P2.8

ASSESSING TWO DIFFERENT COMMERCIAL AIRCRAFT-BASED SENSING SYSTEMS

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1. BACKGROUND

Various studies over the past decade have shown that additional detailed measurements of the vertical, horizontal and temporal atmospheric moisture structure are necessary to improve forecasts of precipitation location, intensity and timing, as well as the onset and strength of severe convective storms. To meet this need, several projects have been established to provide moisture sensors that are appropriate for use on commercial aircraft. These instruments have the potential for filling in the space and time gaps left by all other existing observations by providing 10 or more high-resolution tropospheric moisture profiles (along with wind and temperature needed to determine moisture flux) at different locations throughout the day. One of these system, the Water Vapor Sensing System, has evolved from using a radiosonde-like thin-film capacitive relative humidity sensor (WVSS-I) into a more precise laser diode mixing ratio measurement system (WVSS-II). A second development has occurred through the TAMDAR program, which uses a system of two capacitive sensors.

A test of the WVSS-I system was conducted in 1999 by comparing aircraft data taken in ascent and descent with nearly simultaneous measurements from co-located radiosonde launches and other ground-based observing systems. These tests demonstrated the importance of the observations at non-synoptic times but also pointed to several areas of concern, including different biases in ascent versus descent reports and potential instrument aging effects.

A series of two separate tests of both the newly installed WVSS-II and the TAMDAR systems was conducted in 2005. Approximately 30 B757aircraft participated in the WVSS-II test, while 63 Mesaba Saab 340 aircraft were involved in the TAMDAR evaluation. Radiosondes and other ground-based systems again served as the comparison standard for most of the tests.

However, in order to gauge whether the aircraft data are fully compatible with NWP data assimilation systems, additional assessments were conducted in which the aircraft data were compared with model analysis background fields. These types of assessments are essential to assure the optimal use of the data in operational assimilation systems. Sample results of these aircraft-model comparisons are presented below.

2. PROCEDURES

Data from every aircraft making automated meteorological reports are gathered by the the NOAA/Earth System Research Laboratory (ESRL) in Boulder CO. After quality controlling, these data are matched with full resolution output from 1 hr forecasts from various versions of the RUC model running at ESRL (Moninger et al., 2006). Results presented here show observations matched against the 20-km "dev2" RUC model (See Benjamin et al., 2006 for details).

3. PRELIMINARY RESULTS

NOTE: All results presented here should be considered as preliminary and subject to change and/or improvement. Based in part on these results, engineering and/or software changes are planned for both the TAMDAR and WVSS-II systems to correct certain deficiencies in each system. It is anticipated that further tests will be done during 2006 to reassess the performance of each system.

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3.1 TAMDAR-RUC Intercomparisons

These preliminary results of the TAMDAR-RUC intercomparison are based on weekly summary data available on the web in early 2005; results in subsequent sections are based on more detailed stratification of the data. These early results show distinct differences in some of the basic characteristics of the different observing systems on TAMDAR and other AMDAR aircraft. These include such things as differences in wind speed biases between the smaller and larger aircraft and changes in the bias of humidity data as a function of the humidity itself.

For example, results of comparison of observations made by TAMDAR and all other 'non-TAMDAR' during the first 2 months of the TAMDAR early 2005 data collection period show basic differences in the observations taken by the different system. Figures 1-6 show comparisons of TAMDAR and 'non-TAMDAR' aircraft reports to RUC analysis first guess fields of Temperature, Wind Speed and Humidity respectively.

It should be noted that one of the advantages of comparing observations against model analysis first guess fields is that <u>all</u> observations will have corresponding 'validation match-ups'. Although the model 'validation' fields include a degree of uncertainly related to the short range forecast error, the number of comparisons that are available is much larger than for radiosonde intercomparisons, which require stringent time and space co-location limitation. Individually, neither assessment approach is satisfactory. Instead, the results of both procedures must be taken together.

