4A.2 TAMDAR AND ITS IMPACT ON RAPID UPDATE CYCLE (RUC) FORECASTS

William R. Moninger*, Stanley. G. Benjamin, Brian D. Jamison[1], Thomas W. Schlatter[2], Tracy Lorraine Smith[1], Edward J. Szoke[1]
NOAA Earth System Research Laboratory (ESRL), Boulder, CO, USA
[1]Collaboration with the Cooperative Institute for Research in the Atmosphere (CIRA), Fort Collins, CO, USA
[2]Collaboration with the Cooperative Institute for Research in Environmental Sciences (CIRES), Boulder, CO, USA

1. INTRODUCTION

Commercial aircraft now provide more than 160,000 observations per day of wind and temperature aloft over the contiguous United States. The general term for these data is AMDAR (Aircraft Meteorological Data Reports). These data have been shown to improve both short- and long-term weather forecasts, and have become increasingly important for regional and global numerical weather prediction (Moninger, et al. 2003).

Two shortfalls of the current AMDAR data set are the absence of data below 25,000 ft between major airline hubs and the almost complete absence of water vapor data at any altitude. To address these deficiencies, a sensor called TAMDAR (Tropospheric AMDAR), developed by AirDat, LLC, under sponsorship of the NASA Aviation Safety and Security Program, has been deployed on approximately 50 regional turboprop aircraft flying over the middle US (Daniels, et al. 2006). These turboprops are operated by Mesaba Airlines (doing business as "Northwest Airlink"). The aircraft cruise at lower altitudes (generally below 500 hPa) than traditional AMDAR jets, and into regional airports not serviced by AMDAR jets. Like the rest of the AMDAR fleet, TAMDAR measures winds and temperature. But unlike most of the rest of the fleet, TAMDAR also measures humidity, turbulence, and icing. By 2008, AirDat expects to have more than 400 aircraft operating with TAMDAR in the U.S.

ESRL's Global Systems Division (GSD) has built an extensive system for evaluating the quality of TAMDAR and AMDAR data, and has applied this system for the 2.5 years that TAMDAR has been in operation. Our evaluation system relies on the Rapid Update Cycle (RUC) numerical model and data assimilation system (Benjamin, et al.2004a,b, 2006a).

Under FAA sponsorship, NOAA/ESRL/GSD is performing a careful TAMDAR impact experiment. The RUC is well-suited for regional observation impact experiments due to its complete use of hourly observations and diverse observation types. We report here on statistical measures of forecast improvement; a companion paper by Szoke et al. (2007) discusses several case studies in detail.

* *Corresponding author address:* William R. Moninger, NOAA/ESRL/GSD, R/GSD1, 325 Broadway, Boulder, CO 80304, USA. email: Bill.Moninger@noaa.gov, phone: 303-497-6435

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

Two parallel experimental versions of the RUC have been run at ESRL/GSD since February 2005, with the following properties:

- 'Dev' (or 'development version 1') assimilates all hourly non-TAMDAR observations.
- 'Dev2' is the same as dev but includes TAMDAR wind, temperature, and relative humidity observations.
- The same lateral boundary conditions, from NCEP's North American Model (NAM), are used for both dev and dev2 experiments.
- These RUC experiments are run at 20-km resolution, but using latest 13-km-version code.

In February 2006, and April 2007 the dev/dev2 versions of the RUC used for the TAMDAR impact experiments were upgraded in analysis and model code to improve observation quality control and precipitation physics. These modifications were generally the same as those implemented, or soon to be implemented, into the operational-NCEP 13-km, with the exception that dev and dev2 do not ingest radar data.

