Evaluation of Regional Aircraft Observations using TAMDAR

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

Submitted for publication in

Weather and Forecasting

25 June 2009

Accepted for publication – 24 November 2009

[1]Collaboration with the Cooperative Institute for Research in the Atmosphere (CIRA), Fort Collins, CO, USA

[2]Retired

Abstract

We present a multiyear evaluation of a regional aircraft observation system (TAMDAR). We compare TAMDAR observation errors with errors in traditional reports from commercial aircraft (AMDAR), and evaluate the impact of TAMDAR observations on forecasts from the Rapid Update Cycle (RUC) over a three-year period. Because of the high vertical resolution of TAMDAR observations near the surface, we developed and employed a novel verification system that compares RUC forecasts against RAOBs every 10 hPa; this revealed TAMDAR-related positive impact on RUC forecasts—particularly for relative humidity forecasts—that were not evident when only RAOB mandatory levels were considered. In addition, we performed multiple retrospective experiments over two 10-day periods, one in winter and one in summer; these allowed us to assess the impact of various data assimilation strategies, and varying data resolution. TAMDAR's impact on 3-h RUC forecasts of temperature, relative humidity, and wind is found to be positive and, for temperature and relative humidity, substantial in the region, altitude, and time range over which TAMDAR-equipped aircraft operated during the period of our analysis.

1. Introduction

As of late 2009, commercial aircraft provide more than 239,000 observations per day of wind and temperature aloft worldwide (Fig. 1). 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). Figure 2 shows AMDAR coverage over the contiguous United States.

Two shortfalls of the current AMDAR data set have been the near absence of data below 20,000 ft between major airline hubs (Fig. 3) 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, was deployed on approximately 50 regional turboprop commercial aircraft flying over the north central U.S. and lower Mississippi Valley (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 fly into regional

airports not serviced by AMDAR-equipped jets. Fig. 4 shows TAMDAR data along with traditional AMDAR data, and shows how TAMDAR fills in the region between major hubs in the U.S. Midwest. For example, in the Great Lakes region, traditional AMDAR-equipped aircraft serve 23 airports—providing ascent and descent atmospheric soundings at each, while TAMDAR-equipped aircraft serve 62 airports.

Like the rest of the AMDAR fleet, TAMDAR measures wind and temperature. But unlike most of the rest of the fleet, TAMDAR also measures humidity, turbulence, and icing. (The “WVSS-II” sensor (Helms et al, 2005) also provides water vapor measurements from several commercial aircraft, and is scheduled to expand substantially in the near future. But the then-current version of the WVSS-II provided relatively few reliable water vapor measurements during the time period studied here.)

The NOAA Earth System Research Laboratory (ESRL) / 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 four years that TAMDAR has been in operation. This 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 performed careful TAMDAR impact experiments. The RUC is well suited for regional observation impact experiments due to its complete use of hourly observations and diverse observation types.

2. RUC experiments to study TAMDAR data quality and forecast impact

Between February 2005 and December 2008, we ran two real-time, parallel versions of the RUC with the following properties:

- ‘dev’ (or ‘development version 1’) assimilated all hourly non-TAMDAR observations.
- ‘dev2’ is the same as dev but also assimilated TAMDAR wind, temperature, and relative humidity observations.
- The same lateral boundary conditions, from the National Center for Environmental Prediction’s (NCEP’s) North American Model (NAM, Rogers et al., 2009), were used for both dev and dev2 runs.
- These RUC experiments are run at 20-km resolution, but using more up-to-date 13-km-version code.

In February 2006 and subsequently in April 2007, the analysis and model code in the dev/dev2 versions of the RUC used for the TAMDAR impact experiments were upgraded to improve observation quality control and precipitation physics. These modifications were generally the same as those implemented into the operational-NCEP 13-km RUC, with the exception that dev and dev2 do not ingest radar data (implemented in the NCEP RUC in November 2008).

The studies herein focus on these real-time model runs, and also on retrospective runs (also at 20-km resolution) over two 10-day periods, one in winter and one in summer. These same test periods were used in a broader set of observation sensitivity experiments (OSEs) for eight different observation types described by Benjamin et al. (2010).