The temperature intercomparisons in Fig.1 show notably different behaviors between the TAMDAR systems (which are used exclusively on smaller aircraft) and all other aircraft reports (including both large and small aircraft). The TAMDAR reports, being taken at lower levels of the atmosphere, are much warmer than most non-TAMDAR reports, although the bias in the TAMDAR reports of -0.5°C is notably larger than for other aircraft (+0.1°C). Although the Standard Deviation (SD) statistics compared with the RUC analysis first guess fields were larger than the other aircraft reports, this could be due in part to the extremely large deviations shown for a relative few number of aircraft. When bad aircraft were removed from the calculations, the spreads of SDs were similar. When compared with WMO specification, more than twice as many TAMDAR aircraft exceeded WMO minimum specification than for other aircraft reports. Further investigation of the errors for data from August 2005 showed that the temperature biases changes between ascent and descent report, with the ascents having warmer biases in general and descents having colder biases, possibly a sign of instrument/system "lag". The TAMDAR program is currently addressing these inconsistencies.

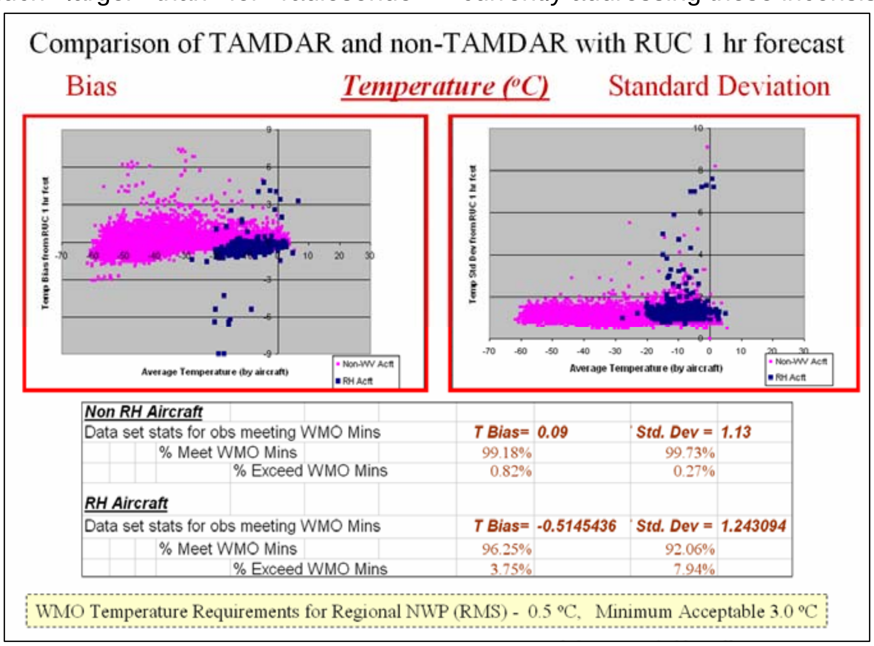

Figure 1 - Scatter plots and statistics for fit of TAMDAR and 'non-TAMDAR' aircraft report of Temperature to RUC analysis first guess fields for the period mid-January to mid-March 2005.