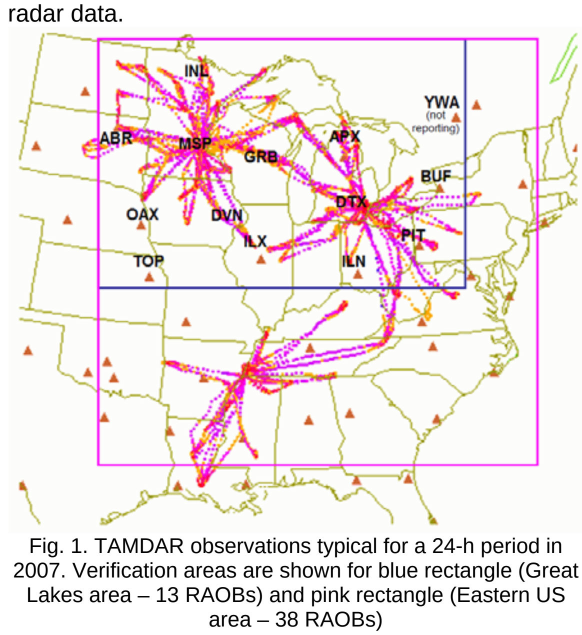

Fig. 1. TAMDAR observations typical for a 24-h period in 2007. Verification areas are shown for blue rectangle (Great Lakes area – 13 RAOBs) and pink rectangle (Eastern US area – 38 RAOBs)

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 includes complete assimilation of nearly all observation types (as used in the RUC13, including cloud analysis (GOES and METAR), full METAR assimilation, GPS precipitable water, GOES precipitable water, all other aircraft, profiler, mesonet, and RAOB. (It does not, however, use radar data, which has been recently added to GSD's development RUC13.) A summary of the characteristics of the June 2006 operational RUC13 is available at http://ruc.noaa.gov/ruc13_docs/RUC-testing-Jun06.htm. More details on the RUC assimilation cycle and the RUC model are available in Benjamin et al. (2004a,b). Other details on RUC TAMDAR experimental design are described in Benjamin et al. (2006a,b).

3. CHANGES IN RAOB VERIFICATION TO BETTER DETECT TAMDAR IMPACT

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

In 2006 we developed a new RAOB verification procedure for these evaluations. Under the previous verification procedure:

- RUC-RAOB comparisons are made only at mandatory sounding levels (850, 700, and 500 hPa in the TAMDAR altitude range).
- Verification uses RUC data interpolated horizontally and vertically to 40-km pressure-based grids 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 operational RUC analysis data. (About a dozen obviously erroneous RAOBs have been eliminated by hand since 23 February 2006.)

Differences between the old and new verification results are discussed in detail in Benjamin et al. 2007. Here, we summarize these differences.

The new verification system provides more vertical precision and allows us to inspect TAMDAR impact in the lowest 1500 m above the surface, below 850 hPa.

For most of the verified variables/levels, the old and new methods give nearly identical measures of TAMDAR impact. However, inclusion of more RAOB data has revealed previously obscured positive TAMDAR impact on relative humidity forecasts. These impacts were obscured in part because some correct RAOB data were 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. Also, the new verification at 10 hPa intervals provides a more realistic assessment of RH, which can often vary more quickly in the vertical than either temperature or wind.

This paper uses the new verification scheme.

4. REAL-TIME RUC FORECAST SKILL WITH AND WITHOUT TAMDAR

4.1 Temperature

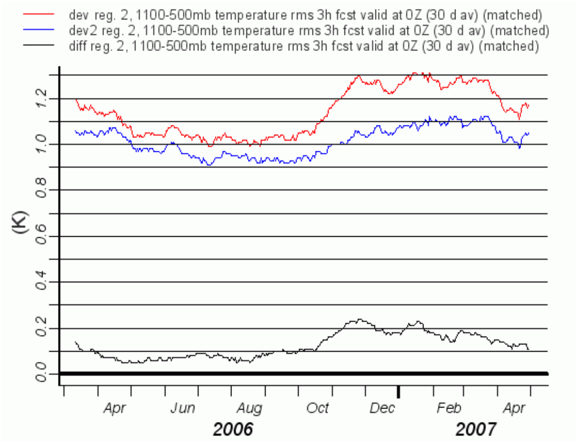

Fig. 2. Time series of 3-h temperature forecast errors (RMS difference from 00 UTC RAOBs) for dev (no TAMDAR, red) and dev2 (TAMDAR, blue), and dev-dev2 difference (black). For Region 2 (Great Lakes), in the layer between the surface and 500 hPa. Mid-March 2006 – May 2007; 30 day running averages. Positive differences indicate a positive TAMDAR impact.

Fig. 2 shows TAMDAR impact on temperature forecasts for the past year. The error shows 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 (also seen in the fall-winter of 2005/06). We consider only 00 UTC RAOBs because this is the time when we expect to see the maximum TAMDAR impact, given the schedule (11-03 UTC, primarily daylight hours) of the Mesaba TAMDAR fleet.

