60 minutes of the rawinsonde launch compared with the rawinsonde report nearest in time without any time-interpolation (upper left), 2) all WVSS-II observations that were made anytime between the first and last rawinsonde launch and passed Quality Control compared with time-interpolated rawinsonde (upper right), 3) the final evaluation results discussed earlier, which are the same as 1), but excluding levels where the rawinsonde data showed extreme vertical and/or temporal moisture changes (lower left), and 4) the same as 2), but using only WVSS-II data taken within +/-60 minutes of rawinsonde observations.

Examination of the upper-left and lower-right panels shows that the addition of time-interpolation only slightly lessens the impact of the singularity found at the top of the subsiding dry layer near 900 hPa in both reducing the Bias and RMS/Stdev there and near 700 hPa. Otherwise, the results are essentially unchanged. 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 (upper-right panel), the number of matches nearly doubled at most levels, going from near 30 to over 50 below 900 hPa. The Bias and RMS/Stdev statistics, however, became generally worse. Below 900 hPa, the Bias nearly doubled, while the RMS/Stdev 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/Sdev increased from ~1 g/kg to nearly 1.5 g/kg. 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 shown in figure 6. Comparison of the lower two panels shows additionally that, even for data 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.

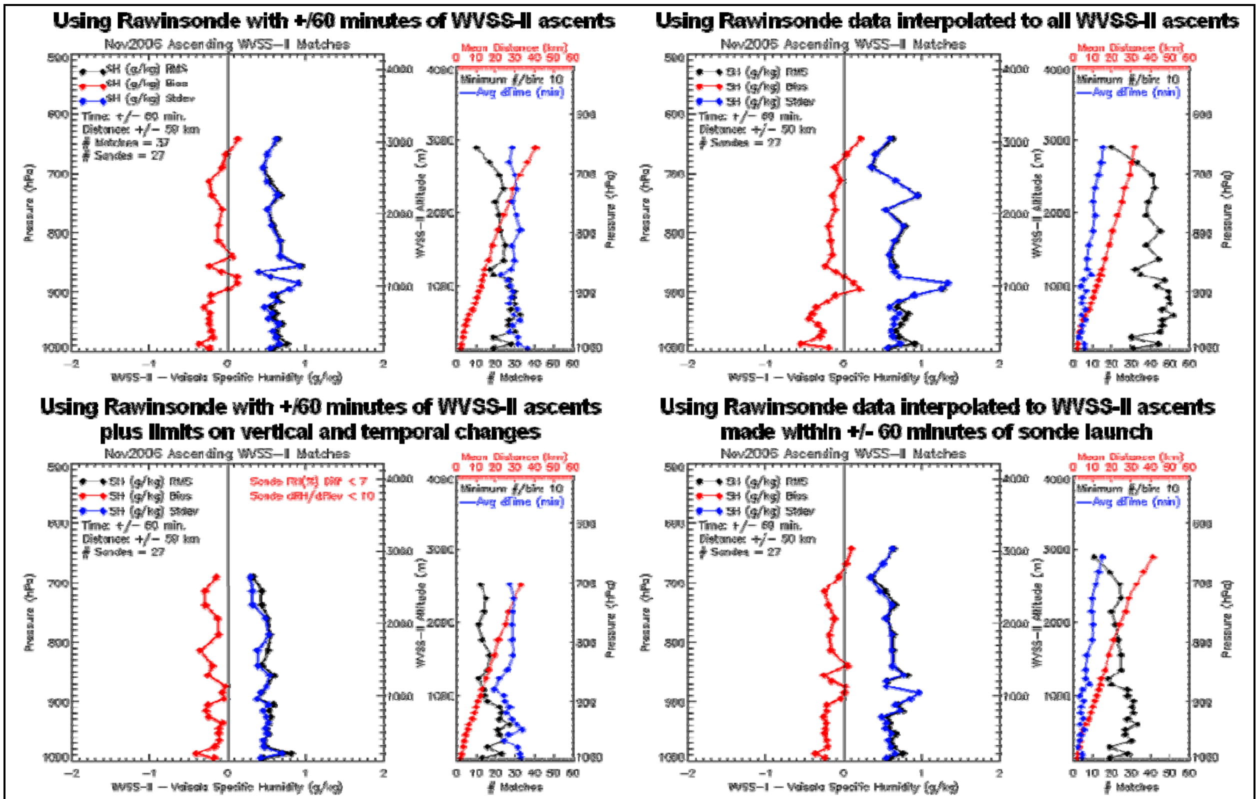


Figure 13: Intercomparisons of WVSS-II Specific Humidity reports (g/kg) with data from nearest rawinsonde launched within +/- 60 minutes of aircraft ascent (upper-left), data using additional limits on allowable vertical and temporal moisture variation (lower-left), data time-interpolated from rawinsondes bracketing the aircraft to the time of <u>all</u> aircraft take-off (upper-right), and data time-interpolated from rawinsondes bracketing the aircraft to the time of aircraft ascents made within +/- 60 minutes of rawinsonde launch (lower-right) at Louisville KY for the period from 7-18 November 2006.

Tests of utility of RUC analysis data as an evaluation standard: In the second alternative assessments technique tests, hourly 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, (Figs. 14-15). 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 (upper left), 2) all observations observations that passed Quality Control compared with the closest hourly RUC analysis data taken from the model grid point nearest the Louisville airport (upper-right), and 3) comparison for rawinsonde data with hourly RUC analysis data taken from the model grid point nearest the Louisville airport (lower right).

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.

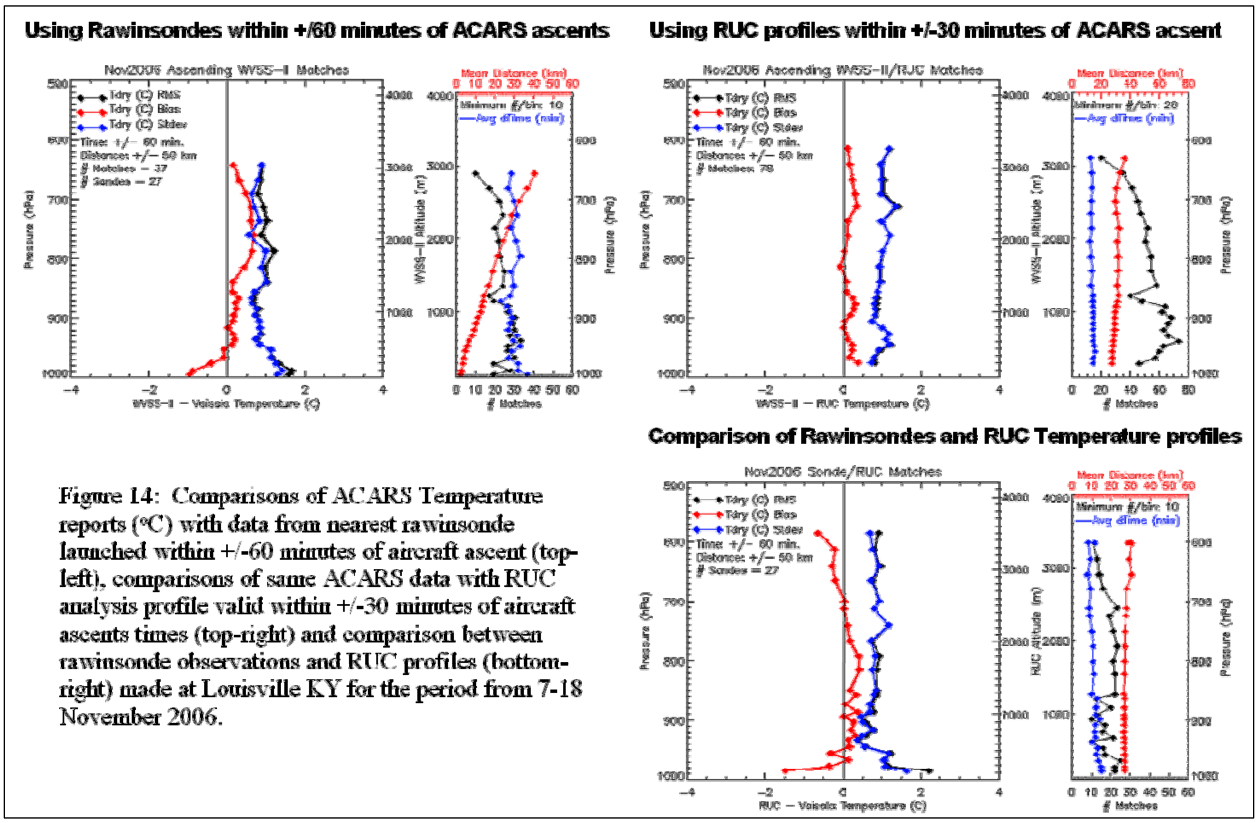


Figure 14: Comparisons of ACARS Temperature reports (°C) with data from nearest rawinsonde launched within +/-60 minutes of aircraft ascent (top-left), comparisons of same ACARS data with RUC analysis profile valid within +/-30 minutes of aircraft ascents times (top-right) and comparison between rawinsonde observations and RUC profiles (bottom-right) made at Louisville KY for the period from 7-18 November 2006.

The temperature intercomparisons show generally similar results, with the RUC analyses having many more matches than the rawinsonde data, as is to be expected. The lower-left panel shows that the RUC temperature analyses fit the rawinsonde data very well except in the lowest 50hPa, where the RUC analyses were systematically colder than observed and had large random differences from the rawinsonde data. Aloft, the agreement between the RUC and rawinsonde temperatures ranged from about 0.8°C between 950 and 750hPa to about 1°C above 750 hPa, with a slight warm Bias from 950 to 750 hPa and a slight cold Bias aloft. The fit of the temperature reports obtained from all ACARS systems on the WVSS-II equipped aircraft to the RUC analyses to the RUC analyses was also very close, but with nearly no Bias. This provides good evidence of the ability of the RUC analyses to retain the information contained in the temperature profiles reported during aircraft ascent and descent. Except very near the surface, the aircraft data taken within +/-60 minutes of the rawinsonde reports fit the rawinsonde data better than the RUC analyses, even in the area of slight warm Bias centered around 750hPa. This would indicate that, even for temperature, the RUC analyses were unable to retain all of the small-scale variability noted in the aircraft data.

For moisture, the picture is less positive. In this case, the fit of the RUC moisture analysis to the rawinsonde data taken at Louisville showed both large Biases and large RMS/Stdev 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 Stdev values exceeding 1g/kg at almost every level. The maximum value > 1.5 g/kg at 700 hPa, corresponding to a RH difference of nearly 50%. By comparison, the Stdev 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/Stdev values between 1 and 1.5 g/kg.

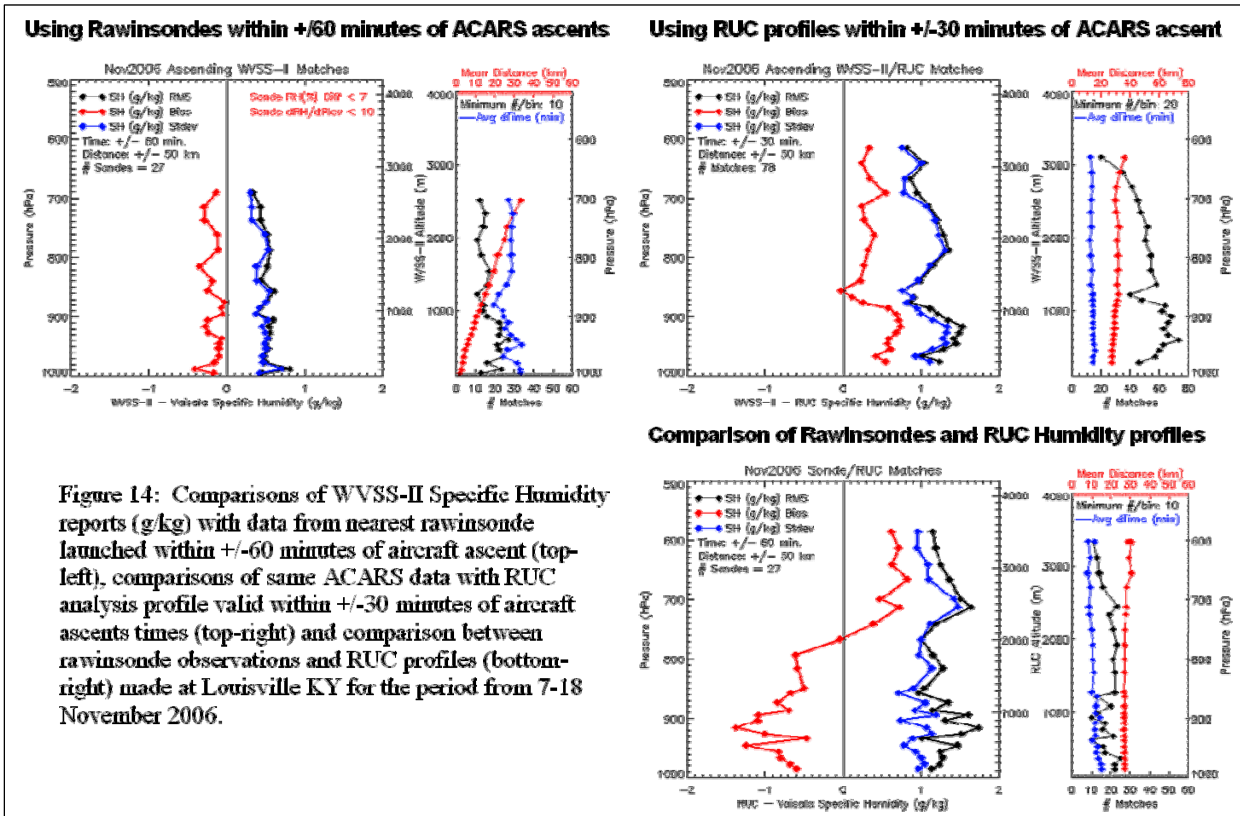


Figure 14: Comparisons of WVSS-II Specific Humidity reports (g/kg) with data from nearest rawinsonde launched within +/-60 minutes of aircraft ascent (top-left), comparisons of same ACARS data with RUC analysis profile valid within +/-30 minutes of aircraft ascents times (top-right) and comparison between rawinsonde observations and RUC profiles (bottom-right) made at Louisville KY for the period from 7-18 November 2006.

From these results 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 that are being carried out under this proposal should help to address that question.

Although the temperature comparisons shown above show that the RUC can add value when used to measure observational accuracy, the fact that the errors in the RUC 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 for that matter short range forecasts) as a validation standard for any moisture observation.

***Summary* –** 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 summarized in Figure 16 show a 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.