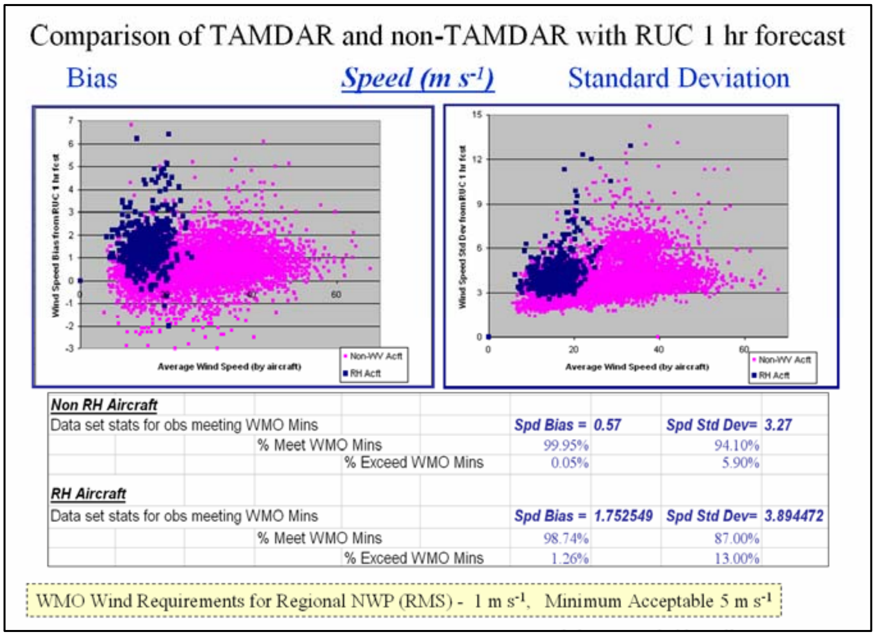

Figure 2 - Scatter plots and statistics for fit of TAMDAR and 'non-TAMDAR' aircraft report of Wind Speed to RUC analysis first guess fields for the period mid-January to mid-March 2005.

The Wind Speed intercomparisons results shown in Fig. 2 also show large differences from the RUC analysis first guess fields. Again, the lower-flying TAMDAR aircraft reports were in lower speed ranges than the ensemble of other aircraft reports. However, both the bias and the SD of the TAMDAR reports were significantly larger than other aircraft. The TAMDAR bias of 1.75 ms^{-1} was nearly 3 times that of other aircraft, with the SD nearing 4 $ms^{-1,}$ even though the TAMDAR reports were taken in lower speed wind regimes. Most notable, the number of TAMDAR wind speed reports that exceeded WMO minimal acceptable criteria was more than double that of other aircraft (10% vs. 5.9%).

Further investigation of vertical structure of the TAMDAR-RUC fits in Fig. 3 show not only that the TAMDAR data have much larger errors in general (as much as 2 time larger), but also that the wind differences between TAMDAR and other aircraft extend through all levels of the atmosphere. In addition, the largest errors occur during descent, when differences at 600 hPa can exceed 6 ms^{-1}. Based on this and other rawinsonde collocation information, the TAMDAR program is presently readdressing these inconsistencies.

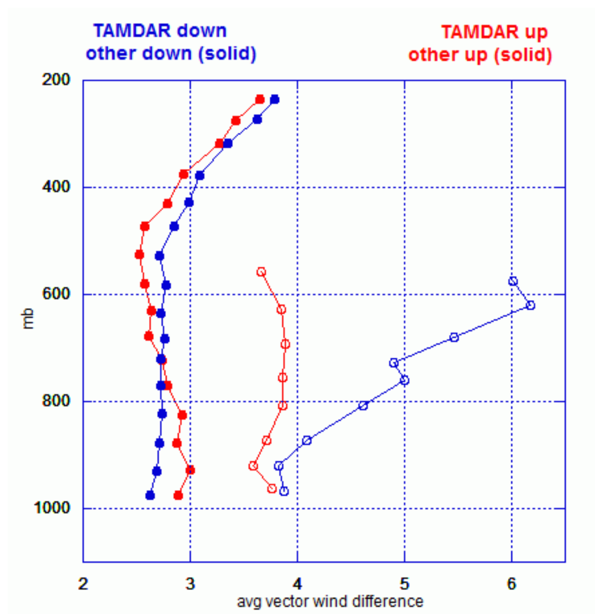

Figure 3 – Comparison of fit of TAMDAR (open circles) and all other aircraft reports (solid circles) winds to RUC for 1-17 August 2005.