The 20-km RUC version used for the TAMDAR experiments includes complete assimilation of nearly all observation types (as used in the operational RUC), including cloud analysis (GOES and METAR), full METAR assimilation (temperature, dewpoint, winds, pressure, cloud, visibility), GPS precipitable water, GOES precipitable water, all other aircraft, profiler, mesonet, and RAOB. A summary of the characteristics of the June 2006 operational RUC 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, 2010).

3. TAMDAR data quality

To evaluate the *quality* (as opposed to the *model forecast impact*) of TAMDAR, ESRL/GSD maintains a database of AMDAR (including TAMDAR) observations, and 1-h forecasts interpolated to the AMDAR observation point from the RUC dev and dev2 cycles. This allows calculating mean and RMS differences between RUC 1-h forecasts and aircraft-observed temperature, wind, and relative humidity.

Model data are interpolated vertically (linear in log-p) and horizontally to the location of the observation. No temporal interpolation is performed; observations are compared with the 1-h forecast valid at the nearest hour.

For each observation time and location, we store observed and forecasted temperature, relative humidity, wind direction and speed, and phase of flight (ascent, descent, or en route). In addition, the

RUC quality control disposition of each observation (independent QC for each variable) was stored between December 2005 and December 2008, as well as which variable(s) were actually used in the RUC analysis.

3.1 Web-based access to the AMDAR-RUC database

Access to the AMDAR-RUC database is available at http://amdar.noaa.gov/RUC_amdar/. Because access to real-time (i.e., less than 48-h old) AMDAR data is restricted to NOAA and selected other users, access to the real-time portions of this site is restricted. (See http://amdar.noaa.gov/FAQ.html.)

Database access is provided in the following forms:

- Seven-day statistical summaries for each aircraft for four altitude ranges (all altitudes, surface to 700 hPa, 700-300 hPa, and above 300 hPa), sortable by a variety of values
- time-series data for any aircraft (restricted)

3.2 Error characteristics of the TAMDAR/AMDAR fleet

In this section we look at aircraft differences with respect to the RUC dev2 cycle. We do not consider the RUC dev2 1-h forecasts to be "truth"; rather we use it as a common benchmark (assimilating all aircraft types) with which to compare the error characteristics of various aircraft fleets. The 1-h forecast through the RUC forecast model and initialization (Benjamin et al. 2004a,b) forces some (but not total) independence from any particular observation type. We focus on 1-30 October 2006, a reasonably representative month in terms of RUC forecast error and TAMDAR impact, as will be discussed further in section 4.2.

We look at aircraft-RUC differences over the "TAMDAR Great Lakes region" (the small rectangle shown in Fig. 5), which includes the upper Midwest region of the U.S., for "daylight" hours (1200 UTC to 0300 UTC) when TAMDAR-equipped aircraft generally fly.

In our analyses of aircraft-RUC differences, we found it useful to stratify the data by phase of flight (descent, and en-route/ascent) as well as altitude. There are enough TAMDAR data that each data point we show in this section is the average of at least 100 observations; in most cases, especially lower in the atmosphere, each data point represents the average of more than 1000 observations.

Temperature bias relative to the RUC 1-h forecast for traditional AMDAR jets and TAMDAR turboprops is shown in Fig. 6. The jets show a small warm bias at most altitudes peaking at 0.3-0.4 K between 800-500 hPa, and descents (blue) show less warm bias than enroute/ascent (red) data above 600 hPa. Below 800 hPa, descents show a slightly warmer bias than ascents for this time period. TAMDAR shows a smaller temperature bias (nearer zero) than AMDAR from 800-500 hPa. In general, both AMDAR and TAMDAR temperature biases with respect to the RUC are small, less than 0.4 K in absolute magnitude.

Temperature RMS difference from RUC 1-h forecasts for TAMDAR and AMDAR (Fig. 7) is about 1 K at most levels, with TAMDAR RMS being generally equivalent to that of AMDAR jets. Some of this difference is attributable, of course, to RUC forecast error, which would affect TAMDAR and AMDAR equally.

