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9.2 2006 TAMDAR impact experiment results for RUC humidity, temperature, and wind forecasts

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1. INTRODUCTION

During 2006, it has become increasingly clear that expansion of the aircraft fleet to serve additional hubs (i.e., *more ascent/descent locations in a denser network*) is the *most important* observational need for improving aviation weather forecasts. Addition of *moisture* data in aircraft observations has also been shown to improve humidity forecasts.

A major effort toward meeting these aviation needs has been made in the TAMDAR (Tropospheric AMDAR – Aircraft Meteorological Data Reports) program, developed by AirDat LLC and originally sponsored by the NASA Aviation Safety and Security Program (Daniels et al. 2004, 2006, Moninger et al. 2006, latest update in Moninger et al. 2007).

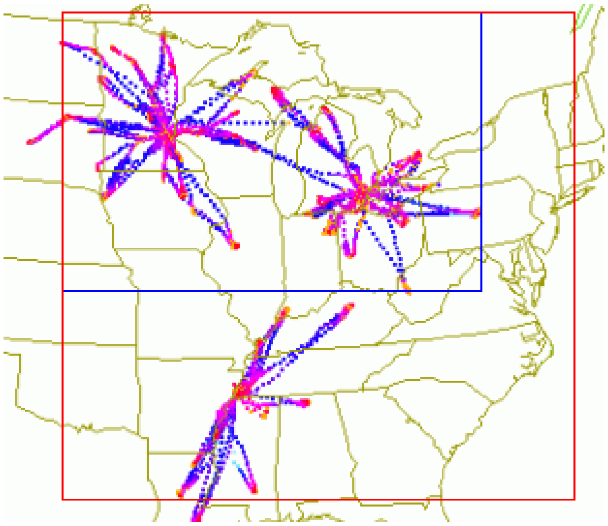

Fig. 1. TAMDAR observations typical for 24h period in 2006. Verification areas shown for blue rectangle (Great Lakes area – 13 raobs) and red rectangle (Eastern US area – 38 raobs).

Two major weaknesses in the current aircraft meteorological report data set are absence of data below 25,000 ft between major airline hubs and the almost complete absence of water vapor data. To address these deficiencies, the TAMDAR system has been deployed on approximately 60 regional turboprop aircraft operated by Mesaba Airlines (subsidiary of Northwest Airlines) flying over the north central U. S. Like the rest of the AMDAR fleet, TAMDAR measures winds and temperature, but also measures humidity.

Under FAA sponsorship, NOAA/ESRL/GSD has continued a careful TAMDAR impact experiment. GSD has conducted real-time parallel experiments with hourly Rapid Update Cycle (RUC) runs to test the impact of these data. The RUC is well-suited for regional observation impact experiments due to its complete use of hourly observations and diverse observation types. These experiments started in March 2005 and we present results here through October 2006, extending the initial six month period reported last year by Benjamin et al. 2006 (a,b). During the last 12 months, the TAMDAR data resolution, quality control, and assimilation methods in the RUC have all changed to increase the positive impact of TAMDAR in forecasts.

2. 2006 UPDATE ON PARALLEL REAL-TIME RUC CYCLES TO STUDY TAMDAR IMPACT ON FORECASTS

Two parallel experimental versions of the Rapid Update Cycle have been run at ESRL/GSD since Feb 2005, differing only in the following:

- 'Dev' (or 'development version 1') assimilated all hourly non-TAMDAR observations (e.g., profiler, aircraft, surface, satellite, GPS-IPW, rawinsonde)
- 'Dev-2', same as dev but adding TAMDAR aircraft observations.
- Same NAM-based lateral boundary conditions used for both Dev and Dev-2 experiments
- These RUC experiments have been run at 20-km resolution, but using latest 13-km-version code.

These RUC experiments have used up-to-date assimilation/model techniques. In February 2006, the dev/dev2 versions of the RUC used for the TAMDAR impact experiments were upgraded in analysis and model code to improved observation quality control

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and precipitation physics. These modifications were the same as those implemented into the operational-NCEP 13-km RUC on 28 June 2006. The 20-km resolution was used to save computer resources.

From June-October 2006, TAMDAR data were also assimilated into experimental 13-km RUC versions at GSD, with similar (but not greater) TAMDAR impact, confirming that use of 20-km resolution in the dev and dev2 RUC cycles has not masked potential TAMDAR impact.

The RUC version used for the TAMDAR experiments also includes complete assimilation of all observation types (as used in the RUC13, including cloud analysis (GOES and METAR), full METAR assimilation including accounting for mixed-layer depth, GPS precipitable water, GOES precipitable water, all other aircraft, profiler, mesonet, and rawinsonde. A summary of the characteristics of the June 2006 operational RUC13 is available at http://ruc.noaa.gov/ruc13_docs/RUC13-summary-Jun06.htm. More details on the RUC assimilation cycle and the RUC model are available in Benjamin et al. (2004a,b).