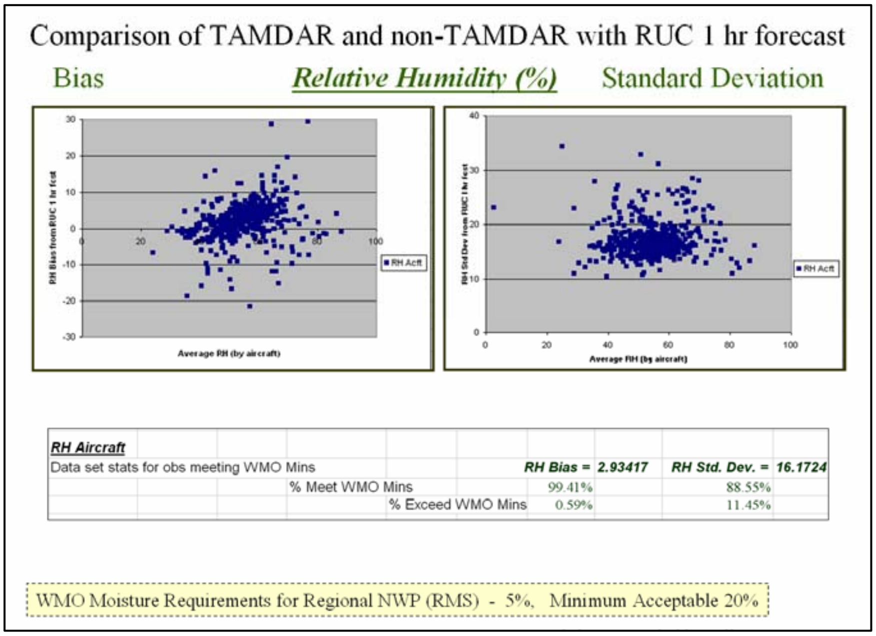

Figure 4 -Scatter plots and statistics for fit of TAMDAR and 'non-TAMDAR' aircraft reports of Relative Humidity to RUC analysis first guess fields for the period mid-January to mid-March 2005.

Relative Humidity (RH) intercomparisons could only be done between the TAMDAR aircraft and the RUC analysis first guess fields, since no other aircraft were making humidity reports at the time of these tests. Here, the analysis showed that although the SD of the RH data (16.2 g/kg) remained relatively constant across all RH ranges, the bias increased as the RH increased. The combination of bias and SD caused more than 1 in 8 of the reports to exceed WMO minimum requirements.

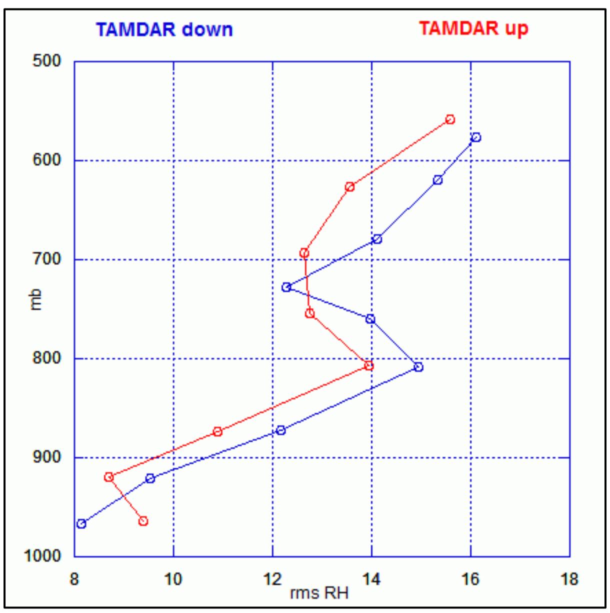

Figure 5 - Comparison of RMS fits of TAMDAR RH observations to RUC analysis first guess fields with height during ascent and descent from 1-17 August 2005.

Additional analyses were then performed using data from August 2005. This data showed that the variability in the TAMDAR-RUC fits (Fig. 5), which was very good near the surface, increases significantly with altitude, possibly reflecting increases in atmospheric variability above the boundary layer. The complex and non-linear behavior of the RH statistics emphasize the need for complementary radiosonde intercomparisons, as reported by Bedka et al. in this preprint volume.

Additional analysis of the variation in the RH RMS and bias with height (Fig. 6) shows very similar patterns during takeoff and landing, but with very different mean values. For ascent, the mean bias is about +1%, while for descent reports show a negative bias of slight more than -1%. The difference in the behavior of the reports during ascent and descent is similar (though not identical) to that noted previously for temperature. One hypothesis is that both problems could be the result of either hardware or software delays.