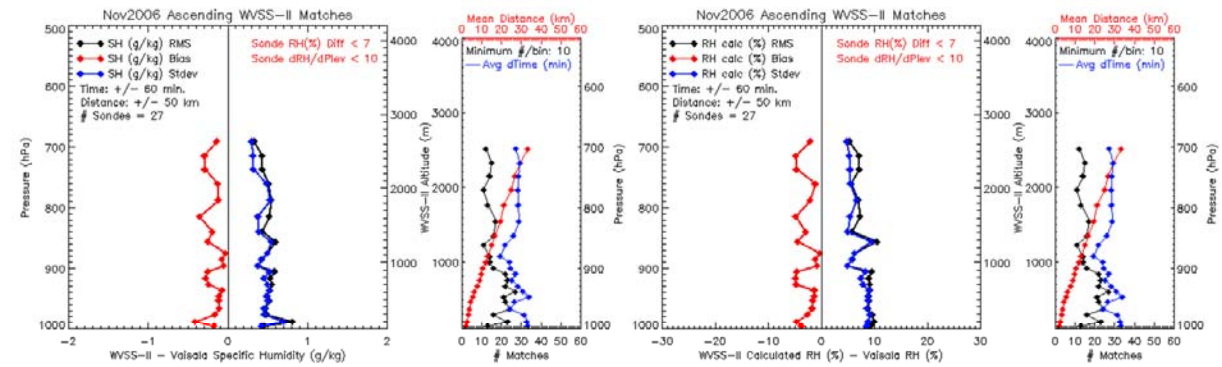


Figure 16: ***Leftmost Panel*** - Statistical comparison of Rawinsonde and WVSS-II moisture observation for the period 7-18 November 2006 at Louisville KY. Excludes WVSS-II observations <2 g/kg or > 10 g/kg and cases where Relative Humidity (RH) between successive rawinsonde reports in distinct 10 hPa layers varied by more than 7%/hr and where rawinsondes showed extreme vertical moisture gradients (Relative Humidity changes greater than 10 % between adjacent 10 hPa). Bias, Root Mean Square (RMS) and Standard Deviation (Stdev) between data sets (g/kg). ***Left-center Panel*** - Number of observations used to calculate statistics (matched within +/- 60 minutes and 50 km) and mean distance between observations shown in right panel.

Right-Center Panel - Statistical comparison of Relative Humidity (RH) calculated by combining Specific Humidity data from Rawinsonde and WVSS-II with Rawinsonde Temperature observation for the period 7-18 November 2006 from Louisville KY. Bias, Root Mean Square (RMS) and Standard Deviation (Stdev) between data sets in %. Same WVSS-II data used as in Left Panels. ***Right-most Panel*** - Number of observations used to calculate statistics (matched within +/- 60 minutes and 50 km) and mean distance between observations.

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.

Acknowledgments - 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, MSG Jeffery Sarver KYANG, and the graduate students and staff of CIMSS who made this verification exercise possible. The work was supported by the NWS/Office of Science and Technology through the NESDIS-UW CIMSS agreement.

Appendix A

A recommended scheme for reporting encoded mixing ratios from WVSS-II observations

Ralph A. Petersen
University of Wisconsin-Madison, CIMSS

Background:

Current air-to-ground reporting conventions within the ARINC 620 standards restrict the precision of reports from the second generation Water Vapor Sensing System (WVSS-II) to two digits of significance for the reported mantissa and one digit to indicate the proper exponent of 10. This scheme allows very small values of mixing ratio to be reported with high accuracy. However, errors in reports of larger amounts of moisture can become unacceptably larger. In addition, there is an abrupt change in precision in the meteorologically important range of moisture values around 10 g/kg. Specifically, values less than 10 g/.kg are reported to the nearest 0.1g/kg, equivalent to about 0.1^{o}C dewpoint temperature (Td) precision and 1% relative humidity (RH). By contrast, values of 10 g/kg or greater are reported to the nearest whole value intervals of 1 g/kg, producing uncertainties in the reports for RH as large at 10% and as much as 1.0^{o}C for Td. This degree of uncertainty could prevent their use in Data Assimilation and Numerical Weather Prediction.

Constraints and Requirements:

The following discussion presents a continuous scheme for converting the mixing ratio values observed by WVSS-II into easily interpreted coded values which retain required reporting precisions at all moisture levels while using only the 3 digits allocated for the reports within the ARINC 620 standard. It should be noted that this study assumed that the primary users of WVSS-II reports will have the capability of decoding the reports electronically and that the reports need not be easily readable from direct printouts of the down-linked data by field forecasters. If a visual decoding capability is needed, simple conversion charts and conventions could be made available.

For reference, the precision of the A/D converter used in the WVSS-II systems is about 0.000625 g/kg. This is greater than the maximum reporting precision required by the National Weather Service (NWS), which states that the reporting precision should range from 0.001 g/kg at coldest temperatures to 0.1 g/kg in very warm/humid conditions. It should also be noted that, according to official NCDC data, global records for Td range from -98.2 to 34.0^{o}C, with unofficial reports reaching 35^{o}C. This maximum Td corresponds to mixing ratios near 36.9 g/kg. This information has led the NWS to suggest that the required reporting range should be from 0.005 to 38.0 g/kg.

The following presentation was based on a desire to preserve precision for all mixing ratio reports in the range from 0.0 to 38.0 g/kg. The scheme could easily be adapted to extend the reporting range from 0.0 to 40.0 g/kg, but with a decrease in reporting precision for all mixing ratio values.

Options tested:

A variety of data compression approaches were considered for this study, but focused primarily on four options that could easily be encoded (on board the aircraft) and decoded (on the ground) using simple and fast analog algorithms. These included a linear fit, quadratic fit, a cubic fit and an intermediate quadratic/cubic option, as discussed below. In all cases, the objectives were to preserve the precision of observations needed by several user communities, most notably the climate community's desire to obtain information about high level cirrus clouds and the weather forecasting community's need for accurate observations of lower-tropospheric moisture and moisture gradients, especially as related to heavy precipitation and severe weather events. These objectives are consistent with NWS precision requirements.

Three different comparisons were made in evaluating the acceptability of each of the schemes. As a first test, the mixing ratio values corresponding to each of the 1000 possible encoding values between 0 and 999 were determined for each of the compression schemes. (It should be noted that the range of encoded values can easily be reduced below 1000 if specific values are needed for other reporting needs, such as error flags). Tests were made using linear fits as well as quadratic, cubic and 2.5 power polynomials. Figure 1 shows that the linear option, while easiest to decode 'visually', uses very few "encoding values" for the lowest mixing ratio values. By comparison, all three of the polynomial approaches provide many more "encoding values for the very low values of interest to the climate community. However, as the power of the polynomial used for encoding increases, the portion of the 0-999 encoding range allocated to reports of meteorological significance (e.g., mixing ratio values greater than approximately 10 g/kg) decreases from 75% for linear encoding methods to 35% for cubic methods.

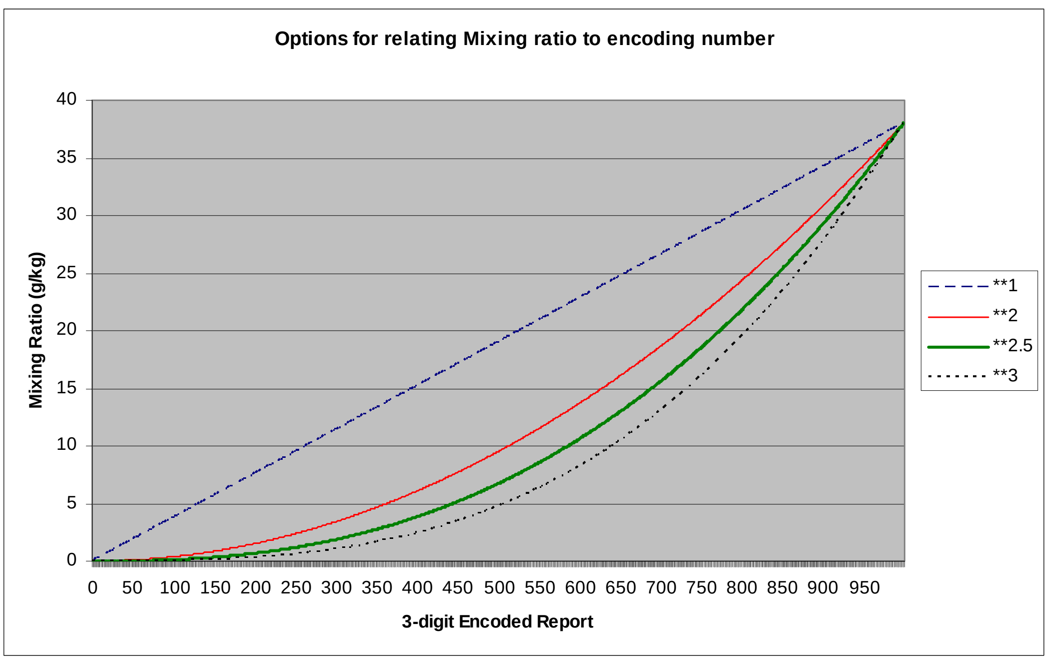


Figure 1 – Comparisons of 4 options for converting mixing ratio values between 0.005 and 38.0 g/kg into 3-digit coded reports. Dashed blue line shows linear encoding, solid red is for quadratic encoding, solid green represents $10^{2.5}$ *encoding, and dashed black is for cubic encoding.*

As a second test of each encoding option, plots were derived showing the precision of each encoded report across the full range of encoded values. The results in Figure 2 show that the linear approach has a constant encoding precision of .038 g/kg across the full range of reports. This option is unacceptable in that it does not provide sufficient accuracy in the colder (lower mixing ratio) range of values important to climate applications, where NWS requirements specify precisions of between 0.001 and 0.01 g/kg. While improved for mid-range values, the quadratic encoding scheme only provides the required 0.001 g/kg precision for mixing ratio values below 0.011 g/kg. This again is unacceptable. By contrast, both the cubic and 2.5 power schemes retain 0.001 precision to 0.034 and 0.026 g/kg.

The cubic and 2.5 power schemes retain 0.01 k/kg precision up to 1.0 and 0.9 g/kg respectively. Also, in the range of mixing ratio values typically observed in the lower troposphere (e.g., 10-20 g/kg), both schemes have precisions between 0.05 and 0.07 g/kg, although the precision of the 2.5 power scheme is somewhat better than the cubic scheme in this reporting range. For values above 31 g/kg, however, the cubic scheme exceeds the NWS precision requirement of 0.1 g/kg, while the 2.5 power scheme meets the required precision for all reports up to 38 k/kg.

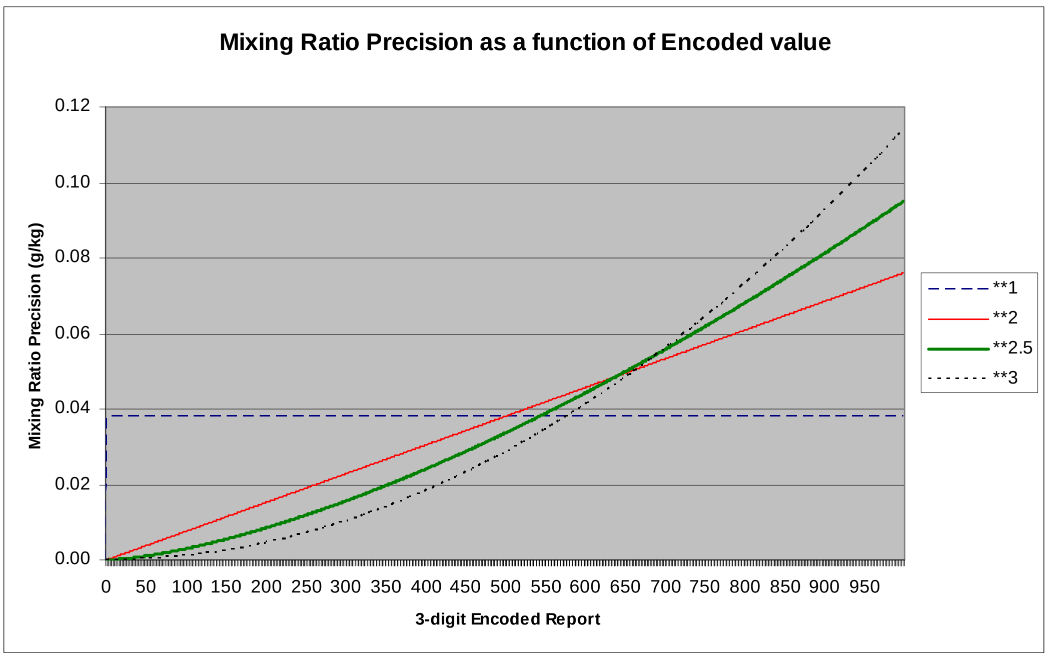


Figure 2 – Comparisons of reporting precision for 4 options of converting mixing ratio values between 0.005 and 38.0 g/kg into 3-digit coded reports. Dashed blue line shows linear encoding, solid red is for quadratic encoding, solid green represents $10^{2.5}$ encoding, and dashed black is for cubic encoding.

Another test of the usefulness of the various encoding options was performed by comparing the encoding precision with the A/D converter accuracy. In an ideal situation, the encoding precision should never become greater than the A/D converter resolution. Otherwise, the reported data will have greater precision than can be observed by the D/A converter. Although this does not harm the data reports themselves, it does produce redundant reports and/or wastes some encoding intervals by leaving them unused.

Figure 3 relates the various encoding intervals into A/D converter units. The results show that for the linear scheme, each encoding interval corresponds to nearly 61 A/D conversion intervals, a large underreporting of system performance, especially for low values of mixing ratios. The quadratic scheme shows the best performance at the lowest mixing ratio range, with only the smallest 10 encoded reports having precisions that are smaller than the A/D – with 5 wasted encoding 'bins' (a situation where 2 or more encoding numbers could be used to represent the same observed value). For the cubic the cubic scheme, the number of wasted encoding 'bins' increases over 50, while the 2.5 power scheme meets reporting precision requirements but still leaves over 21 unused encoding 'bins'.

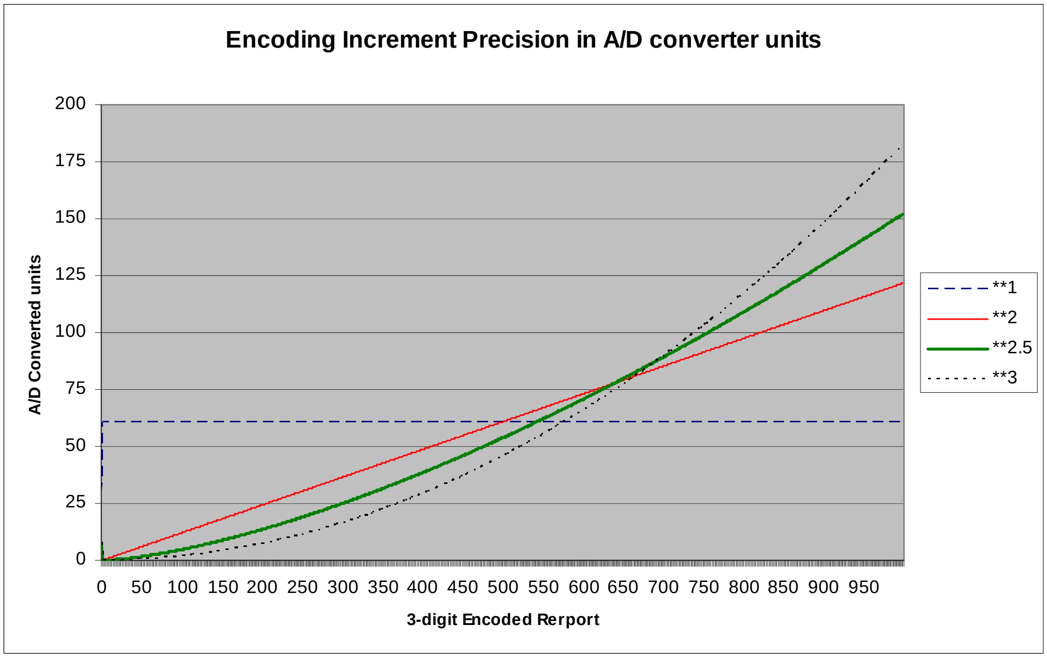


Figure 3 –Calculation of number of A/D converter units between each 3-digit coded reports for 4 options of converting mixing ratio values between 0.005 and 38.0 g/kg. Dashed blue line shows linear encoding, solid red is for quadratic encoding, solid green represents $10^{2.5}$ encoding, and dashed black is for cubic encoding.