Among the changes to the RUC made since our report 12 months ago, the following are most relevant to the ongoing TAMDAR experiment:

- Increase of TAMDAR RH moisture observation error from 4% to 12% (Dec 2005). The RH observational error was set inadvertently to 4%, too low a value, from Sept-Dec 2005. The change in Dec 2005 *increased* TAMDAR impact.
- Implementation of improved aircraft QC internal to the RUC analysis program, flagging observations where excessive differences from RUC 1-h forecasts were noted.

Other details on RUC TAMDAR experimental design are described in Benjamin et al. (2006a,b).

3. 2006 CHANGES IN RAOB VERIFICATION TO BETTER DETECT TAMDAR IMPACT

Forecast skill of these parallel RUC cycles is evaluated against RAOBs. Figure 1 shows the specific regions for which we generate results, Region 1 – Eastern US, and Region 2 – Great Lakes.

During 2006, we developed an alternative RAOB verification procedure for these comparisons between dev and dev2 forecasts. Under the previous verification procedure:

- Comparisons are made only at mandatory sounding levels (850, 700, and 500 hPa in the TAMDAR altitude range)
- Verification uses RUC data taken from 40-km pressure-based grids interpolated horizontally and vertically from the RUC native coordinate (isentropic-sigma 20-km) data.
- RAOB data that fail quality control checks inferred from the *operational* RUC analyses are not used.

Under the new verification system,

- Full RAOB soundings, interpolated to every 10 hPa, are compared with model soundings.
- Model soundings, interpolated to every 10 hPa, are generated directly from RUC native files (20-km resolution, isentropic-sigma native levels).
- Comparisons are made every 10 hPa up from the surface.
- No RAOB data are automatically eliminated based on difference from the oper-RUC analysis data. (About a dozen obviously erroneous RAOBs have been eliminated by hand since 23 February 2006.)

For most of the verified variables/levels, the old and new methods gave nearly identical answers, as shown in Figs. 2a,b for 850-hPa temperature. For this variable and level, the difference in QC screening between the old and new verification made almost no difference. Almost identical results were evident, with an average 0.2 K improvement from dev2 (TAMDAR) over dev 3-h forecasts in the Great Lakes area for the April-October 2006 period and a similar month-by-month behavior.

Use of the new verification system has allowed us more vertical precision and allows us to inspect TAMDAR impact in the lowest 1500 m above the surface, below 850 hPa. Moreover, inclusion of more RAOB data has revealed previously obscured positive TAMDAR impact on relative humidity forecasts. These impacts were also obscured because some correct RAOB data was rejected by the old verification system—primarily at 500 hPa—and inclusion of these data resulted in greater calculated skill for dev2 with respect to dev, and hence greater TAMDAR impact, especially for RH in the middle troposphere. No longer excluding RAOB data based on its difference from operational RUC values has made a substantial difference using the new verification of 600-400 hPa RH forecasts, as shown in the next example.

Figures 3a and 3b below show RMS for 500-hPa RH for dev and dev2 using the previous and new verification respectively. The new verification yields higher RMS error because of the use of all RAOB RH values. However, the new verification also shows a much greater *difference* between dev and dev2 indicating that the previously missing RAOB data has affected verification of the two cycles unequally. Note that the spacing on the vertical axis is equal, even though the magnitude of the error is larger with the new verification.

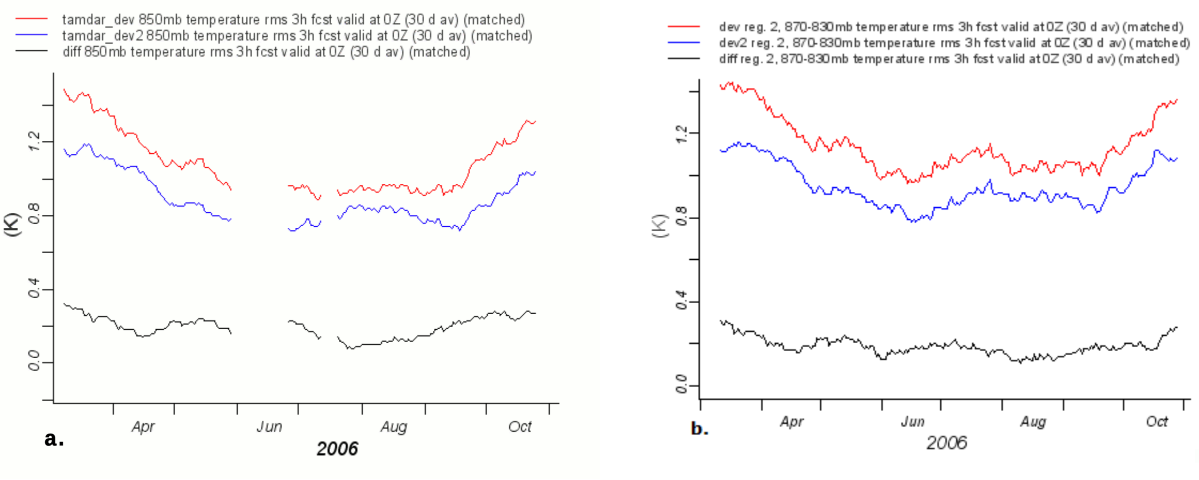

Figure 2. 850-hPa temp 3-h forecast (valid at 00z, Region 2 – Great Lakes) verification with RAOBs for 3-h dev and dev-2 RUC using two different verification programs. a) old verification, b) new