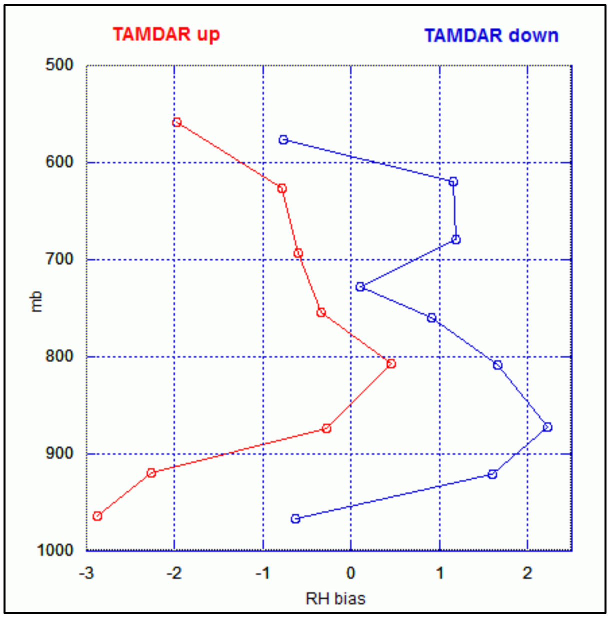

Figure 6 - Comparison of biases (%) of TAMDAR RH observations to RUC analysis first guess fields with height during ascent and descent from 1-17 August 2005.

Based on these findings, the TAMDAR program is developing means of correcting these problem at this time.

3.2 WVSS-II - RUC Intercomparisons

The WVSS-II analysis shown here covers the period 1 through 29 Sept 2005. Aircraft observations archived at ESRL are compared with 1-h forecasts (analysis guess fields) from the RUC model. WVSS-II reports that resulted in relative humidity > 100% are excluded from the data. For all but the first figure, descent data are excluded due to a known problem in the WVSS-II systems describe in Petersen et al. elsewhere in this preprint volume. As with the TAMDAR data, corrections are being made to the WVSS-II sensors as a result of these validation studies.

Because the FSL data database contained only Relative Humidity (RH), water vapor mixing ratio was recreated by reversing the process used to produce RH and verified against value down-linked from the WVSS-II sensors. The same process was used to create RUC mixing ratio data.

Because it was known that the incursion of moisture within the pressurized part of some WVSS-II systems produced biases, the first step of this study was to determine the minimum mixing ratio value reported by each aircraft during the month. Taking this error into account becomes particularly critical at high altitudes where the ambient mixing ratio is small. In general, aircraft with higher minimum mixing ratio reports in September were consistent with those noted by UPS during the June 2005 radiosonde intercomparison.

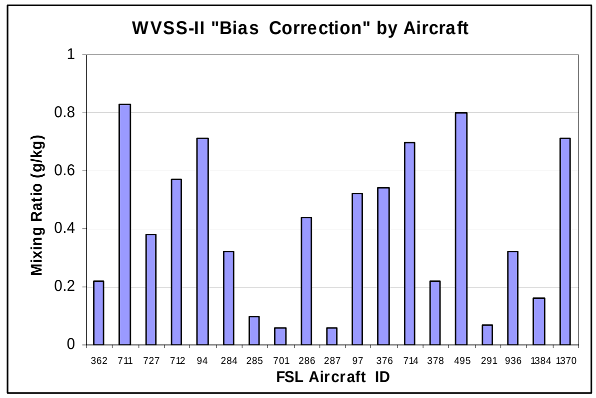

Figure 7 - Minimum Mixing Ratio observed by each WVSS-II equipped aircraft during August 2005. The abscissa is the ESRL (formerly FSL) aircraft ID number.

Assuming that the minimum mixing ratio reported by each aircraft during the month (Figure 7) gives a reasonable first estimate of the amount of moisture trapped in the WVSS-II sensor, "corrected" mixing ratio were calculated by subtracting minimum mixing ratio reported by each aircraft from each mixing ratio report for that aircraft. Statistics were calculated between the WVSS-II data (excluding data taken during descent) and RUC analysis first guess fields using both “raw” and “corrected” WVSS-II data.

Figure 8 shows that most aircraft have a decided positive bias in “raw” reports with respect to the RUC, due, in part perhaps, to the trapped moisture mentioned above. The RMS error with respect to the RUC varies from 1.28 to 2.99 g/kg.

The "corrected" reports, however, show substantially decreased biases (from 0.49 g/kg to 0.15 g/kg) for the full fleet of WVSS-II equipped aircraft. The RMS is also decreased slightly (from 1.97 g/kg to 1.92 g/kg), due again to the decrease in bias.

surface properties and where the radiosonde-WVSS-II intercomparisons were more closely matched in time. We currently have no explanation for the increased bias.