Fig. 3 shows a vertical profile of temperature RMS for dev and dev2 3-h forecasts for the time period indicated. The dev2 RUC has lower errors for all levels between the surface and 450 hPa. The maximum RMS error difference between dev and dev2 occurs at 900 hPa and is about 0.4 K.. Because the *analysis* fit to RAOB verification data is about 0.5

K as described in Benjamin et al. (2006a,b, 2007), the maximum possible reduction in RMS error difference would be about 1.1 K (the difference between the ~1.6 K RMS shown for dev in Fig. 3 at 900 hPa and the 0.5 K analysis fit). Thus **TAMDAR data result in about a 35% reduction in 3-h temperature forecast error at 900 hPa**.

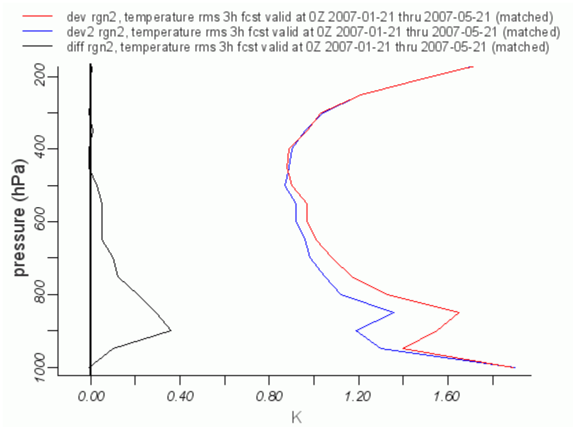

Fig. 3. Vertical profile of 3-h temperature forecast errors (RMS difference from 00 UTC RAOBs) for dev (no TAMDAR, red) and dev2 (TAMDAR, blue), and dev-dev2 difference (black). For Region 2 (Great Lakes), 21 Jan – 21 May 2007.

4.2 *Wind*

Fig. 4 shows TAMDAR impact on winds for the past year, averaged over the surface-500 hPa layer. The impact is small but consistently positive. TAMDAR wind errors are greater than those of the traditional AMDAR jet fleet because the quality of the heading information from the Mesaba turboprop aircraft is lower than that found on jets flown by most major airlines (Moninger et al. 2007). Heading information is a critical variable for calculating winds aloft.

Fig. 5 shows the corresponding vertical profile. The TAMDAR impact on winds shows a broad peak, with a maximum at 700 hPa. At this level, the RMS reduction due to TAMDAR is about 0.25 m/s. This represents about **a 15% reduction in 3-h wind forecast error due to TAMDAR** since the analysis fit to RAOB winds is about 2.2 m/s in this altitude range.

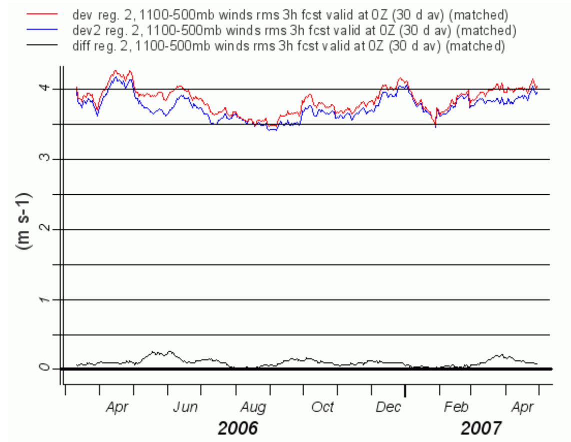

Fig. 4. as for Fig. 2, but for 3-h wind forecasts.

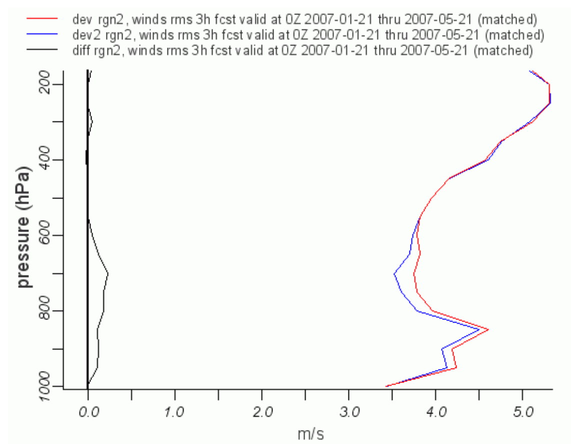

Fig. 5. as for Fig. 3, but for 3-h wind forecasts.