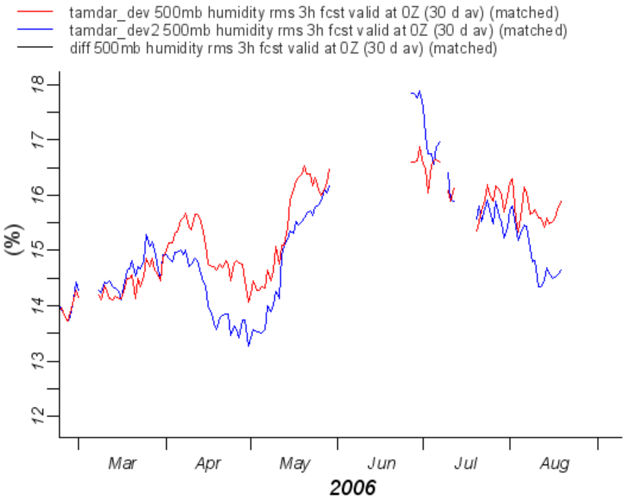

Figure 3a. RMS RH at 500 hPa for 3h forecasts for the old verification system (centered at 15% RH).

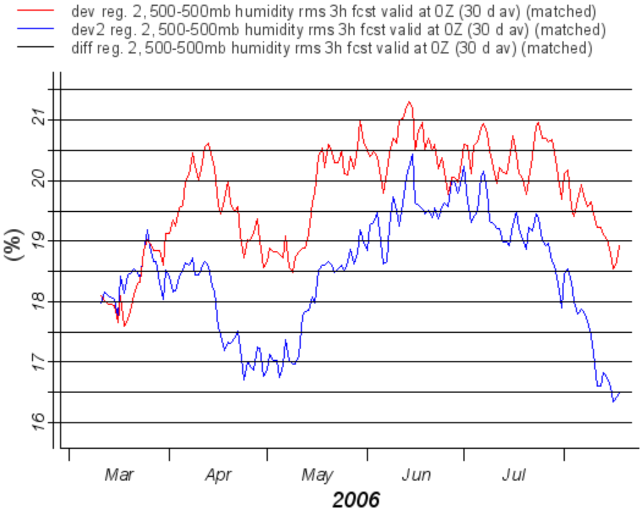

Figure 3b. RMS RH at 500 hPa for 3h forecasts for the new verification system (centered at 19% RH).

To see why this is so, we look at a particular case. Table 1 shows 500 hPa RH values for the RAOB observation and the 3-h dev and dev2 RUC forecasts, all valid at 00 UTC 1 July 2006.

Table 1. RH values at 500 hPa – 00 UTC 1 July 2006

name	RAOB	3h dev	3hdev2	
ILN	33	61	48	
TOP	57	83	75	
PIT	3	76	33	<--
BUF	8	37	7	
OAX	15	53	41	
DTX	14	15	11	
APX	6	6	9	
GRB	30	18	31	
MPX	9	28	33	
ABR	85	90	87	
INL	26	10	21	
DVN	16	39	41	
ILX	19	84	40	<--

The old verification did not use the 500-hPa RH RAOBs at PIT and ILX. In both cases (see soundings in Figs. 4 and 5), strong subsidence layers were evident, with very dry air with bases just below 500 hPa, accompanied with sharp vertical moisture gradients in the 500-520 hPa layer. The QC screening algorithm used in the previous verification method flagged the 500-hPa RH observations at these two stations since the NCEP-oper RUC analysis did not maintain this vertical gradient quite as sharply as in the full RAOB data. In both of these cases, the TAMDAR data led the dev2 RUC to better capture this vertical moisture gradient.

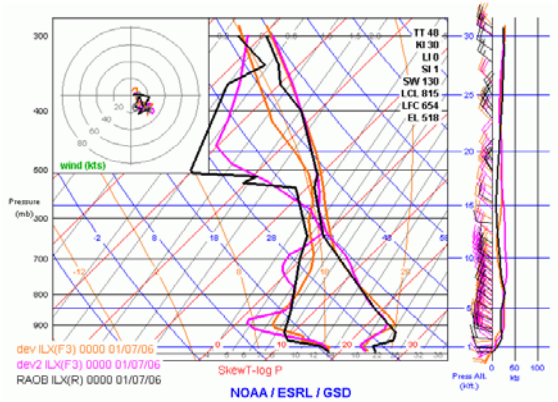

Figure 4. Soundings at ILX for 0 UTC 1 July 2006. RAOB in black, dev 3h forecast in orange, dev2 3h forecast in purple.