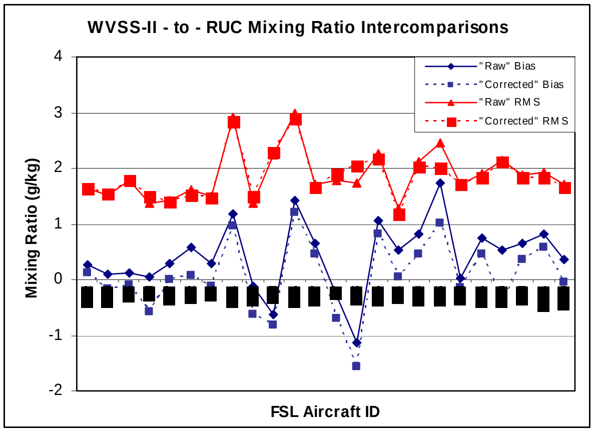

Figure 8 - Bias and RMS fits of WVSS-II mixing ratio reports to RUC analysis guess fields using "raw" and "bias corrected" data

When the results are stratified by altitude (see Fig. 9), the statistics can be compared with the radiosonde intercomparison described by Petersen et al. elsewhere in this preprint volume. Compared with those results, the WVSS-II-to-RUC intercomparisons show:

- Substantially higher mixing ratio biases with respect to the RUC up to 800 hPa for the uncorrected data, averaging 0.5 g/kg in the lowest 4 bins in the table above.
- Somewhat higher mixing ratio biases above 800 hPa - up to 0.52 g/kg (at 425 hPa) for the uncorrected data.
- Higher RMS values to 800 hPa (2.5 g/kg compared to 1 g/kg) with respect to the RUC in this region for the uncorrected data.
- Decreasing RMS values above 800 hPa (ranging from 2.2 to 1.6 g/kg), which become smaller higher up (although becoming a larger fraction of the average RUC-forecasted mixing ratio).

The dashed Bias and RMS fits in figure 9 show that removing the biases from the individual aircraft reports ("corrected" data) greatly improved the biases in the upper regions, along with modestly improved RMS values there.

It should be noted that the greater RMS seen in the RUC comparison is likely due to the greater uncertainty and variability in the RUC forecasts over radiosonde in-situ measurements. This is particularly evident at low levels, where the RUC fields can be highly influenced by the model's land

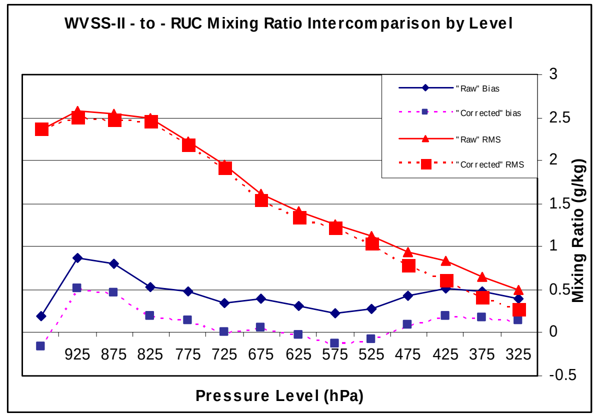

Figure 9 - Vertical distribution of Bias and RMS fits of WVSS-II mixing ratio reports to RUC analysis guess fields using "raw" and "bias corrected" data

In an effort to take a more detailed and representative look at the vertical structure of error characteristics, we eliminated the 7 aircraft having the worst RMS errors -- all above 2 g/kg. These are the aircraft with FSL ID's 284, 701, 286, 376, 378, 495 and 380.

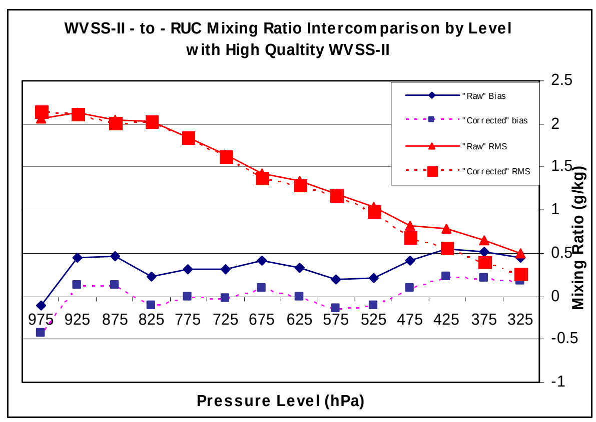

Figure10 - Same as Fig 9 except only using reports from highest quality WVSS-II systems

This cleaner sample (Fig.10) shows substantially decreased bias below 800 hPa (0.26 g/kg instead of 0.49 g/kg.), while the "corrected" data shows a bias below 800 hPa reduced to 0.07 g/kg. RMS errors are also modestly improved in this sample.