In order to assure that the encoding increment at least as large as the A/D converter precision, an additional factor was included in the 2.5 power encoding algorithm (see appendix for details). As shown in Figure 4, the degree of reporting precision in the modified 2.5 scheme changes only slightly, and then only at the lowest reported values. However, only 1 reporting bin was wasted using this modification. The additional precision allowed by the additional useful reporting increments was spread across the entire reporting range.

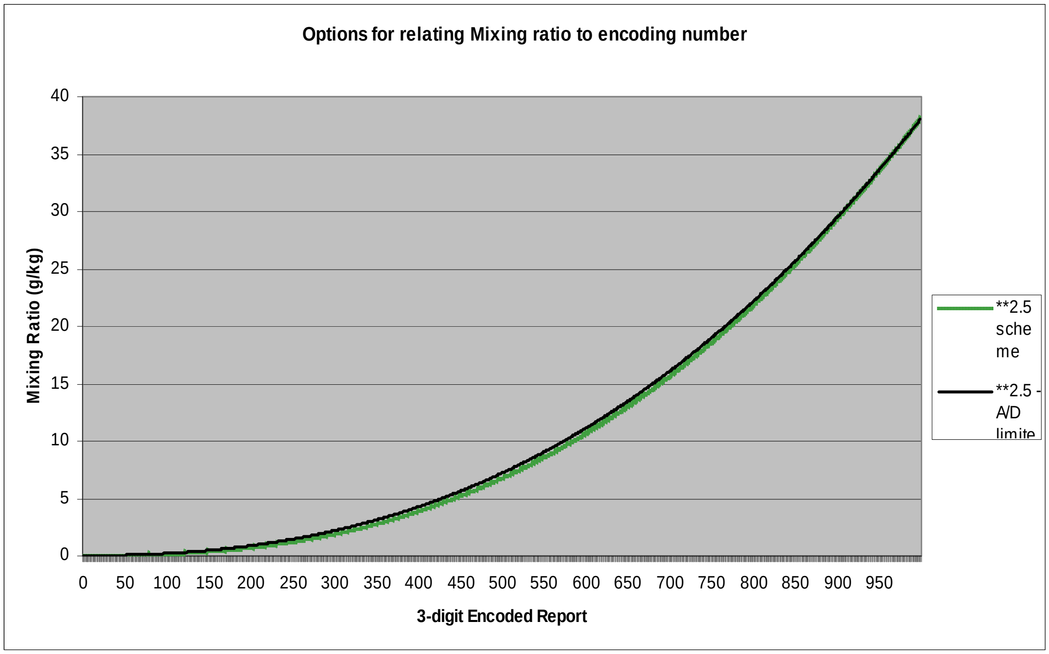


Figure 4 – Comparisons of original $10^{2.5}$ encoding scheme (green) with scheme modified to restrict encoding increment to be equal to or greater than the A/D converter precision (black).

The coded reporting values and the precision of each report as a function of mixing ratio value using the modified 2.5 power scheme is shown in Figure 5. About 40% of the reporting values continue to be used for mixing ratios corresponding to dewpoint temperatures below freezing (mixing ratios < 4 g/kg) and of interest to climate. The remainder of reports has precisions ranging from 0.025 to 0.92 g/kg. In the important meteorological range of 10-20 g/kg, the reports have precisions of about 0.04 – 0.06 g/kg, a 10-20 times improvement over the 1.0 g/kg precision present in the current reporting system.

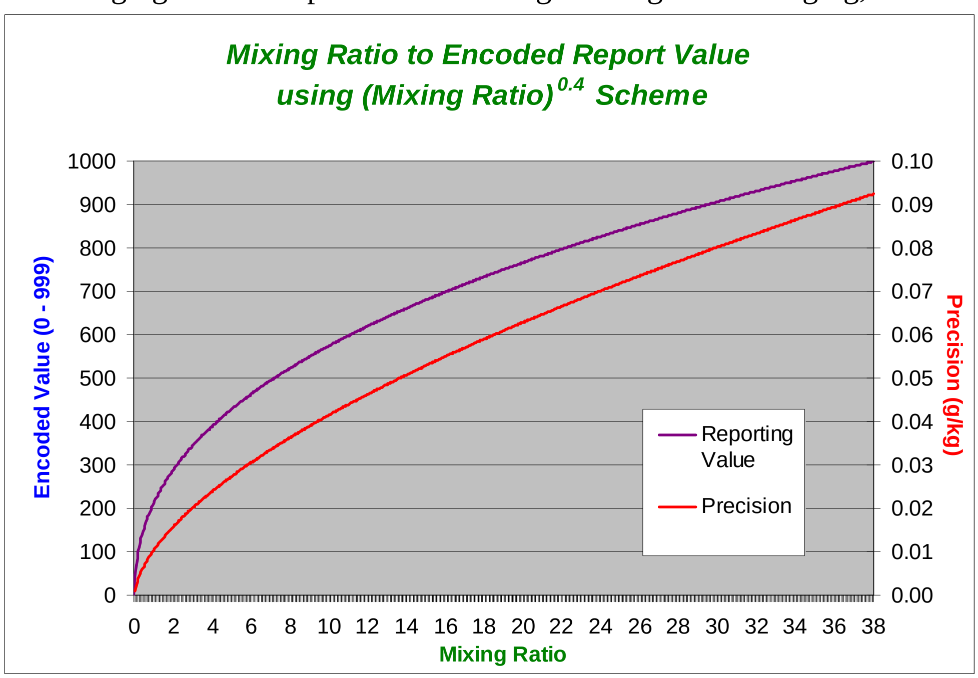


Figure 5 –Coded reporting values in range from 0 to 999 and associated reporting precision.

Recommendation:

Four different WVSS-II encoding/decoding schemes were tested as options both to increase the precision of WVSS-II reports and to remove the detrimental and abrupt decrease of precision in the current encoding algorithm. When compared with linear, quadratic and cubic fitting schemes, a 2.5 power based scheme worked best in that it met the NWS reporting precision requirements at all mixing ratio values and could be easily modified to make good use of the full range of possible reporting values. Details of the scheme are given in the appendix. Unlike the current algorithm, the proposed scheme can not be decoded directly by humans. However, if a visual decoding capability is needed, simple conversion charts and conventions can be made available to forecasters.

Supplementary Information

Details of proposed encoding/decoding schemes for WVSS-II water vapor mixing ratio reports

Conventions and assumptions:

"000" – Minimum reporting value -V_N
"999" – Maximum reporting value - V_X
V = Three digit reporting value
Q = Mixing ratio (g/kg) – (Range of Q_N = 0.005 to Q_X = 38.0 g/kg)
C_1 = Data Compression Constant = (Q_X / ($999^{2.5}$))
C_2 = 28 - A scaling constant used to constrain range of reporting values be remain between 0 and 999 for mixing ratio values between 0.005 and 38.0 g/kg. The value of 28 is the encoded value that would have been reported using an "unmodified" $Q^{0.4}$ encoding scheme in which C_2 = 0.0.

Encoding:

$V = (((Q / C_1)^{0.4} – C_2) * V_X) / (V_X - C_2)$, and

Decoding:

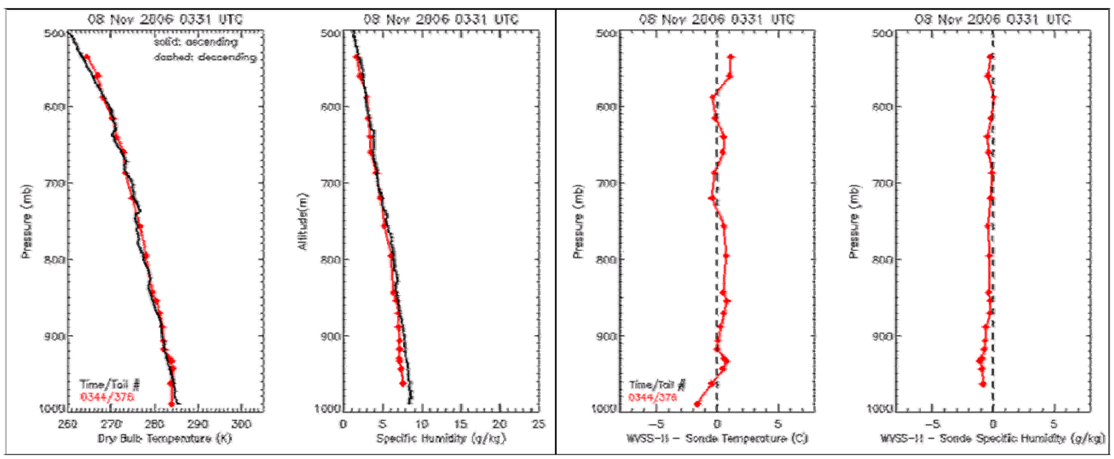
$Q = C_1 * (C_2 + (((V_X - C_2) * V) / V_X))^{2.5}$.

Note: If some of the reporting values are reserved for other purposed and fewer than 1000 'bins' are available for reporting mixing ratios, the values of VN, VX, C_1 and C_2 can be recalculated. Likewise, if letters in addition to numerals can be used in the reporting scheme, the numbers of possible reported values can increase substantially (to 36^3 *(46656)*, instead of 10^3*(1000)*) along with another major increase in reporting precision.

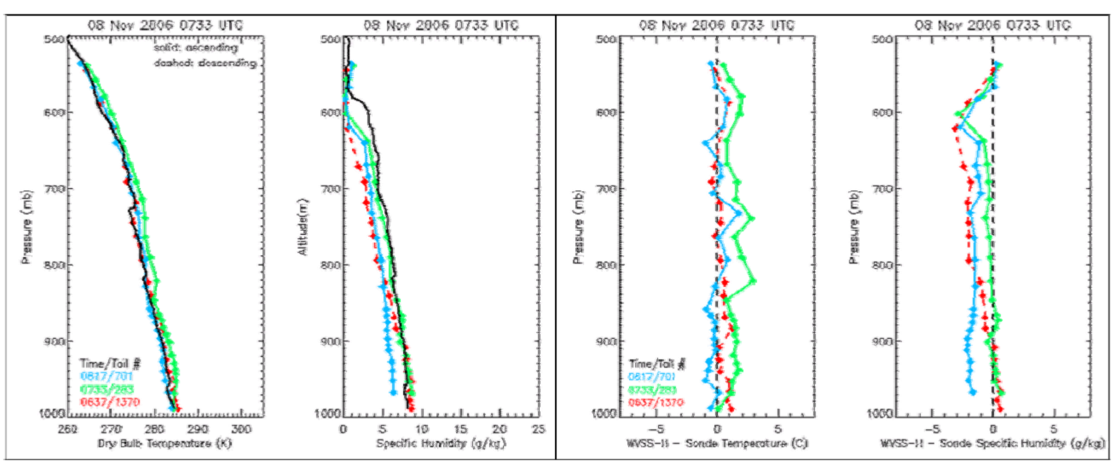
Appendix B

Comparisons of each of the 19 individual rawinsonde profiles for Temperature and Specific Humidity taken from 7 through 18 November 2007 at Louisville, KY with WVSS-II data observed within +/- 60 minutes and 50km.

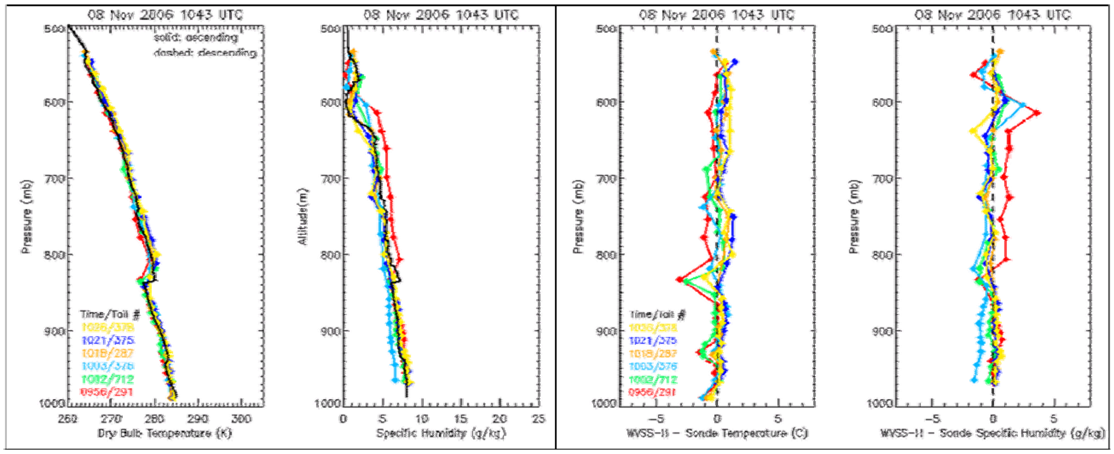
Profiles of Temperature and Specific Humidity on left. Differences between rawinsonde and individual aircraft data shown on right. Data taken during aircraft ascent are represented by solid lines, while descent data are dashed.