Fig. 4 shows the observed RAOB and 3-h forecasts for dev and dev2 soundings for ILX (Lincoln, IL). The dev2 forecast sounding suggests that TAMDAR had detected a dry layer at 500 hPa. Nearby RAOBs (not shown) also suggest that the dry layer at and above 500 hPa is real.

Fig. 5 shows the soundings for PIT. In this case, the accuracy of the dry RAOB observation at 500 hPa is less clear, but is not obviously wrong.

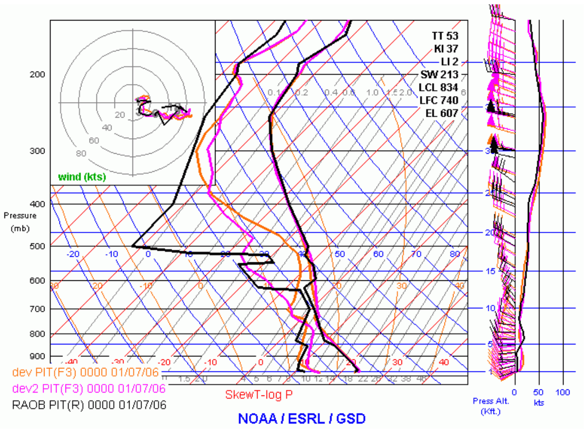

Figure 6. As for Fig. 5 but for PIT.

Apparently, the much stronger TAMDAR impact shown in Fig. 3 between the dev and dev2 500-hPa RH forecasts with the *new* verification screening is attributable to these cases with very sharp vertical moisture gradients near 500 hPa, also suggested by Szoke et al. (2007). Assimilation of the TAMDAR data allows the dev2 RUC forecasts to better capture these features. Properly initializing the sharp moisture gradients can lead to improved cloud forecasts in subsequent hours.

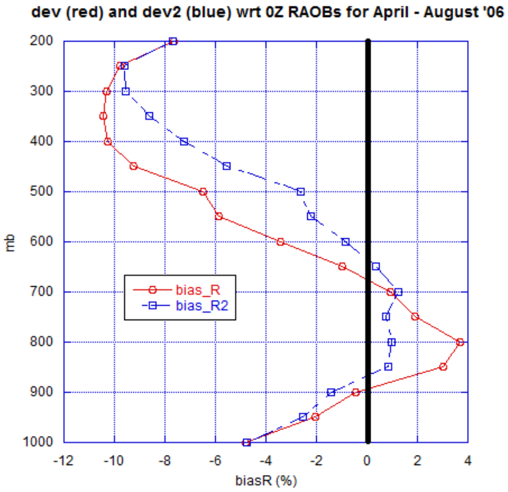

Figure 7. Vertical profile for RH bias (ob-minus-model) for dev and dev2 3h forecasts for Apr–Aug 2006.

Another aspect of the new verification system is that it provides *much finer vertical resolution* than the old. Fig. 7 shows a vertical profile of RH bias for dev and dev2. Note that the RH bias of both models changes sign between 850 hPa and 500 hPa. Looking only at mandatory levels, and in particular, *averaging* over multiple levels can obscure trends such as these. Clearly, having 11 vertical levels between the surface and 500 hPa can reveal far more detail than could be seen in the old verification system, which produced data on only 3 levels at and below 500 hPa (500, 700, and 850 hPa).

4. RUC FORECAST SKILL WITH AND WITHOUT TAMDAR

4.1 2006 results added to the 20-month history of the RUC TAMDAR impact experiments

We are now able to summarize the TAMDAR impact RUC experiment results over a 20-month period starting in Feb. 2005 through October 2006. (All following results are for the Great Lakes area, Region 1). Over this period, AirDat has improved its own TAMDAR data quality (see Moninger et al. 2007), in part due to the NASA/FAA-funded TAMDAR-related research since 2005. Also, GSD has improved its own QC techniques and analysis techniques (see Section 2 and Benjamin et al. 2006a,b).

Note: In Section 4.1 for 2005-2006 results, all statistics used the “old” verification” as described in section 3 of this paper.

Temperature:

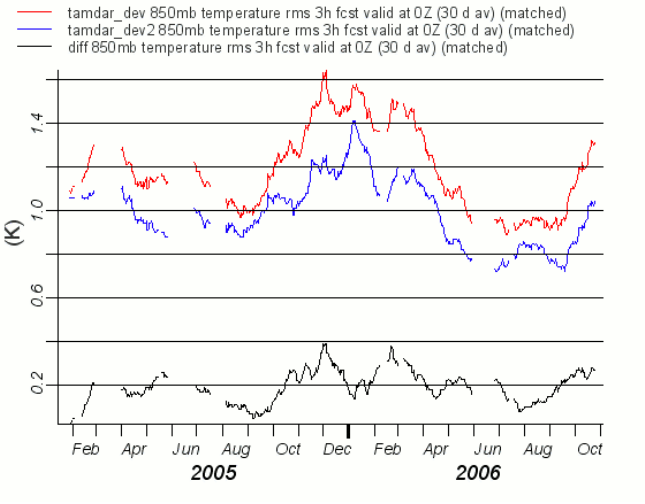

Fig. 8. 850-hPa temperature errors – 3-h forecasts for dev (no TAMDAR- red), dev2 (w/ TAMDAR – blue), and dev-dev2 difference (black). For Region 2 (Great Lakes), Feb. 2005-October 2006.