The uncorrected relative humidity (RH) measurements were then studied for an 80 day period starting in early August 2005 with the 7 questionable sensors removed. (It must be noted that aircraft temperature errors can also contribute to the RH values derived from the WVSS-II mixing ratio data. These errors have not yet been accounted for in this study.) The effect of trapped moisture may be seen clearly above 500 hPa in Fig. 11 by the large increase in bias there. The RMS statistics for the difference between the

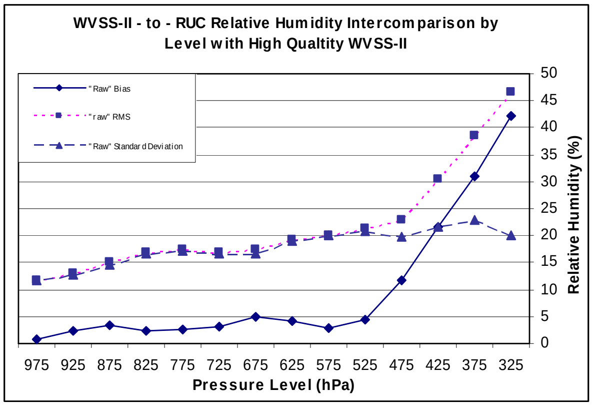

Figure 11 - Bias, RMS and Standard Deviation fits of WVSS-II Relative Humidity reports compared with RUC analysis guess fields using only high quality "raw" WVSS-II data

observed and RUC RH below 700 hPa compare very favorably with the RMS between radiosondes and RUC (which averages about 15% at all levels). This suggests that even the existing WVSS-2 has approximately the same accuracy as radiosondes in regions where the moisture trapped in the WVSS-II systems is a small fraction of the ambient moisture.

Based on these findings, the WVSS-II program is developing means of correcting these problems at this time.

3. SUMMARY

Comparisons of meteorological data collected from aircraft have been compared with RUC analysis first guess fields. These comparisons provide an excellent compliment to similar studies being conducted comparing the aircraft data with radiosonde data, The data-to-model comparisons allow all observations to be included, to include all times of day, all locations, and all seasons, and (when combined with the radiosonde intercomparison results) provides information to modelers about specific performance strengths and deficiencies.

The results have shown a number of strength and weaknesses in both the TAMDAR and WVSS-II systems. Biases in Relative Humidity and Temperature were noted with the TAMDAR data which changed sign between takeoff and landing. The wind data also showed considerable error with very different characteristics during ascent and descent. The WVSS-II results showed the impact of moisture trapped in the sensing systems on measurement biases throughout the depth of the atmosphere, but that these errors appear to be systematic and correctible at least to large degree.

Additional results will be presented at the meeting, including further subdivision of the data by phase of flight (ascent / descent / en-route), elevation and season.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Benjamin, S., W. Moninger, T. L. Smith, B. Jamison, and B. Schwartz, 2006: Impact of TAMDAR humidity, temperature, and wind observations in RUC parallel experiments. *12th Conference on Aviation Range and Aerospace Meteorology*, Atlanta, GA, Amer. Meteor. Soc.

Moninger, W. R., M. F. Barth, S. G. Benjamin, R. S. Collander, B. D. Jamison, P. A. Miller, B. E. Schwartz, T. L. Smith, and E. Szoke, 2006: TAMDAR Evaluation Work at the Earth System Research Laboratory: an Overview. *10th Symposium on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface*, Atlanta, GA, Amer. Meteor. Soc.

Petersen, R. A., W. Feltz, E. Olson and S. Bedka, 2006: Evaluation of the WVSS-II moisture senson using co-located in-situ and remotely sensed opbservations. *10th Symposium on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface*, Atlanta, GA, Amer. Meteor. Soc.