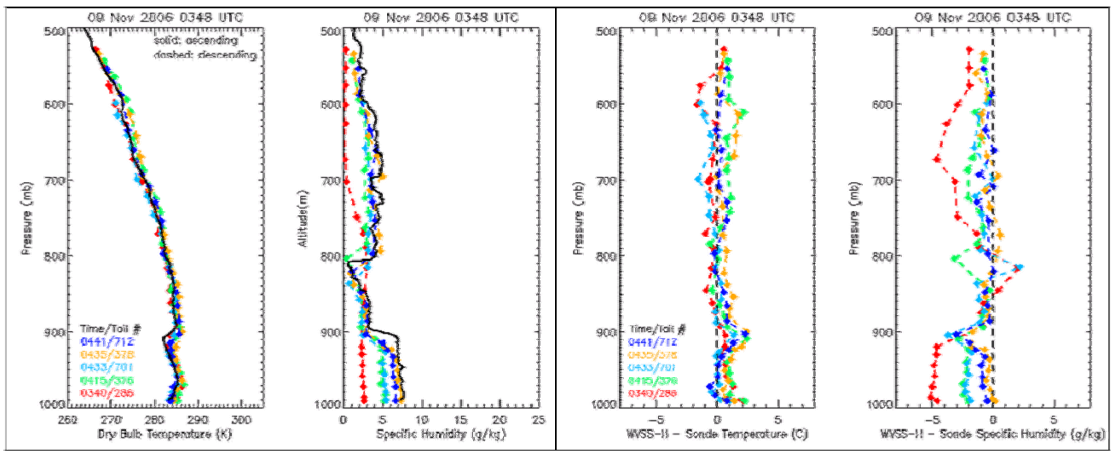
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0331 UTC on 8 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



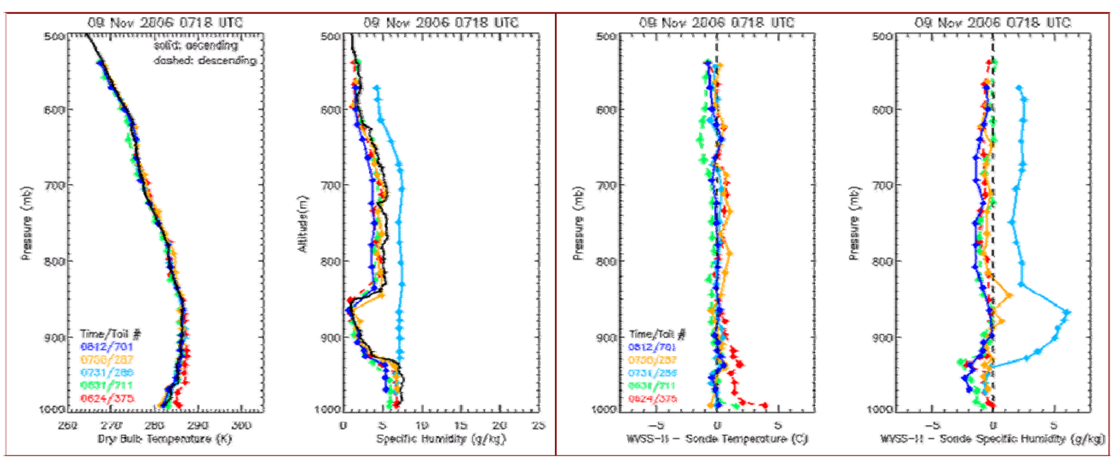
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0733 UTC on 8 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



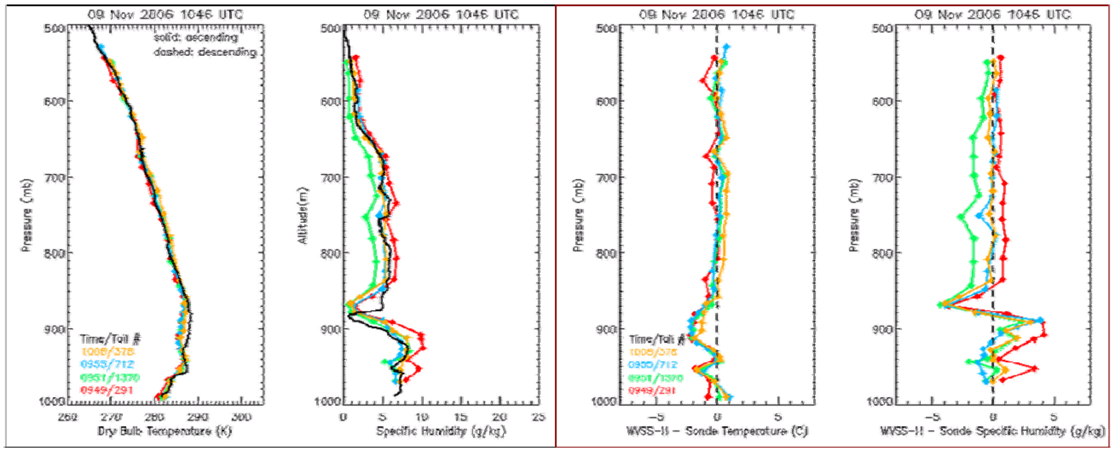
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 1043 UTC on 8 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



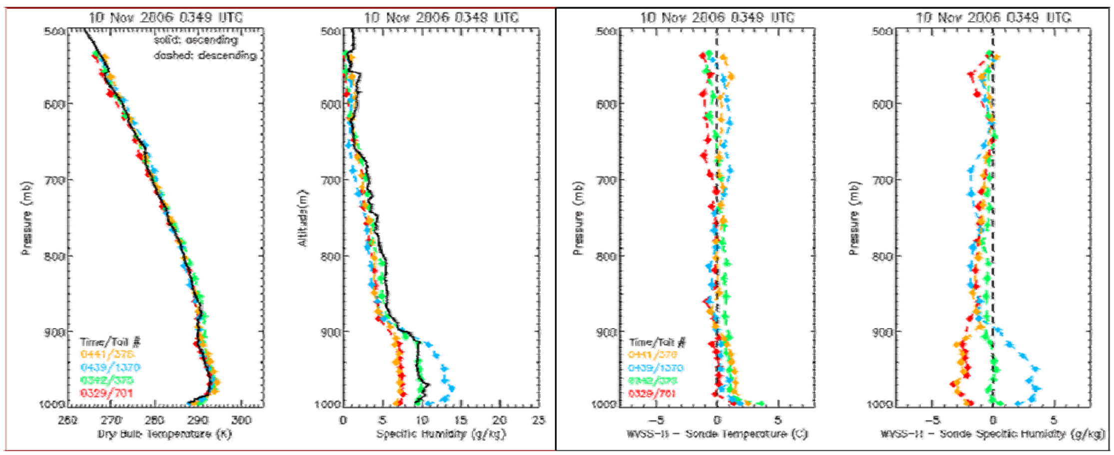
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0348 UTC on 9 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



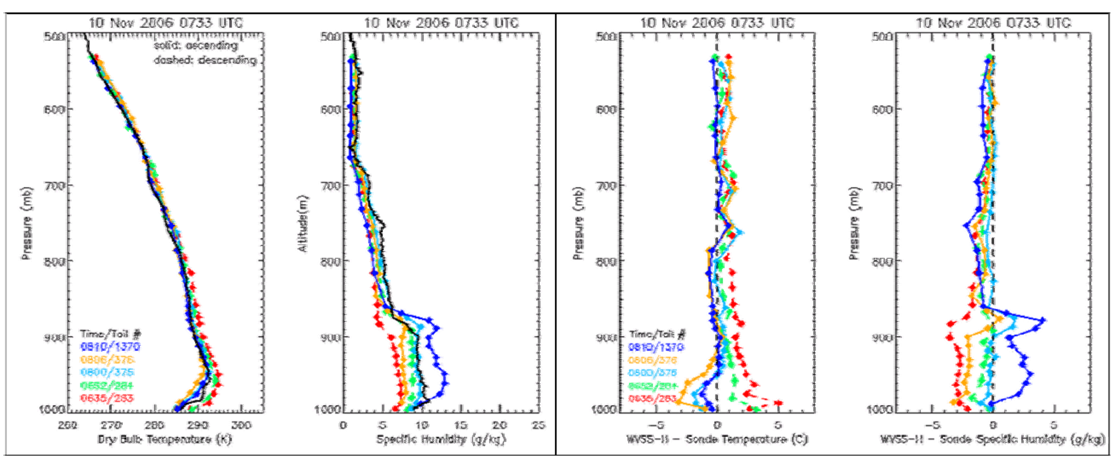
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0718 UTC on 9 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



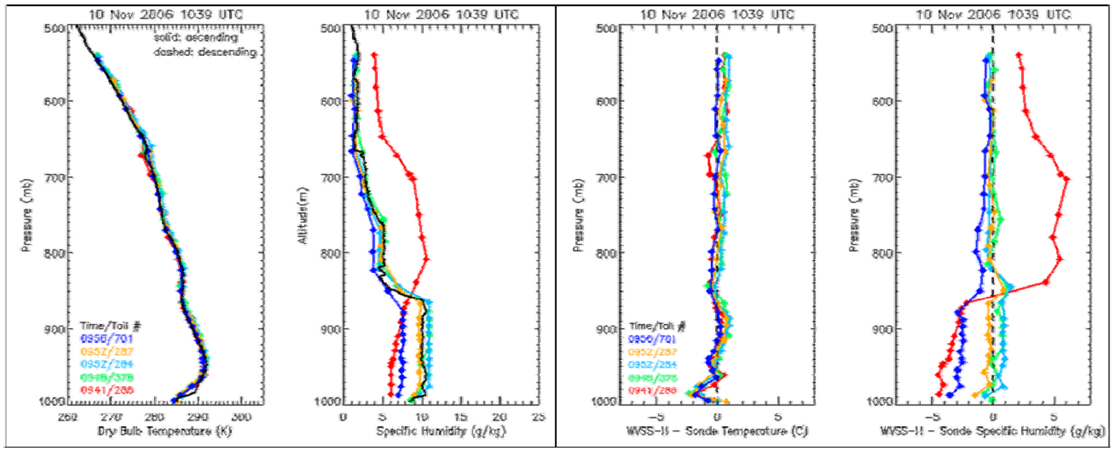
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 1046 UTC on 9 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



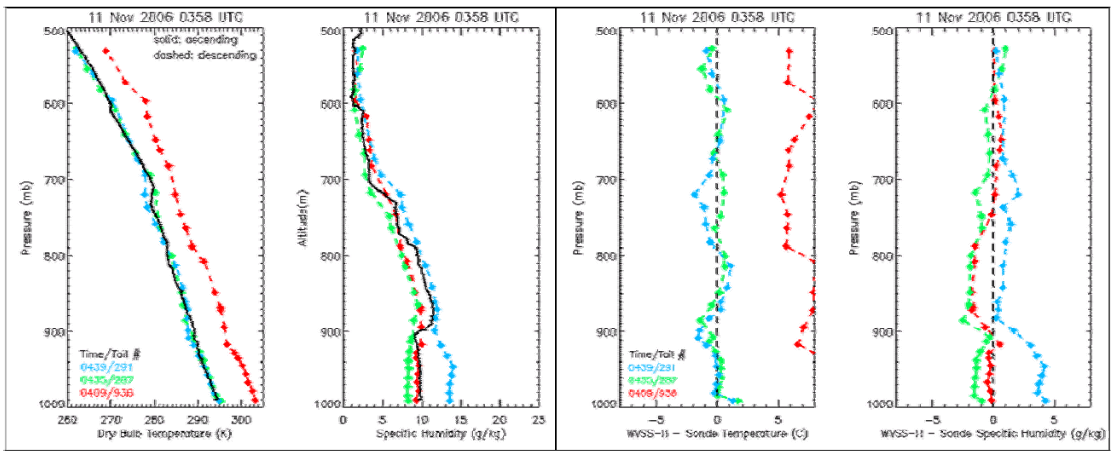
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0349 UTC on 10 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



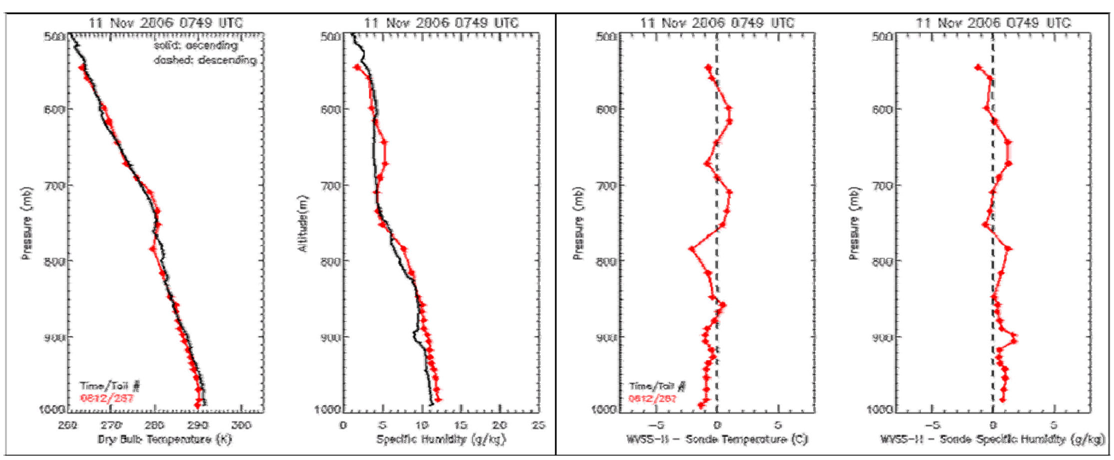
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0733 UTC on 10 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



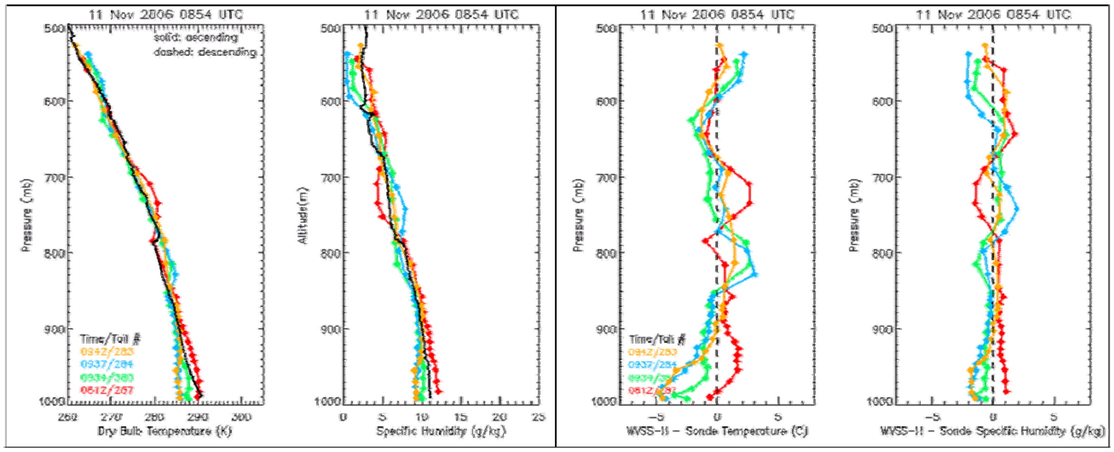
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 1039 UTC on 10 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



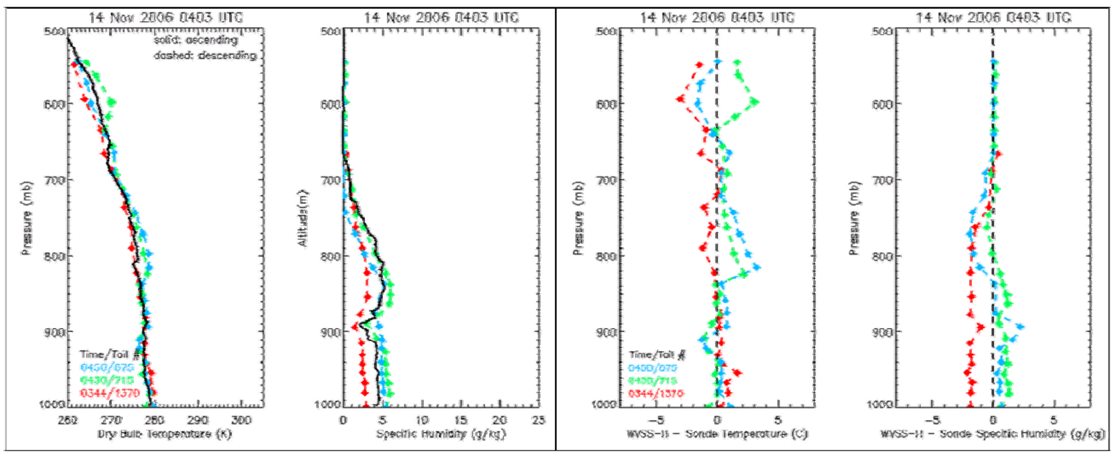
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0358 UTC on 11 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