The degree of improvement of RUC 3-h 850-hPa temperature forecasts was generally larger in 2006 averaging 0.2-0.3 K every month in 2006 except July and August (Fig. 8). The 850-hPa temperature error has continued to show the common seasonal variation with larger errors in winter and smaller errors in summer when the lower troposphere is more commonly well-mixed with a deeper boundary layer.

Relative Humidity:

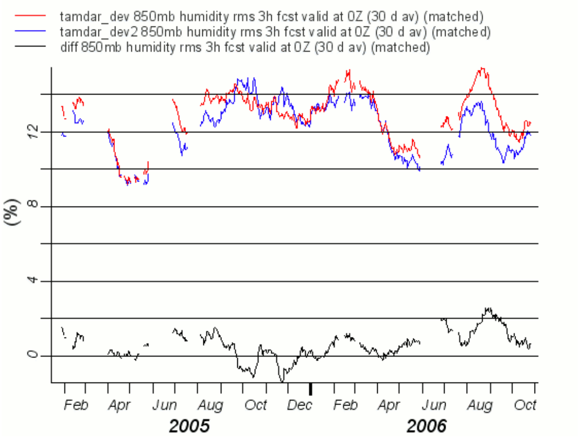

Figure 9. Same as Fig. 8 but for RH at 850-hPa level.

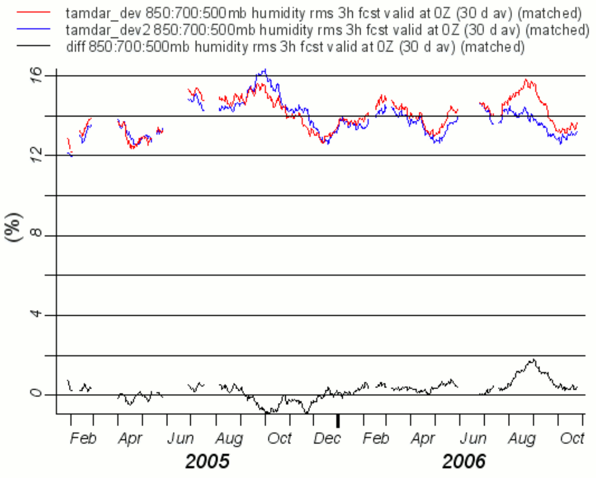

Figure 10. Same as Fig. 9 but for an *average* of the 850-700-500 hPa level.

In 2006, the TAMDAR impact on 3-h RH RUC forecasts was generally larger than in 2005. The 850-hPa RH impact (Fig. 9) was above 1% RH much of the time in 2006, up to as high as 2% RH in Aug-Sept 2006. With the 850-700-500-hPa average of 3-h RH errors (Fig. 10), the overall TAMDAR impact (using the “old” verification) ranged from 0.3-0.7% during most of 2006 except for the same Aug-Sept period, during which even the 3-layer average TAMDAR impact was as high as 2% RH.

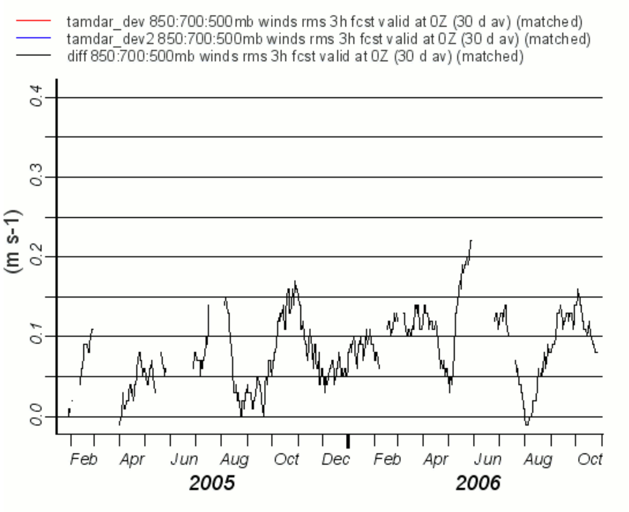

Figure 11. Wind -- 850-700-500-hPa rms vector wind errors – 3-h forecasts - dev-minus-dev2 difference (black). For Region 2 (Great Lakes), Feb. 2005-October 2006.

Winds:

In 2006, TAMDAR impact on 3-h RUC forecasts averaged over the 850-700-500-hPa layer was over 0.1 m/s in 5 of the 9 observed months so far in 2006 (Fig. 11), a slightly larger impact, on average, than in 2005. This is attributed to improved QC in both AirDat processing and in GSD improvements in observation screening within the RUC analysis code.

4.2 2006 verification using new enhanced verification

In this section, we examine the TAMDAR impact for the same three variables using the revised "new" verification processing described in section 3. The following figures show time series data, averaged from the surface up to 500 hPa. We show 30-day running mean averages and using the Great Lakes domain, both as in previous verification results in this paper.