4.3 *Relative Humidity*

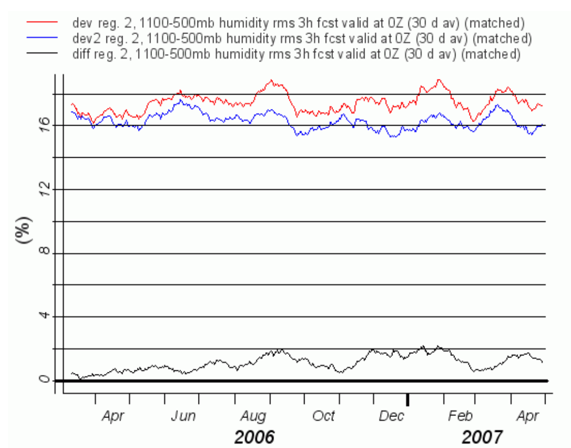

Fig. 6. as for Fig. 2, but for 3-h Relative Humidity forecasts.

Fig. 6 shows TAMDAR impact on RH for the past year. The impact is generally between 1% and 2% when averaged between the surface and 500 hPa.

Fig. 7 shows the corresponding vertical profile. The RH impact is seen to be relatively uniform from the surface to 550 hPa—the general altitude range in which TAMDAR flies, and is 1-2%. (Interestingly, the apparent TAMDAR impact is slightly *negative* between 250 and 150 hPa, but this is far above the altitudes where TAMDAR flies, and an altitude where RAOB RH data are often suspect. We therefore consider this of little importance.)

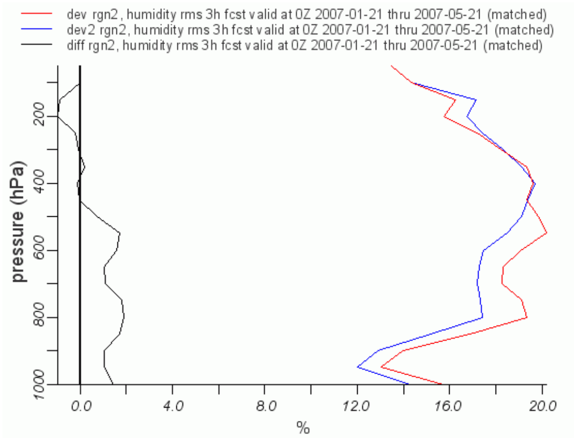

Fig. 7. as for Fig. 3, but for 3-h Relative Humidity forecasts.

Fig. 8 shows the *analysis* fit for RH for the same temporal and spatial region, along with the same dev and dev2 3-h forecast errors shown in Fig. 7. The RMS for the analysis varies between 5 %RH at 950 hPa and about 11 %RH between 750 and 400 hPa. Thus, the 1-2% reduction in RMS due to TAMDAR moves the 3-h RMS about 15-25% of the way to the analysis fit, so represents **a reduction in 3h RH forecast error of 15-25%**. But see section 5; we expect recent changes in the way the RUC assimilates TAMDAR RH data to increase this impact.

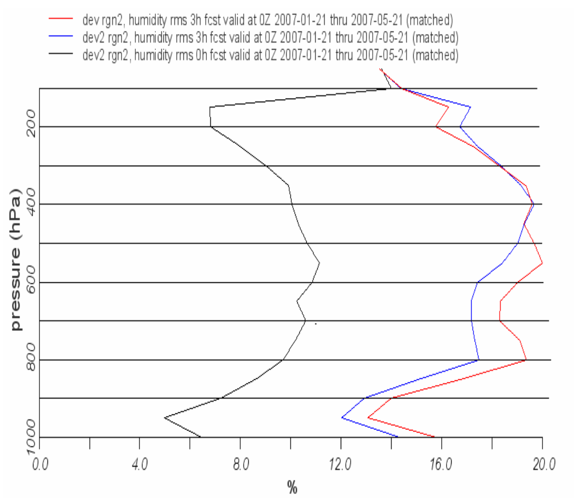

Fig. 8. dev2 RH analysis RMS difference (black) with 0 UTC RAOBs in the Great Lakes region. 21-Jan through 21-May 2007, along with dev (red) and dev2 (blue) 3-h RH forecasts.