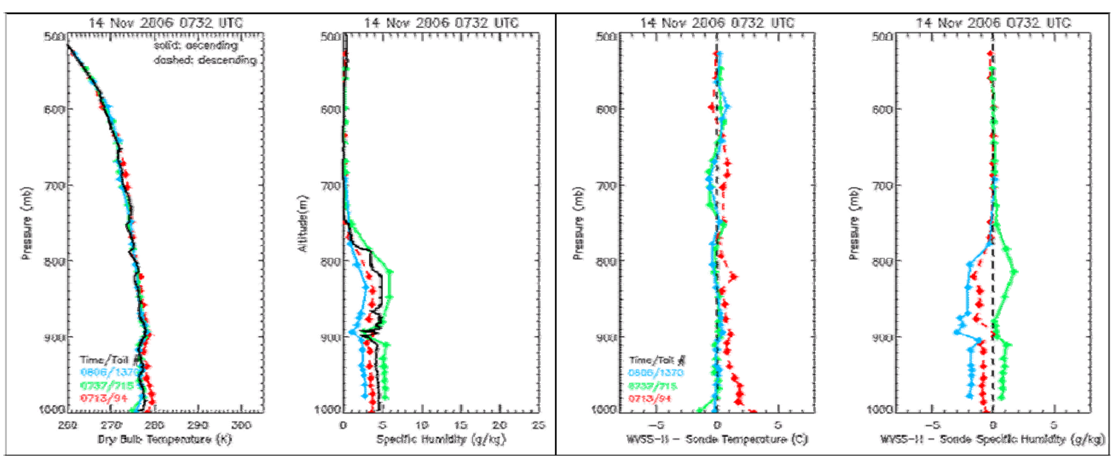
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0749 UTC on 11 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



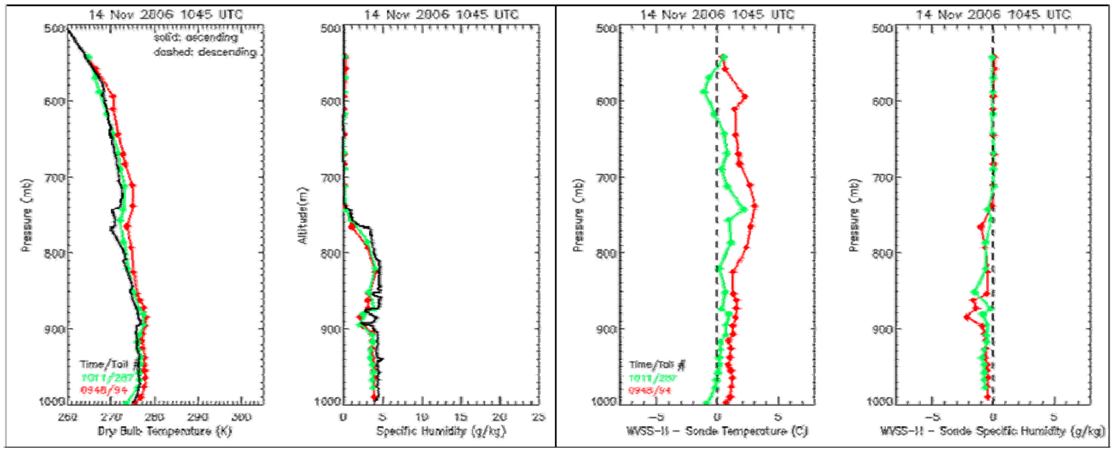
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0854 UTC on 11 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



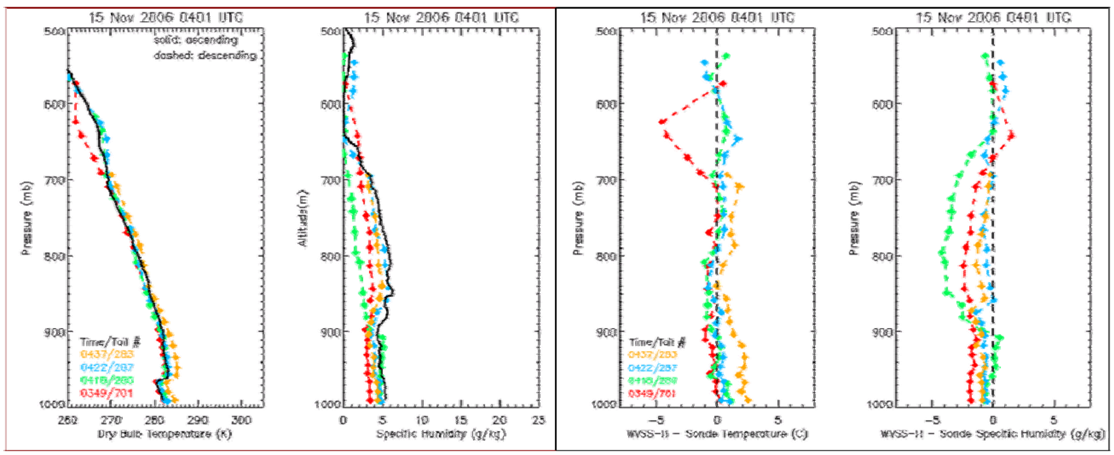
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0403 UTC on 14 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



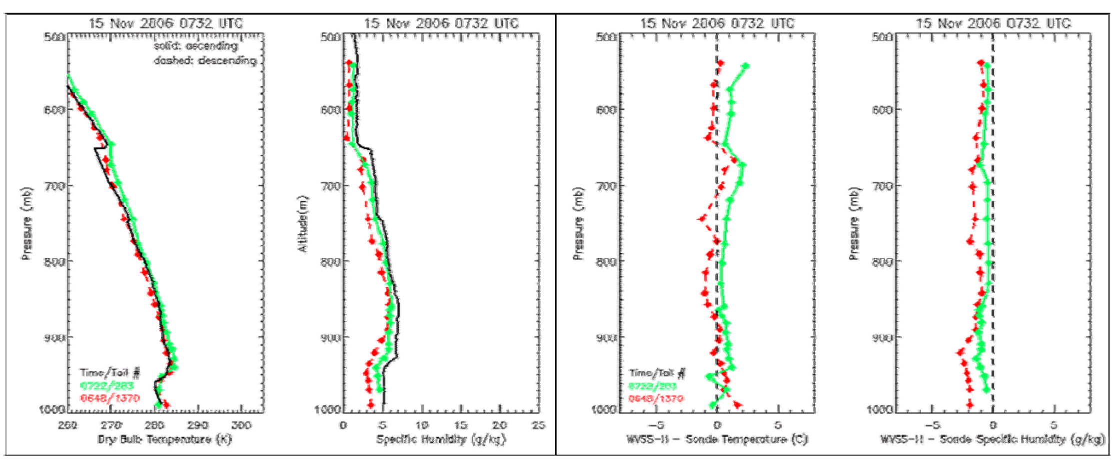
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0732 UTC on 14 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



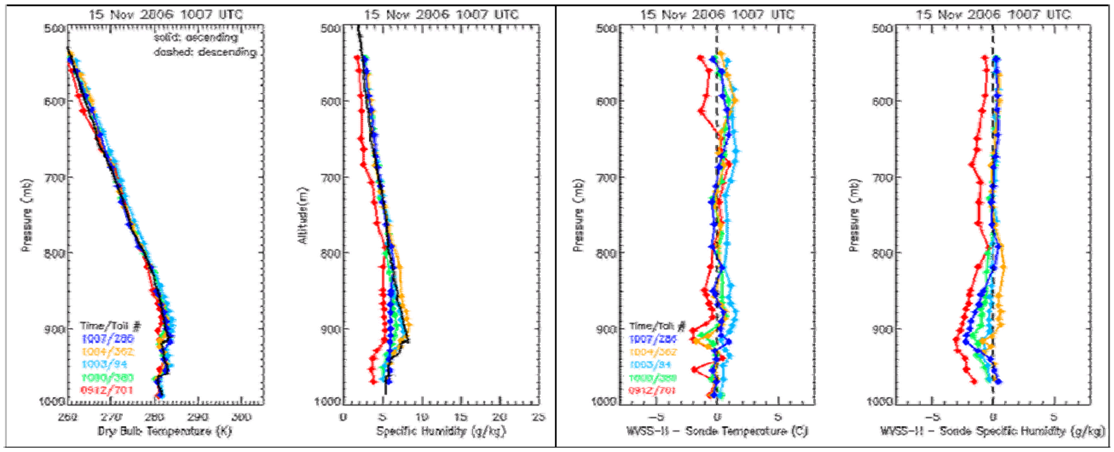
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 1045 UTC on 14 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



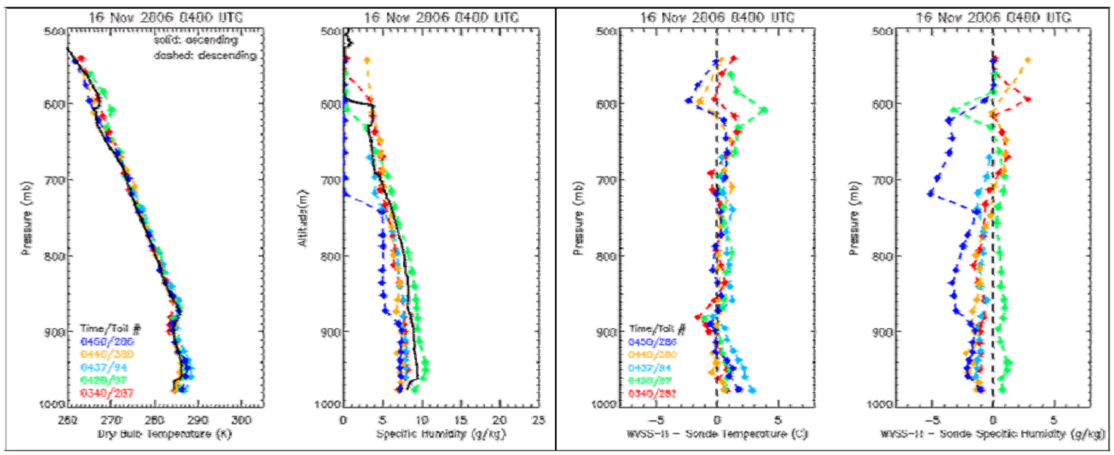
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0401 UTC on 15 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



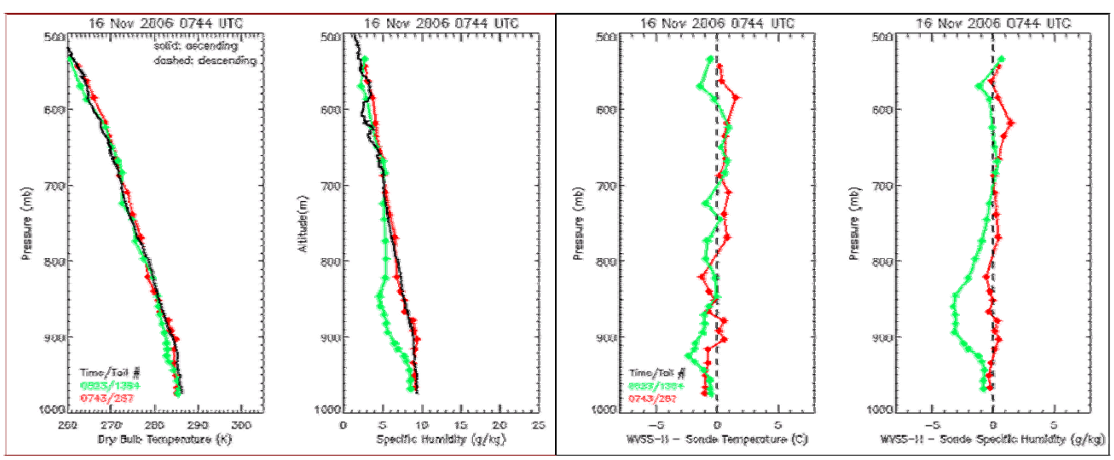
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0732 UTC on 15 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



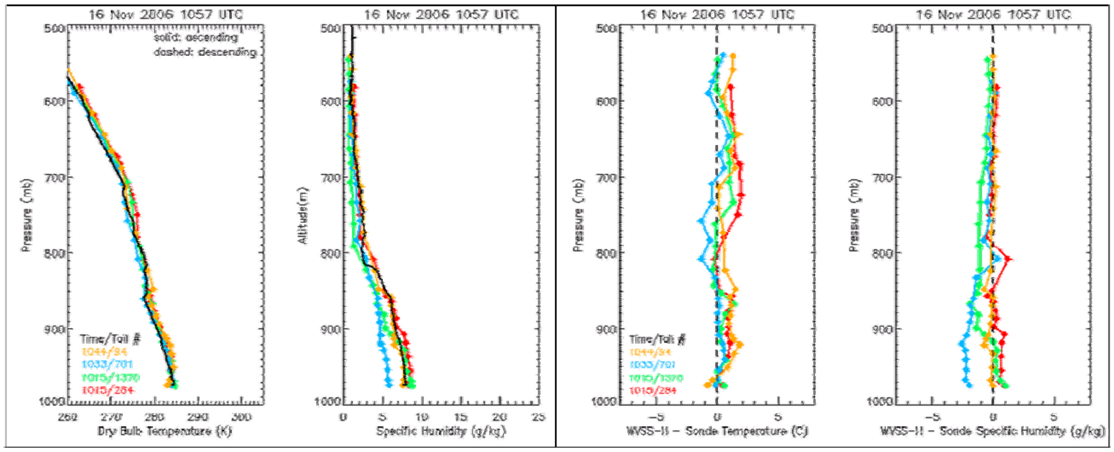
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 1007 UTC on 15 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



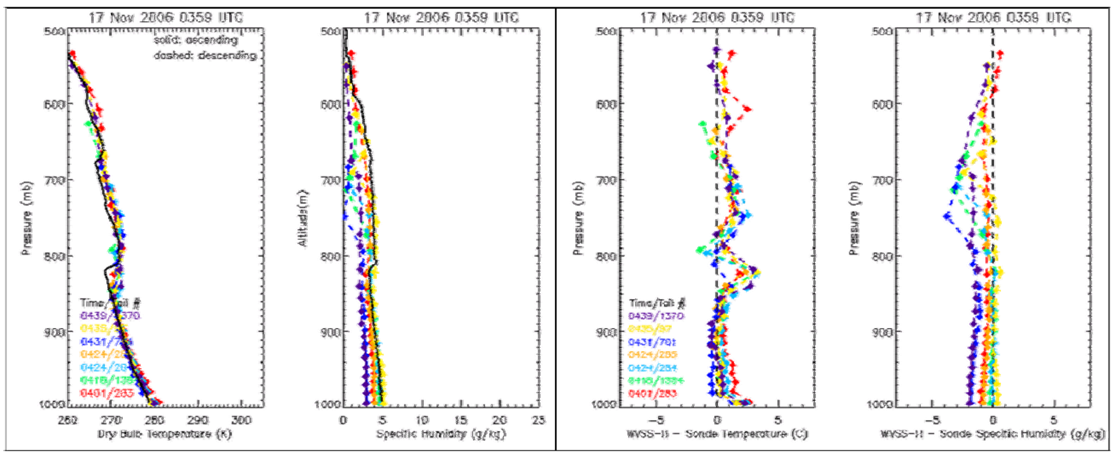
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0400 UTC on 16 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