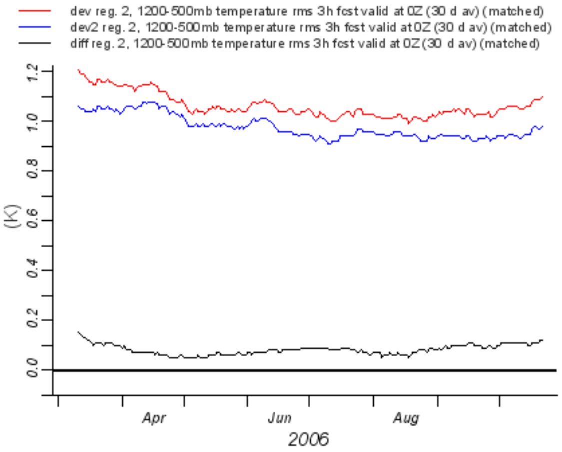

Figure 12. 1000-500 hPa Temperature RMS for 3h forecasts, verified against 00 UTC RAOBs for dev (red) and dev2 (blue). Difference (dev minus dev2) is shown in black. Positive difference indicates positive TAMDAR impact.

Temperature:

Fig. 12 shows that TAMDAR has made a consistent positive impact on 3h temperature forecasts. The impact is approximately 0.1 K when averaged from the surface to 500 hPa. As will be shown in the next section, TAMDAR temperature impact varies with altitude, peaking at 0.2 K at 850 hPa.

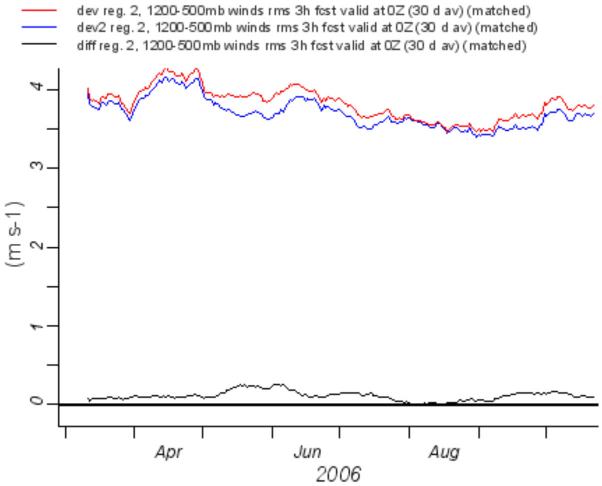

Figure 13. As for Fig. 12 except for wind RMS.

Winds:

Figure 13 shows that TAMDAR's impact on wind forecasts has been consistently positive, although small during August 2006. This is relatively consistent with the results shown from the old verification in Fig.11.

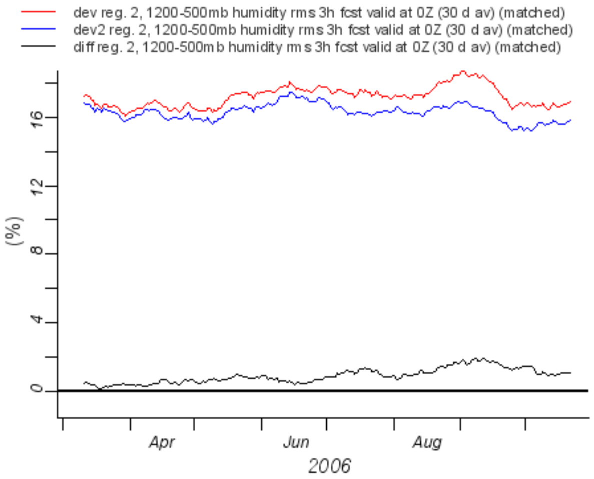

Figure 14. As for Fig. 12 except for RH RMS.

Relative Humidity:

Fig. 14 shows that RH impact has been consistently positive, and has been greater during the Summer than during the Spring. The mean 1000-500 hPa impact is somewhat stronger with the new verification than the old system, averaging 1% RH. This is also different from the initial RUC experiment TAMDAR impact for RH reported one year ago (Benjamin et al. 2006a,b), now with TAMDAR showing a consistent positive impact averaged over a fairly deep layer.

4.3 Vertical profiles of 2006 verification

Most of the results shown here are for Region 2 (Great Lakes) for 3-h forecasts validated against 0000 UTC RAOBs. This is the time and location where we expect to see the maximum TAMDAR impact, given the schedule (13z-03z, primarily daylight hours) of the Mesaba TAMDAR fleet. We also concentrate on the 2006 warm season (April-October).