5. RETROSPECTIVE RUNS

In order to study TAMDAR impact in more detail, and to study how these new data are best assimilated in the RUC, we saved all data for a 10-day period: 12 UTC 26 November to 12 UTC 5 December 2006, and have rerun the RUC with a variety of different assimilation schemes and TAMDAR data variations.

We chose this period because it included a potent early winter storm that dropped a significant band of heavy snow and ice through the heart of the TAMDAR network, mainly from 30 November through 1 December, and includes more typically moderate weather in the later portion of the period.

5.1 *Relative Humidity Observation Error Specification for Assimilation*

Because high temporal and spatial resolution RH measurements aloft at nonsynoptic times have been unavailable in the past, we have no firm guidance for choosing the appropriate error for these measurements. Both instrument errors and representativeness errors must be accounted for, so that the importance of each observation relative to the model background field is correctly assessed. Choosing an RH error that is too large will result in less-than-optimal TAMDAR impact. Choosing a value that is too small will result in overfitting, causing numerical noise that will degrade forecasts.

We experienced overfitting when, during the fall of 2005, the TAMDAR RH error was inadvertently set to 1%. During this period, TAMDAR impact of 3-h RH forecasts was *negative* (Benjamin et al. 2007, Figs 9 and 10). However, for most of the 2.5 years we have assimilated TAMDAR data, we have run with RH errors between 3% and 12%. With these errors, TAMDAR has had a positive impact of 10-25% (see section 4.3).

In early 2007, it was discovered that the observation errors for all RH observations (TAMDAR, surface observations, RAOBs, integrated precipitable water data from GPS-Met (Smith et al. 2007)) were being inadvertently divided by a factor of 4. We corrected this in a retrospective run, and found that the correction (called “new processing” below) resulted in slightly increased model skill (decreased RMS) for RH forecasts at nearly all levels, as Fig. 9 shows, even in the absence of TAMDAR.

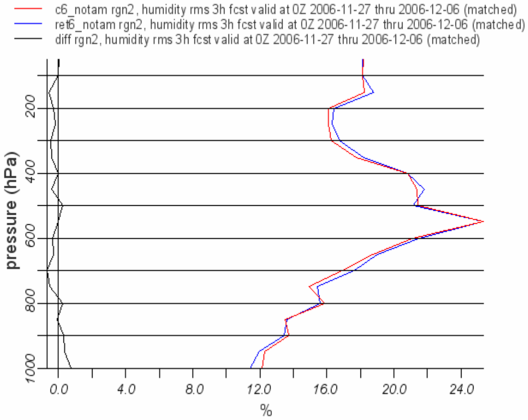

Fig. 9. Vertical profile of 3-h temperature forecast errors (RMS difference from 00 UTC RAOBs) for "old processing" (blue—RH errors divided by 4), and "new processing (RH errors corrected). **Without TAMDAR data**. For Region 2 (Great Lakes). The black curve shows the difference; negative values indicate that the new processing has lower RMS errors.

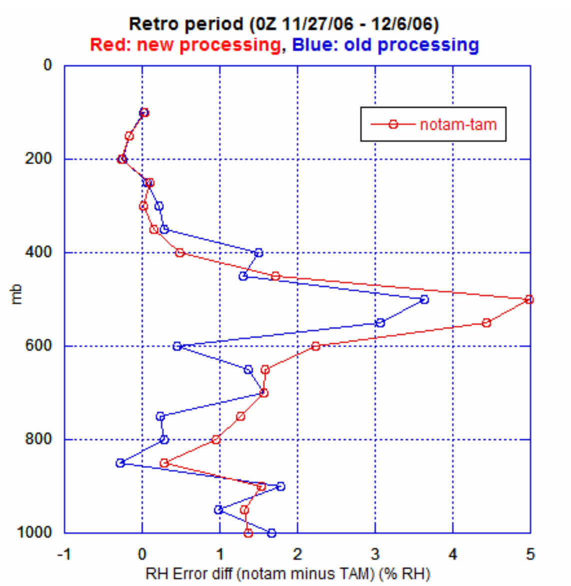

Fig. 10. TAMDAR impact for 3-h RH forecasts (see text for explanation) for "new processing" (12% TAMDAR RH error, red) and "old processing" (3% TAMDAR RH error, blue) for the retrospective time period.

Moreover, when TAMDAR data are included, the new processing increased TAMDAR impact, as shown in Fig. 10.