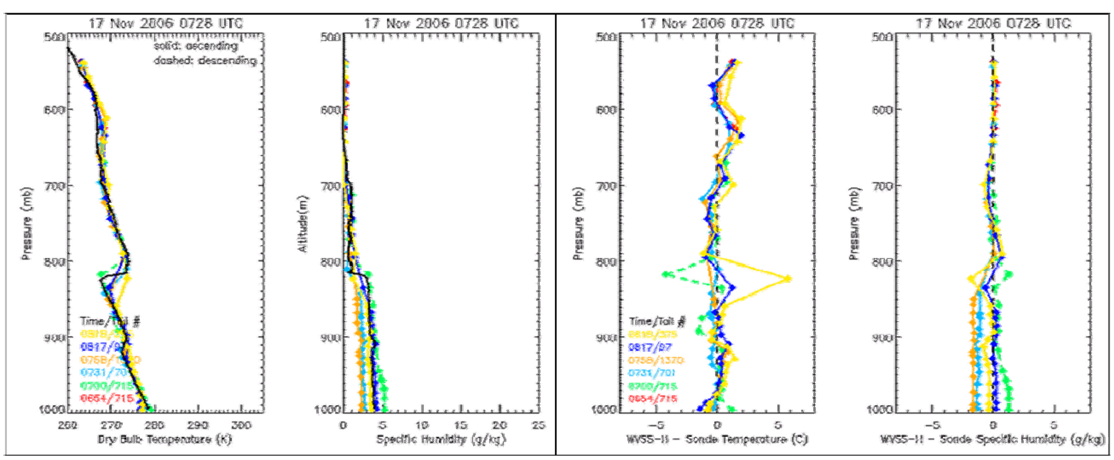
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0744 UTC on 16 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



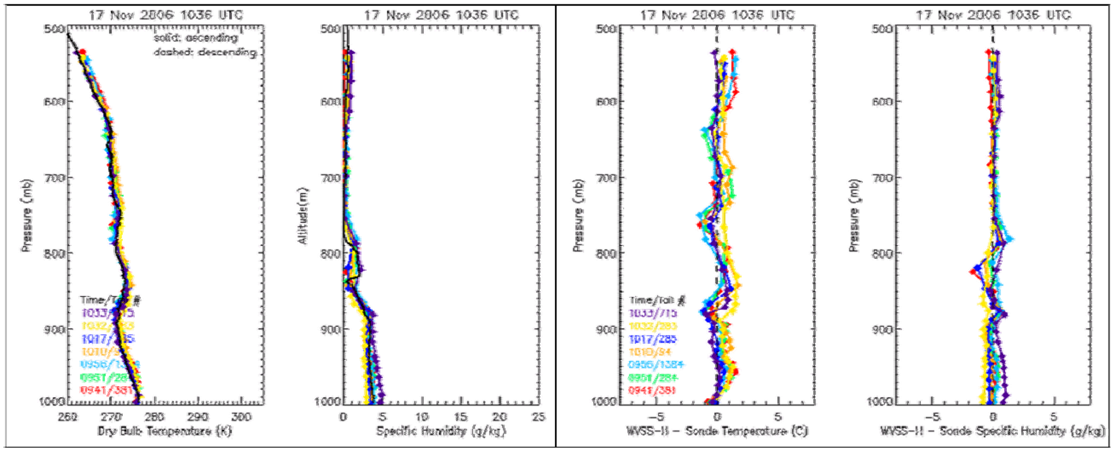
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 1057 UTC on 16 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



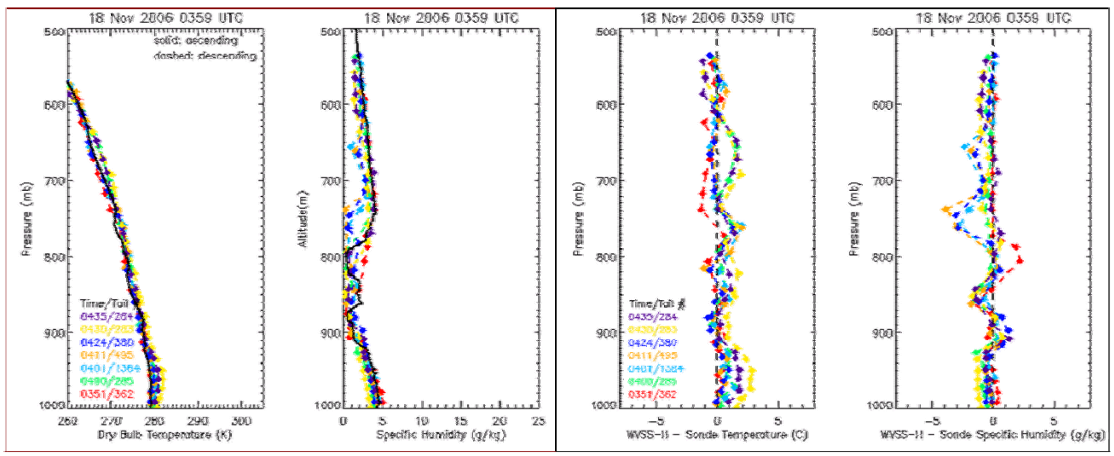
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0359 UTC on 17 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



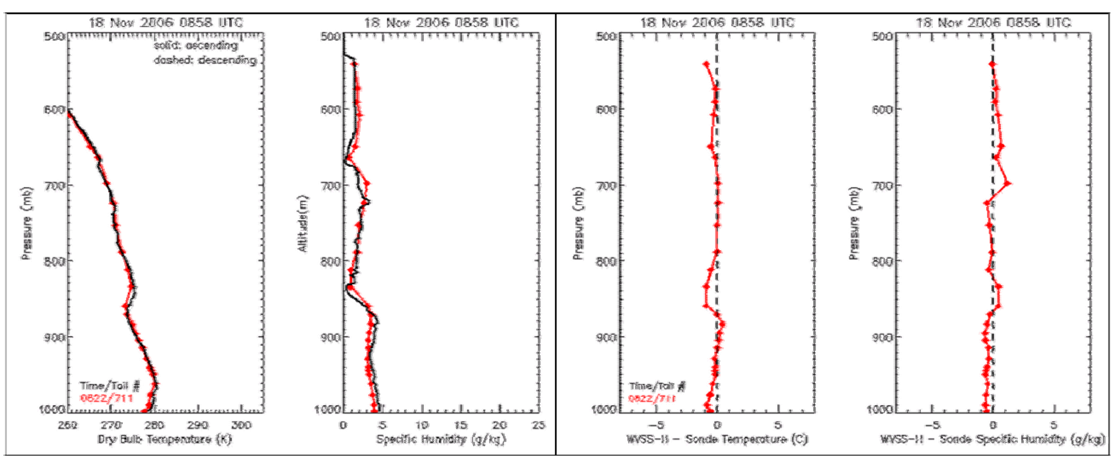
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0728 UTC on 17 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 1036 UTC on 17 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0359 UTC on 18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.



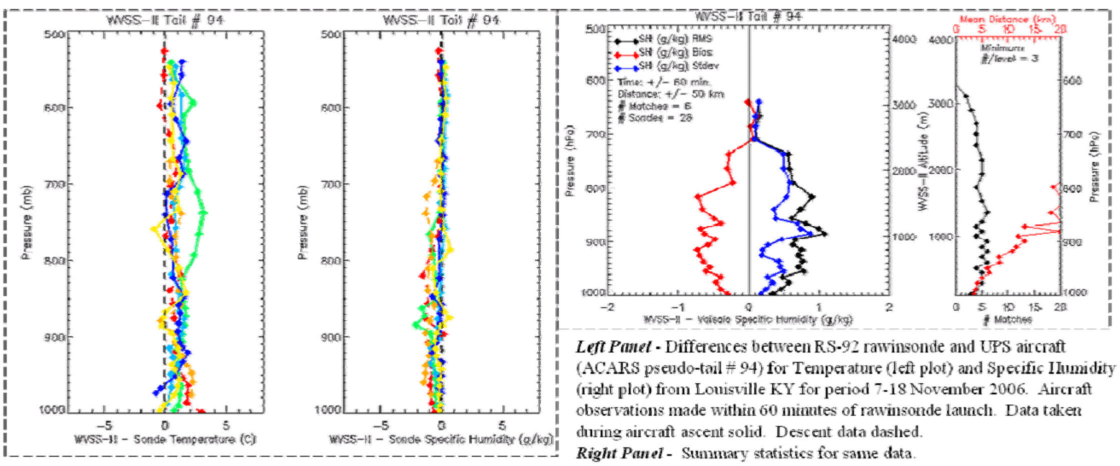
Left Panel - Comparison of Rawinsonde (black) and individual UPS Aircraft Profiles of Temperature (left plot) and Specific Humidity (right plot) from rawinsonde launched from Louisville KY at 0858 UTC on 18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed. ***Right Panel*** - Differences between rawinsonde and individual aircraft profiles for same data.

Appendix C

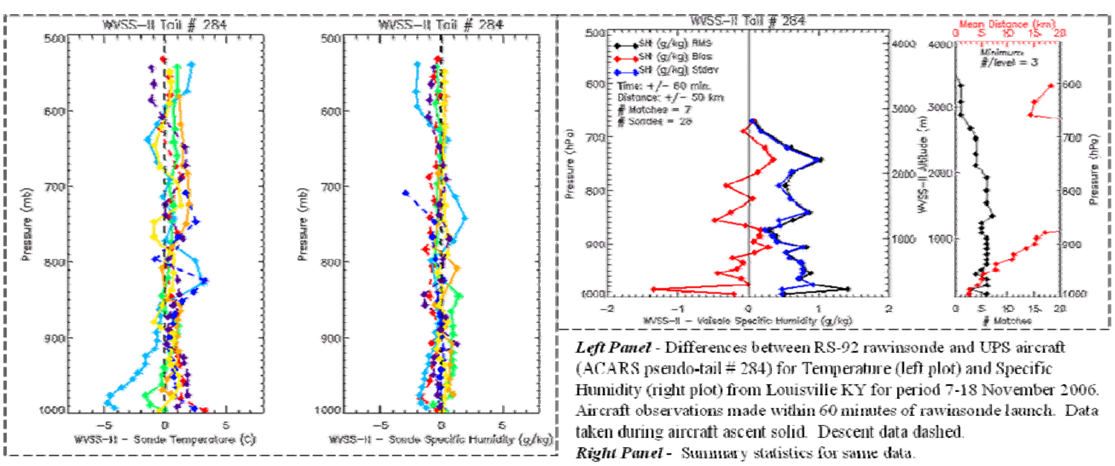
Plots of Temperature and Humidity data by individual UPS B-757 aircraft that participated in the 2006 VWSS-II field test and were used in assessment statistics.

Left panels show differences of reports of Temperature and Specific Humidity from individual aircraft (identified by unique ACARS pseudo-tail number) with rawinsonde data taken within +/- 60 minutes and 50km for the period from 7 through 18 November 2007 at Louisville, KY. Differences using aircraft data taken during ascent are represented by solid lines, while descent data are dashed. Statistical summary for each aircraft are shown in right panels.

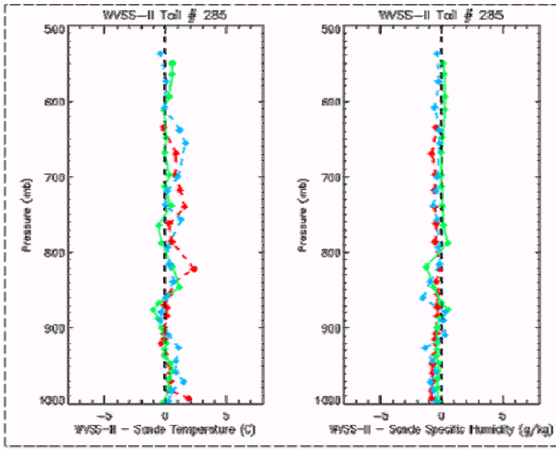
Data from aircraft that showed consistent, unbiased sensor performance and were used in statistical calculations are shown below.

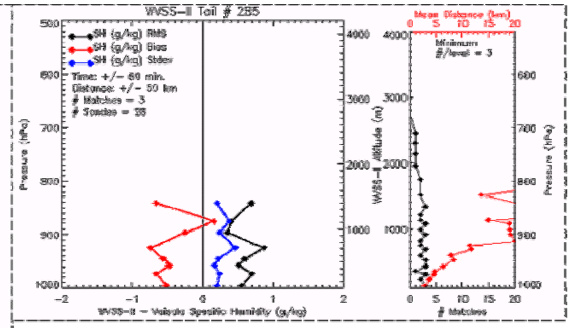


Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 94) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.



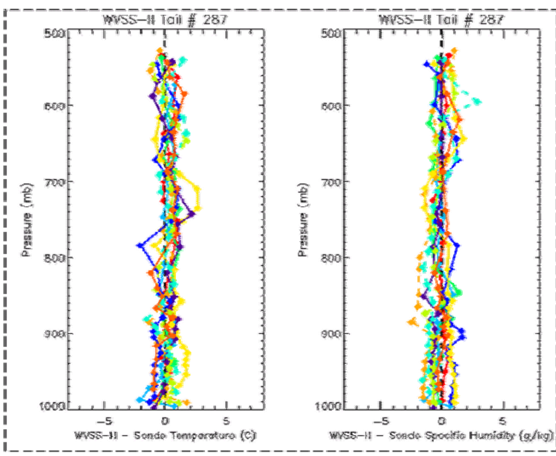
Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 284) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.

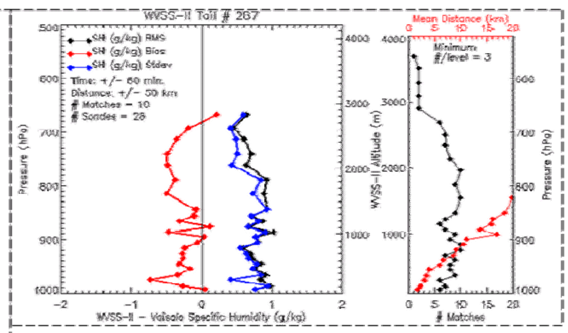




Left Panel **- Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 285) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.**

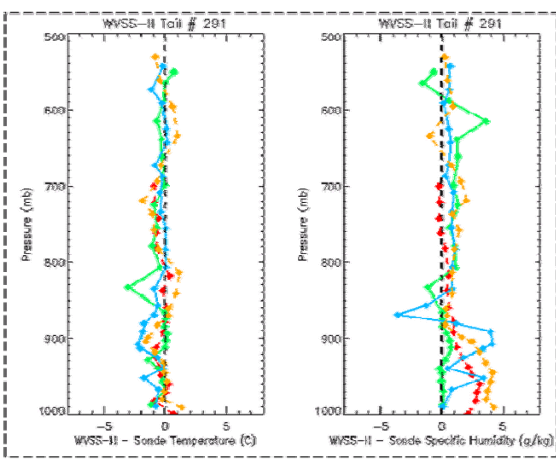
Right Panel **- Summary statistics for same data.**

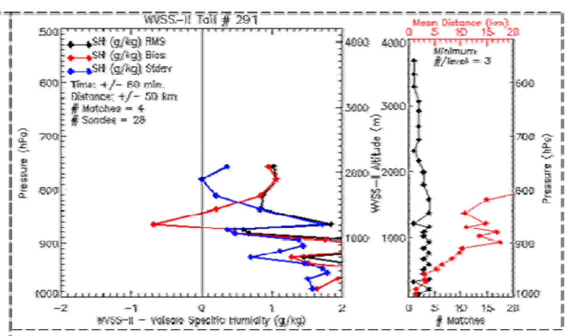




Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 287) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.