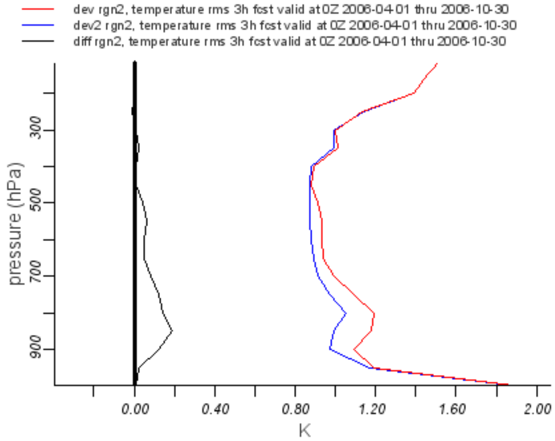

Figure 15. Temperature RMS for 3h forecasts, verified against 0 UTC RAOBs for dev (red) and dev2 (blue) for 1 April to 30 October 2006. Difference (dev minus dev2) is shown in black. Positive difference indicates positive TAMDAR impact.

Fig. 16 shows temperature RMS for dev and dev2 3h forecasts for the time period indicated. The dev2 RUC is shown to have lower errors for all levels between the surface and 450 hPa. The maximum RMS error difference between dev and dev2 occurs at 850 hPa and is about 0.2 K, similar to the 2006 TAMDAR 850-hPa temperature impact shown in Figs. 2a,b.. This represents about **a 30% reduction in 3h temperature forecast error due to TAMDAR**, since the analysis fit to RAOB temperature is about 0.5 K as described in Benjamin et al. 2006a,b.

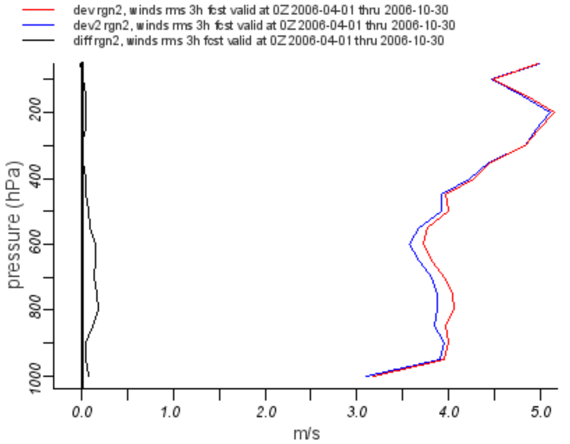

Figure 16. Same as Fig. 15 but for RMS of vector wind difference between models and RAOBs.

Fig. 16 shows that, in spite of the relatively large TAMDAR wind errors (in comparison with the AMDAR jet fleet, see Moninger et al. 2007), TAMDAR is able to make a small but positive impact on 3h wind forecasts between 900 and 450 hPa. The TAMDAR wind impact is strongest in the 800-600 hPa layer.

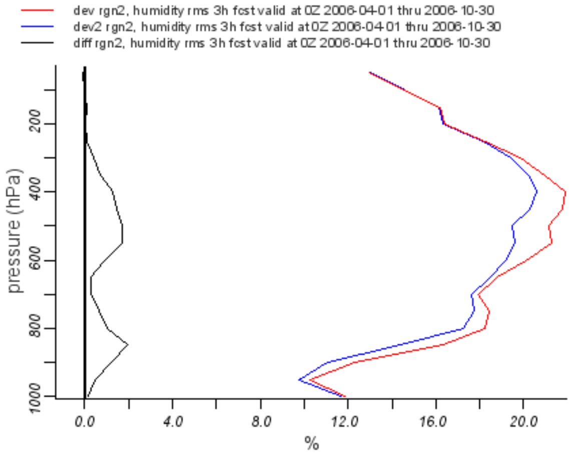

Figure 17. Same as Fig. 16 but for RMS of relative humidity.

Fig. 17. shows RMS of relative humidity. At most levels, the RUC dev2 forecasts show 1-2 %RH less 3h forecast RH error than the dev RUC. **This represents approximately a 15 - 30% reduction in**

3h RH forecast error due to TAMDAR between the surface and 500 hPa.

Interestingly, the RH impact is less at 700 hPa—a mandatory level—than elsewhere. This is one of the reasons the old verification underestimated the full vertical extent of TAMDAR RH impact.

Fig. 7 (see Section 3) shows relative humidity bias for 6 months. At most levels, dev2 shows substantially less bias than dev—a major positive TAMDAR impact. We note that both dev and dev2 have bias near 0 near 650 hPa – the same altitude as the minimum TAMDAR impact on RH RMS shown in Fig 17. This is consistent with RH bias being an important component of the RH RMS.

5. CONCLUSIONS

The continuation of the TAMDAR impact experiments with parallel versions of the RUC has shown improvements in overall impact for temperature and especially for relative humidity.