Fig. 10 shows two impact curves. Each curve shows the *difference* between the RMS errors of the TAMDAR and no-TAMDAR runs (with respect to 00 UTC RAOBs in the Great Lakes Region). The blue curve shows the impact under the old processing; the red curve shows impact with the new processing. The larger values for the red curve show that the TAMDAR impact in RH forecasts increases substantially at levels between 850 and 450 hPa with the new processing.

Additional retrospective runs using TAMDAR RH observation errors of 18% and 25% showed that these values resulted in slightly less TAMDAR impact than the 12% value. Therefore, we implemented the 12% RH error, and the correction of the other RH observation errors, in our real-time dev2 runs on 26 April 2007.

5.2 *Indirect Relative Humidity Impact*

There has been some speculation that improved resolution in temperature and wind data alone will indirectly improve RH forecasts, because better wind and temperature fields will result in better placement of humid areas. We therefore performed a retrospective run in which we included TAMDAR wind and temperature observations, but no TAMDAR RH observations. (All other data were included.)

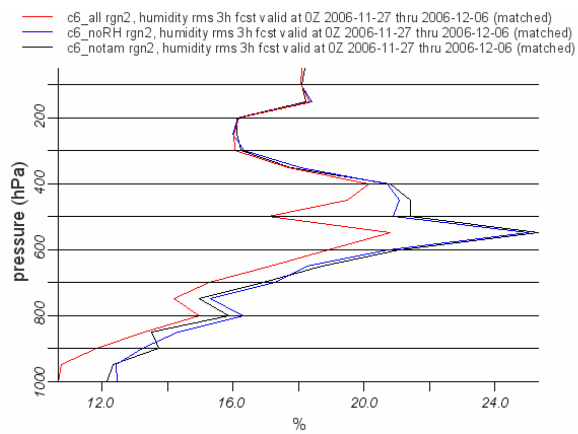

Fig. 11. 3-h RH forecast errors (RMS difference from 00 UTC RAOBs) for Region 2 (Great Lakes), for the retrospective period, for 3 cases:

- Red: all TAMDAR data
- Black: no TAMDAR data
- Blue: TAMDAR wind and temperature data only

Fig. 11 shows that, for 3-h forecasts of RH, TAMDAR has virtually no impact when its RH data are excluded. However, Fig. 12, which shows the same statistics but for 9-h forecasts, *does* show some RH impact due to TAMDAR wind and temperature observations alone: between 500 and 450 hPa, the blue curve shows RH errors about halfway between the all TAMDAR (red) and no TAMDAR (black) runs. Interestingly, this is at a higher altitude than TAMDAR generally flies. This suggests that model vertical motion is improved by the temperature and wind data, thereby improving the modeled water-vapor advection.

Thus, we can conclude that for 3-h forecasts, RH observations are needed to improve RH forecasts, at least on the 20-km scale our RUC model runs. However, at longer forecast projections such as 9-h, there appears to be some improvement in RH forecasts attributable to the increased spatial resolution of wind and temperature observations provided by TAMDAR aircraft flying into regional airports.

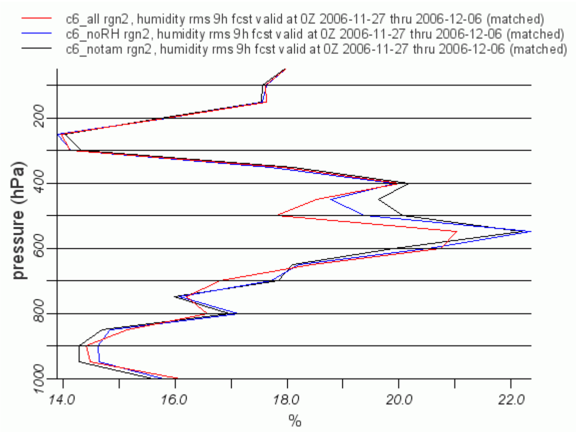

Fig. 12.as in Fig. 11 but for 9-h RH forecasts.

5.3 *Vertical Resolution*

During the retrospective time period, AirDat provided high vertical resolution data (10 hPa in the lowest 200 hPa (for both ascents and descents), and 25 hPa above that). At other times, to save communication costs, they have provided data at lower vertical resolution. To study the impact of different vertical resolution, we artificially degraded the resolution above the lowest 100 hPa AGL to 50 hPa; we kept the 10-hPa resolution in the lowest 100 hPa. This removed about one half of the TAMDAR observations.