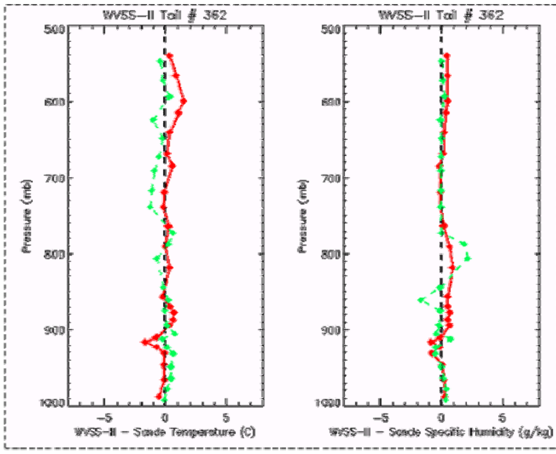
Right Panel - Summary statistics for same data.





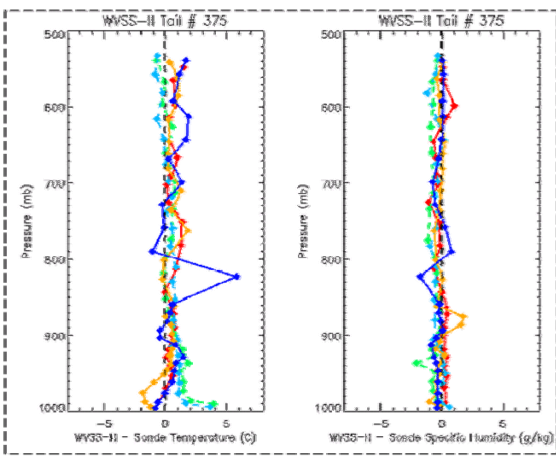
Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 291) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.

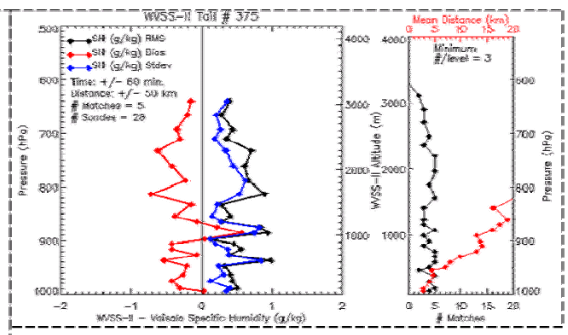
Right Panel - Summary statistics for same data.



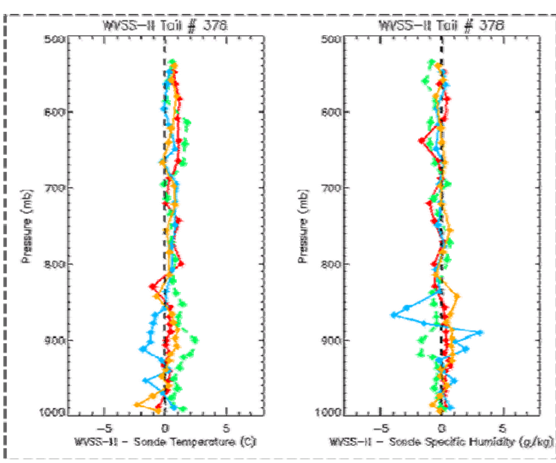
No statistics calculated for this aircraft and/or WVSS-II sensor - too few ascents/descents -

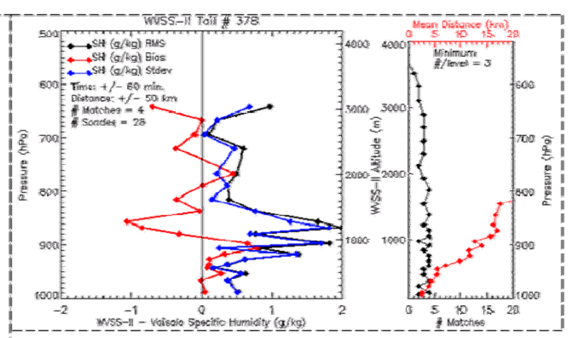
Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 362) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics not available.



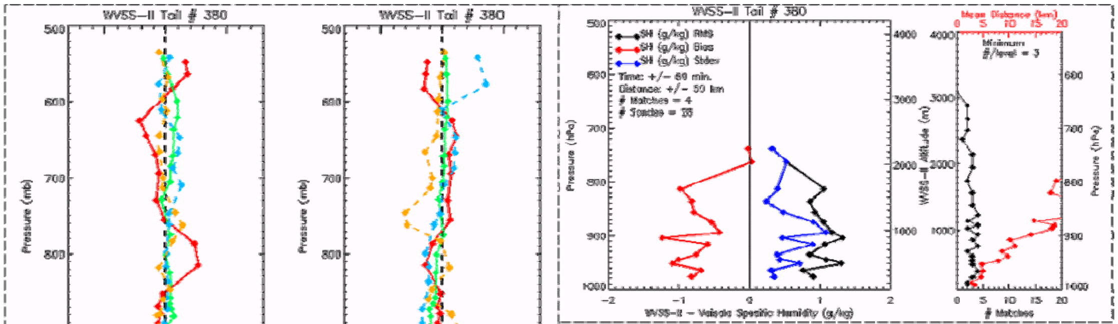


Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 375) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.

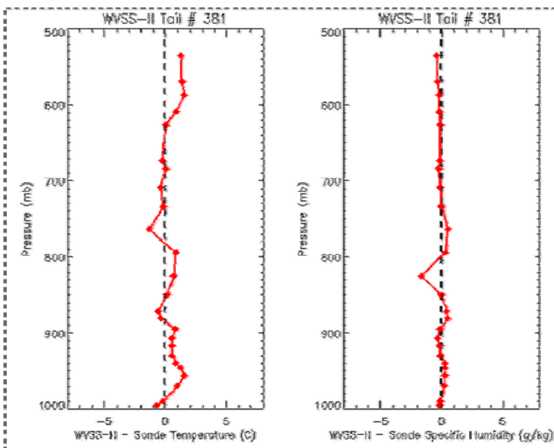




Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 378) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.

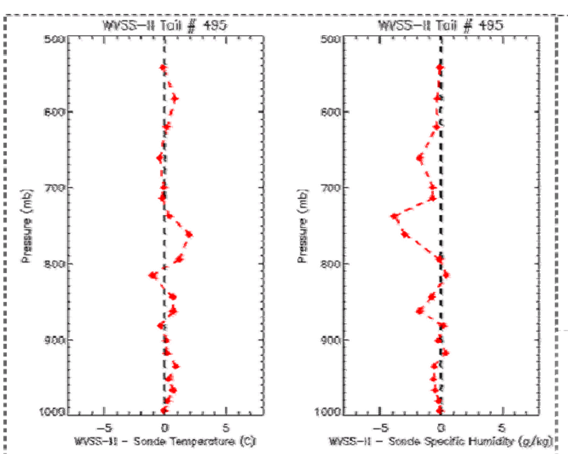


Left Panel **- Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 380) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.**
Right Panel **- Summary statistics for same data.**



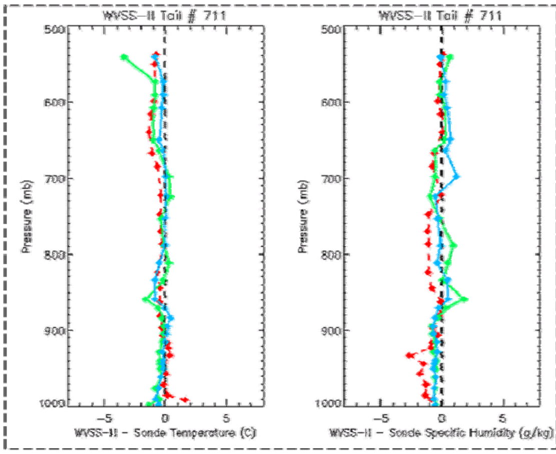
No statistics calculated for this aircraft
and/or WVSS-II sensor
- too few ascents/descents -

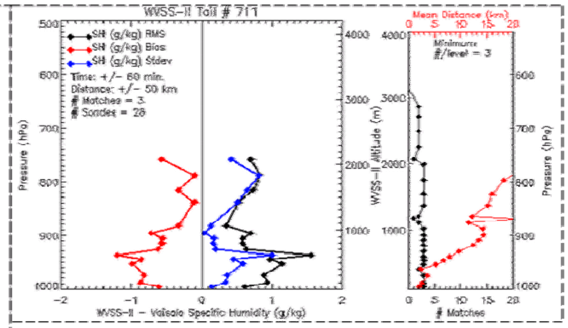
Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 381) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics not available.



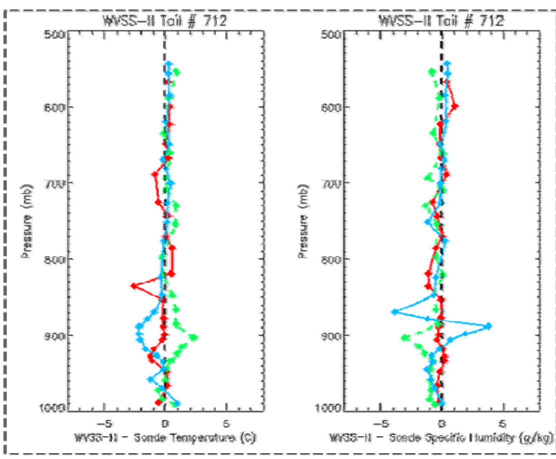
No statistics calculated for this aircraft
and/or WVSS-II sensor
- too few ascents/descents -

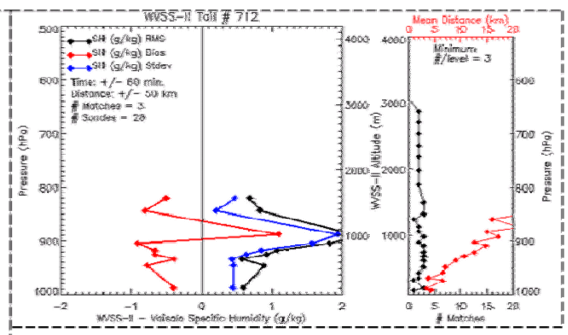
Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 495) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics not available.



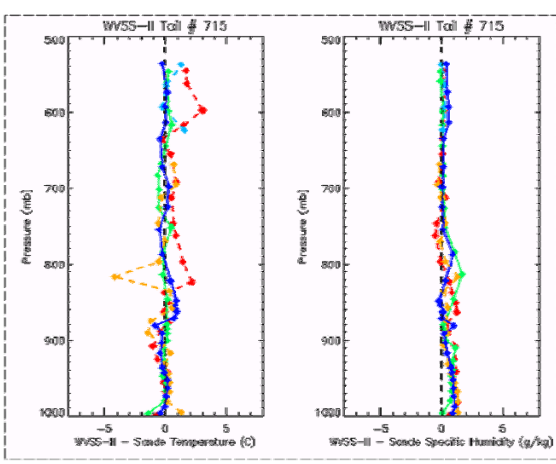


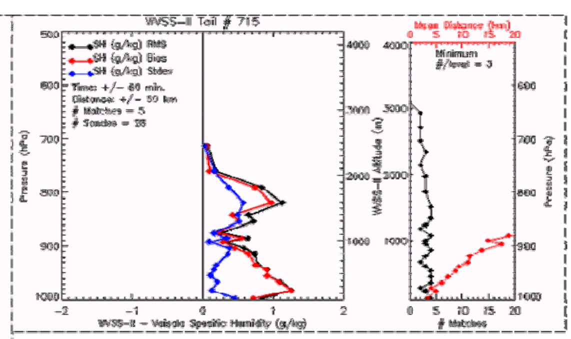
Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 711) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.





Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 712) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.





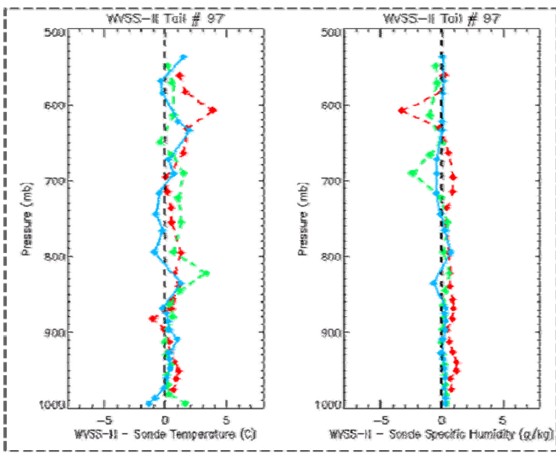
Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 715) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.

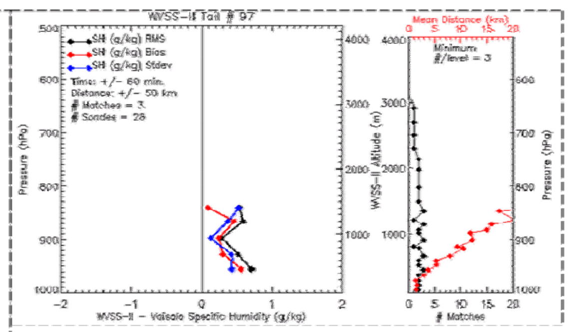
Appendix D

Plots of Temperature and Humidity data by individual UPS B-757 aircraft that participated in the 2006 VWSS-II field test but were <u>not</u> used in assessment statistics.

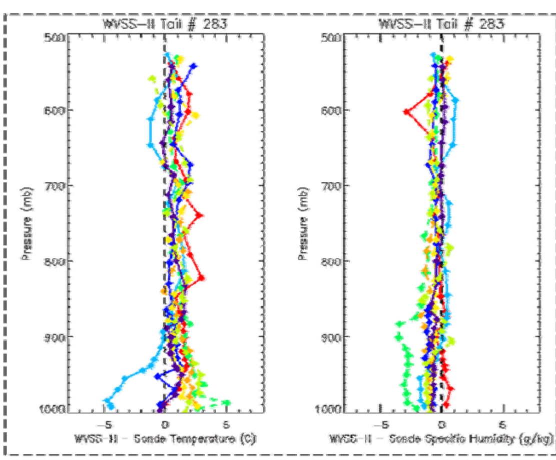
Left panels show differences of reports of Temperature and Specific Humidity from individual aircraft (identified by unique ACARS pseudo-tail number) with rawinsonde data taken within +/- 60 minutes and 50km for the period from 7 through 18 November 2007 at Louisville, KY. Differences using aircraft data taken during ascent are represented by solid lines, while descent data are dashed. Statistical summary for each aircraft are shown in right panels.