The parallel experiments with RUC to examine TAMDAR impact have now been conducted from February 2005 to October 2006 over a 20-month period. As shown in Benjamin et al. 2006a,b, and 2004c (Eq 3, Fig. 11c), these results can be normalized using analysis fit to observations as equivalent to a perfect forecast score. We use the following values for analysis fit:

- 850 hPa wind - 3.0 m/s
- 850 hPa temp - 0.5 K
- 850 hPa RH - 10% (RH)

Including use of this normalization, we draw the following preliminary conclusions on the TAMDAR impact experiments:

- TAMDAR impact results have continued to improve.
- The TAMDAR impact experiments using RUC have continued to contribute to the shakedown of the TAMDAR observation quality.
- Temperature impact from TAMDAR
    - Strongest results at 850 hPa – 20-30% improvement for 3-h forecasts over Great Lakes area (using normalization).
    - 15-20% positive impact at 700-500 hPa, where errors are usually smaller.
- RH impact
    - Strongest at 900-800 hPa and 600-450 hPa – up to 20% normalized improvement for 3-h forecasts (considerably larger TAMDAR impact for RH overall than in 2005 results).
- Wind impact
    - Averaged 15-20% improvement for the 800-600 hPa layer.
- Diurnal variations (as in previous report, not shown here)
    - More impact for 3-h forecasts at 00 UTC than at 12 UTC
    - More impact for 6-9h forecasts at 12 UTC than at 00 UTC

Results should further improve with additional improvements in TAMDAR data accuracy (e.g., reducing ascent vs. descent temperature biases – Moninger et al. 2006, 2007 - wind errors) and as TAMDAR is implemented in other aircraft fleets with more improved heading information. We note that all of these results are consistent with subjective forecaster TAMDAR impact studies (e.g., Szoke et al. 2006a,b).

6. ACKNOWLEDGMENTS

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REFERENCES

Benjamin, S.G., D. Devenyi, S.S. Weygandt, K.J. Brundage, J.M. Brown, G.A. Grell, D. Kim, B.E. Schwartz, T.G. Smirnova, T.L. Smith, G.S. Manikin, 2004a: An hourly assimilation/forecast cycle: The RUC. *Mon. Wea. Rev.,* **132**, 495-518

Benjamin, S.G., G.A. Grell, J.M. Brown, T.G. Smirnova, and R. Bleck, 2004b: Mesoscale weather prediction with the RUC hybrid isentropic/terrain-following coordinate model. *Mon. Wea. Rev*., **132**, 473-494.

Benjamin, S.G., B.E. Schwartz, E.J. Szoke, and S.E. Koch, 2004c: The value of wind profiler data in U.S. weather forecasting. *Bull. Amer. Meteor. Soc.*, **85**, 1871-1886.

Benjamin, S. G., W. R. Moninger, T. L. Smith, B. D. Jamison, and B. E. Schwartz, 2006a: TAMDAR aircraft impact experiments with the Rapid Update Cycle. *10th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS)*, Atlanta, GA, Amer. Meteor. Soc.

Benjamin, S.G., W. R. Moninger, T. L. Smith, B. D. Jamison, and B. E. Schwartz, 2006b: Impact of TAMDAR humidity, temperature, and wind observations in RUC parallel experiments. *12th Conf. on Aviation, Range, and Aerospace Meteorology (ARAM)*, Atlanta, GA, Amer. Meteor. Soc.

Daniels, T., W.R. Moninger, D. Mulally, G. Tsoucalas, R. Mamrosh, and M. Anderson, 2004: Tropospheric airborne meteorological data reporting (TAMDAR) sensor development. *11th Conf. on Aviation, Range, and Aerospace Meteorology*, Hyannis, MA, Amer. Meteor. Soc., CD-ROM, 7.6.

Daniels, T. S., W. R. Moninger, R. D. Mamrosh, 2006: Tropospheric Airborne Meteorological Data Reporting (TAMDAR) Overview. *10th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS)*, Atlanta, GA, Amer. Meteor. Soc.

Moninger, W. R., T. S. Daniels, and R. D. Mamrosh 2006: Automated Weather Reports from Aircraft: TAMDAR and the U.S. AMDAR Fleet. *12th Conference on Aviation Range and Aerospace Meteorology*, Atlanta, GA. Amer. Meteor. Soc.

Moninger, W.R., S. Benjamin, R. Collander, B. Jamison, T. Schlatter, T. Smith, and E. Szoke, 2007: TAMDAR/AMDAR data assessments using the RUC at NOAA's Global System Division. *11th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS)*, San Antonio, TX, Amer. Meteor. Soc.

Szoke, E. J., B. D. Jamison, W. R. Moninger, S. G. Benjamin, B. E. Schwartz, T. L. Smith, 2006a: Impact of TAMDAR on RUC forecasts: Case Studies. *10th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS)*, Atlanta, GA, Amer. Meteor. Soc.

Szoke, E.J., R.S. Collander, B.D. Jamison, T.L. Smith, T.W. Schlatter, S.G. Benjamin, and W.R. Moninger, 2006b: An evaluation of TAMDAR soundings in severe storm forecasting. 23rd Conf. Severe Local Storms, St. Louis, MO, Amer. Meteor. Soc., 8.1

Szoke, E.J., S. Benjamin, R. Collander, B. Jamison, W. Moninger, T. Schlatter, and T. Smith, 2007: Impact of TAMDAR on the RUC model: A look into some of the forecasts. *11th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS)*, San Antonio, TX, Amer. Meteor. Soc.