The curves in Fig. 13 may be compared to the black curve in Fig. 3. That is, each is the difference in the RMS temperature error between an all TAMDAR run and the no-TAMDAR run. The results indicate that the lowered vertical resolution does indeed reduce TAMDAR impact for temperature. This is on the average about 10% of the maximum TAMDAR impact on 900-hPa, 3-h temperature forecasts to 30% at 750 hPa.

For RH forecasts, reducing the vertical resolution had little consistent impact.

However, for all variables the impact of reduced vertical resolution is certainly larger in certain situations likely related to adverse weather conditions. We note that higher vertical resolution has been very useful in some critical weather situations by human forecasters who look directly at the TAMDAR soundings.

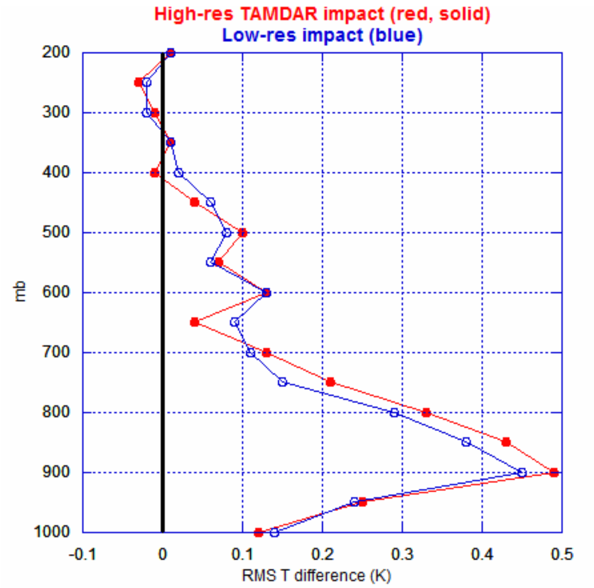

Fig. 13. TAMDAR 3-h temperature forecast impact (see text for explanation) for the full vertical resolution run (red) and the low vertical resolution run (blue), for the retrospective period.

6. SUMMARY AND A LOOK AHEAD

The TAMDAR sensor provides meteorological data on a regional scale over the US Midwest. We have evaluated the impact of TAMDAR's wind, temperature, and relative humidity data on the RUC model with 1) real-time matched TAMDAR and no-TAMDAR runs for the past 2.5 years, and 2) retrospective runs over a 10-day active weather period during the fall of 2006.

We have shown that TAMDAR improves 3-h RUC forecasts in the region and altitude range in which TAMDAR flies. After accounting for instrument and representativeness errors in the verifying observations (i.e., the quality of the analysis fit to RAOBs), we estimate the TAMDAR impact as follows:

- Temperature forecast errors are reduced by about 35%.
- Wind forecast errors are reduced by about 15%.
- Relative humidity forecast errors are reduced by about 15-25%.

Retrospective runs have revealed the following:

- The optimal RH error to use for assimilating TAMDAR RH observations is 12%. Lower values than this result in overfitting; higher values result in a gradual drop off of TAMDAR RH impact. The 12% RH error is now being used in our real-time runs.
- RH observations are generally required to improve 3-h forecast skill. However, for longer (9-h) forecasts, wind and temperature observations alone, on sufficiently fine resolution, can improve RH forecasts indirectly.
- Lowered vertical resolution degrades forecast skill from 10-30% for temperature forecasts,

but in individual cases, lowered skill may cause important meteorological conditions to be unobserved.

TAMDAR data from the current Mesaba fleet will continue to be made available by AirDat to the US government for at least the next year. TAMDAR will also be deployed on additional fleets over the next year. These fleets will cover Alaska and the Western US. The fleets will include jet aircraft, which will expose the TAMDAR sensors to higher altitudes and higher speeds than they have been exposed to thus far. Data from these new fleets will be made available by AirDat to ESRL/GSD (but not for redistribution) so that we can evaluate the quality of the data and the impact of these new fleets and expanded coverage on weather forecasts.

6. ACKNOWLEDGMENTS

This research is in response to requirements and funding by the Federal Aviation Administration (FAA) under interagency agreement DTFAWA-03-X-02000. The views expressed are those of the authors and do not necessarily represent the official policy or position of the FAA or NASA. We thank John Brown (ESRL/GSD) for his helpful review of this manuscript, and Annie Reiser (ESRL/GSD) for her careful editing.

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