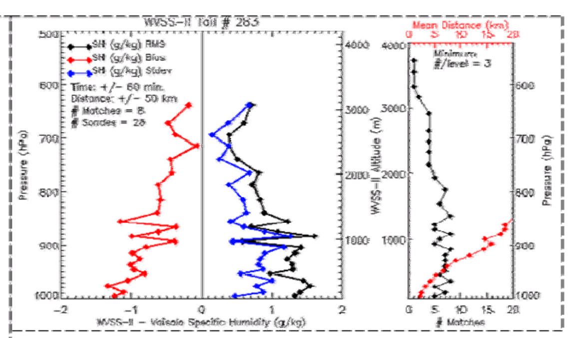
Data from aircraft that showed inconsistent or biased sensor performance and were therefore **<u>not</u>** used in statistical calculations due to apparently poor instrument performance are shown below.



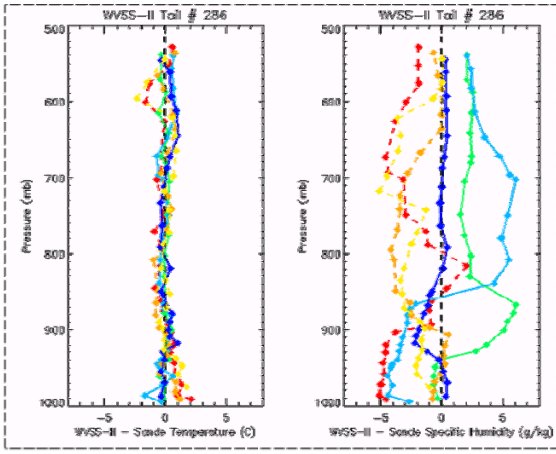


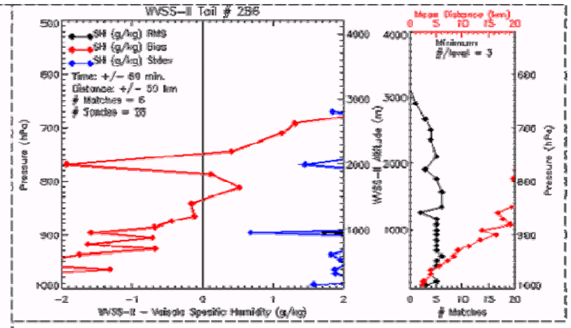
Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 97) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.



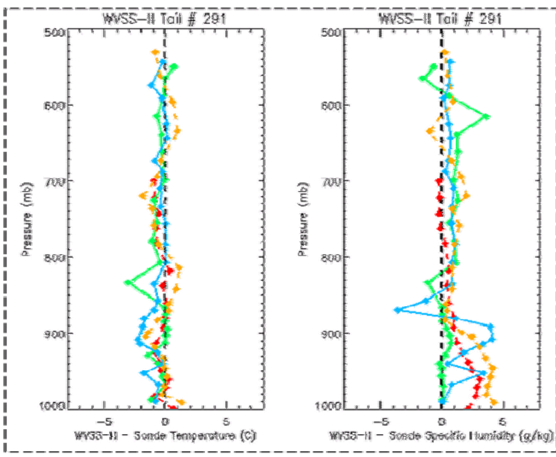


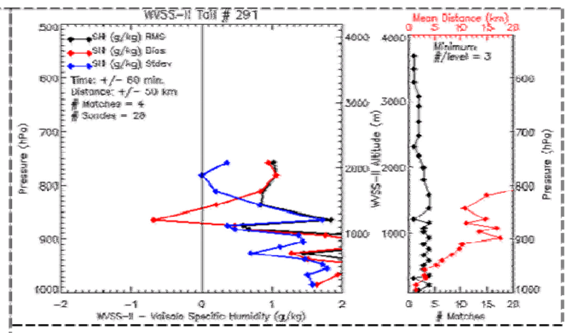
Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 283) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.



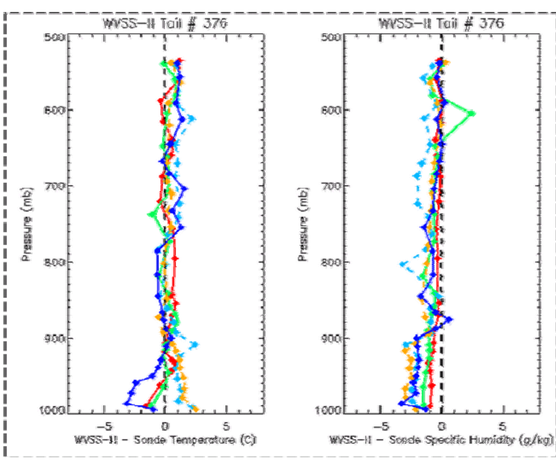


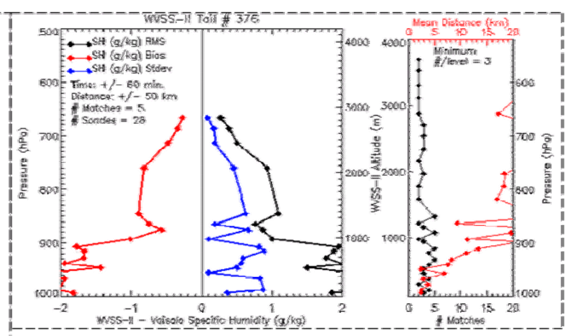
Left Panel **- Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 286) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.**
Right Panel **- Summary statistics for same data.**



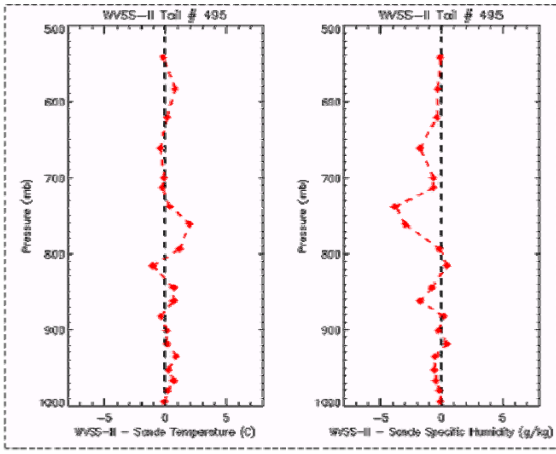


Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 291) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.



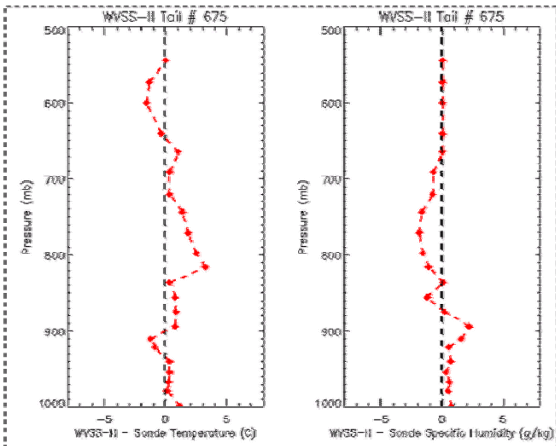


Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 376) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.



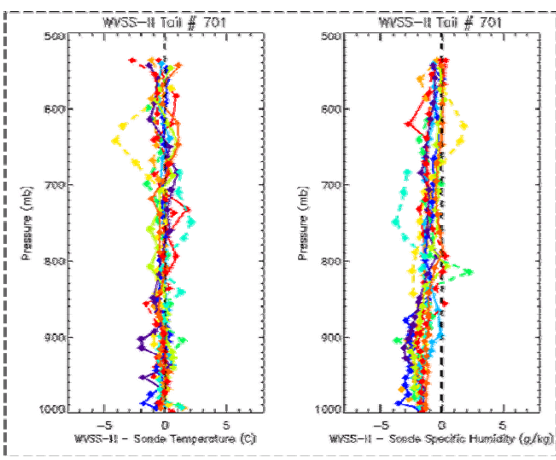
No statistics calculated for this aircraft
and/or WVSS-II sensor
- too few ascents/descents -

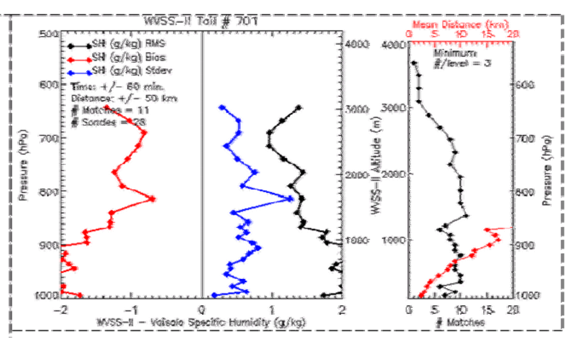
Left Panel **- Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 495) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.**
Right Panel **- Summary statistics not available.**



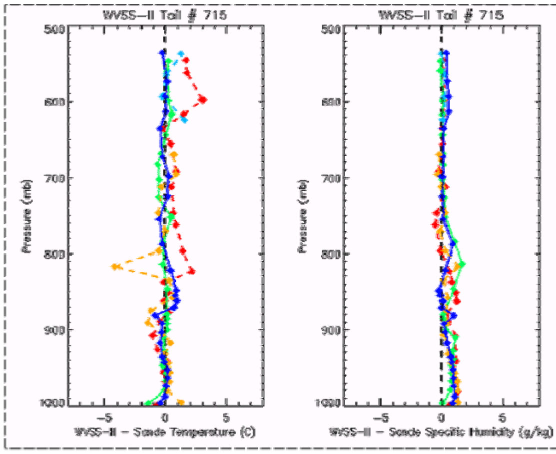
No statistics calculated for this aircraft
and/or WVSS-II sensor
- too few ascents/descents -

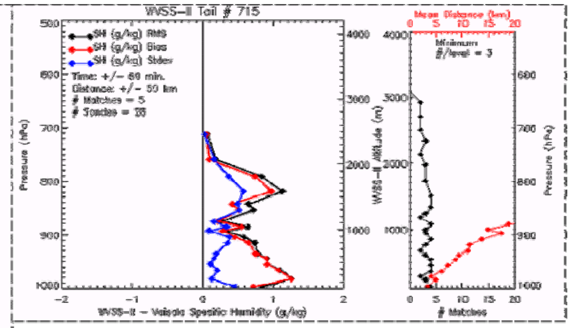
Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 675) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics not available.



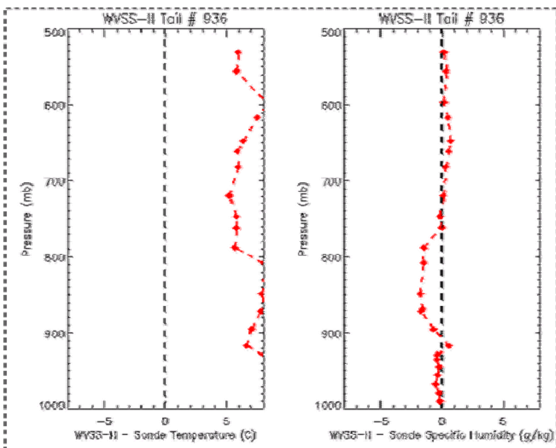


Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 701) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.



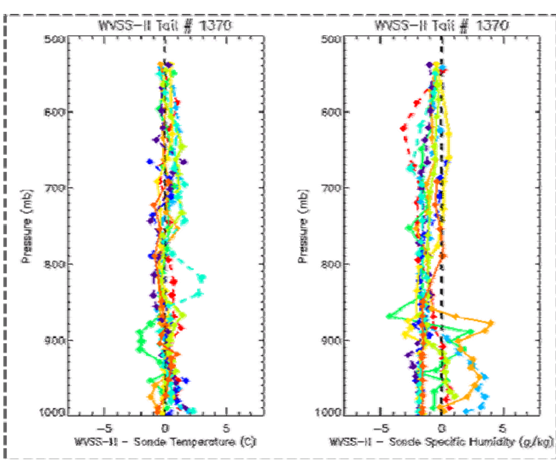


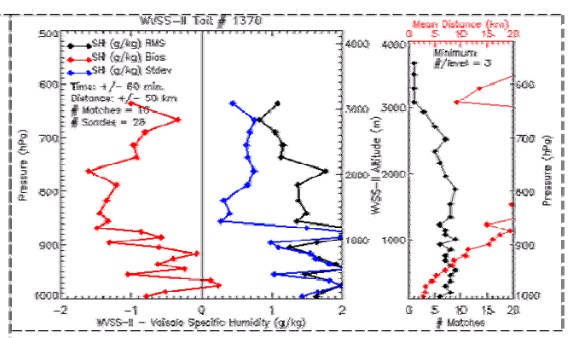
Left Panel **- Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 715) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.**
Right Panel **- Summary statistics for same data.**



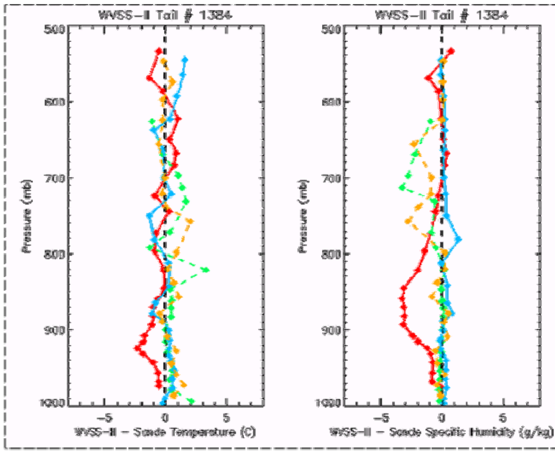
No statistics calculated for this aircraft and/or WVSS-II sensor - too few ascents/descents -

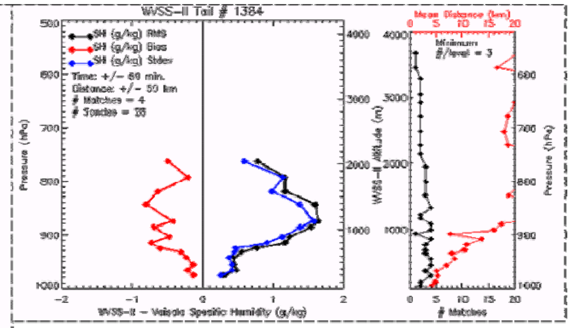
Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 936) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics not available.





Left Panel - Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 1370) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.
Right Panel - Summary statistics for same data.





Left Panel **- Differences between RS-92 rawinsonde and UPS aircraft (ACARS pseudo-tail # 1384) for Temperature (left plot) and Specific Humidity (right plot) from Louisville KY for period 7-18 November 2006. Aircraft observations made within 60 minutes of rawinsonde launch. Data taken during aircraft ascent solid. Descent data dashed.**

Right Panel **- Summary statistics for same data.**