The RMS vector wind differences between aircraft-measured winds and RUC 1-h forecast winds (Fig. 8), in contrast to temperature, are considerably larger for TAMDAR (turboprops) than for AMDAR jets, and TAMDAR's differences on descent are larger than those on ascent and

en-route. The lower quality of wind data from TAMDAR is likely due to the less accurate heading information provided to TAMDAR by the SAAB-340b avionics system. Accurate heading information is required for the wind calculation, and the SAAB heading sensor is magnetic, and known to be less accurate than the heading sensors commonly used on large jets.

The greater error on descent is due, we believe, to aircraft maneuvers, which occur more often on descent than on ascent. In response to this, we eliminated TAMDAR wind measurements taken on descent in the RUC experiments described here. Also, in our current versions of the RUC, we have also implemented a larger observational error estimate for TAMDAR turboprop winds in the RUC analysis, where code allows for different error estimates for each aircraft fleet.

We also examine relative humidity bias (observation-minus-forecast, Fig. 9) for TAMDAR but not for other aircraft, because most traditional AMDAR jets do not measure moisture. (A few WVSS-II moisture sensors (Helms 2005) were flying at this time; we do not consider them in our analysis.) The humidity bias is generally below 5%RH.

Relative humidity RMS difference for TAMDAR from RUC 1-h forecasts (Fig. 10) is generally similar for ascent/en-route vs. descent reports, and increases from ~9%RH near the surface to ~20%RH at 500 hPa. To put this statistic in perspective, the assumed RAOB RMS observational error used by the North American Mesoscale (NAM) model, run operationally at NCEP in its assimilation cycle (Dennis Keyser 2006, personal communication), is shown in black. This error varies from ~8 %RH near the surface to ~16% above 600 hPa. Note that assumed RH errors for RAOBs (often taken as a rough data standard, reflecting observation error only from measurement and spatial representativeness) do not differ greatly from the RH errors shown by TAMDAR (reflecting the combination of TAMDAR observations error, representativeness error, and RUC 1-h forecast error).

To summarize this section:

- Temperature measurements from TAMDAR turboprops and AMDAR jets are approximately equally accurate.
- Wind measurements from TAMDAR turboprops are worse than for AMDAR jets, due to less-accurate heading information from the turboprops. (The SAAB-340B turboprops flown by Mesaba, like many turboprop aircraft, use flux-gate heading sensors,

which are less accurate than the laser-gyroscopic sensors used on most jets.)

- On descent, wind measurements from TAMDAR turboprops are significantly degraded over those taken on ascent, likely due to enhanced heading errors during maneuvers.
- Relative humidity measurement errors from TAMDAR are commensurate with assumed errors for RAOBs.

4. TAMDAR's impact on RUC forecasts

The forecast skill of the RUC is evaluated against RAOBs. Figure 5 shows the specific regions for which we generate results, the Eastern US, and the Great Lakes.

In studying TAMDAR's impact, we take a two-pronged approach. First, we consider the two real-time RUC cycles discussed above (dev and dev2), to see long-term stability and trends. Second, we consider two 10-day intensive study periods, one in winter and one in summer. For each of these periods, we performed several retrospective experiments, with and without TAMDAR, and with varying data assimilation strategies. These experiments complement a broader set

of observation impact experiments for the same summer and winter retrospective periods described in Benjamin et al. (2010).

4.1 Forecast verification procedure

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

- RUC-RAOB comparisons were made only at mandatory sounding levels (850, 700, and 500 hPa in the TAMDAR altitude range).
- Verification used 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 failed quality control checks in the operational RUC analyses were 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. (Fifteen obviously erroneous RAOBs were eliminated by hand between 23 February 2006 and December 2008.)

To compare the old and new verification methods, we look at the temperature impact from TAMDAR at 850 hPa (discussed further in section 4.2.1 below). For most of the verified variables at various levels, the old and new methods give nearly identical answers, as shown in Figs. 11a,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 (assimilating TAMDAR) over dev (no TAMDAR) 3-h forecasts in the Great Lakes region for the April-October 2006 period. As will be discussed in section 6, this is generally consistent with current results.

The new verification system has allowed us more vertical precision; we can now inspect TAMDAR's 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 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. No longer excluding RAOB data based on their difference from operational RUC values has made a substantial difference in the new verification of 600-400 hPa RH forecasts, as shown in the next example.

A comparison using the old and new verification for 500-hPa RH RMS error for dev and dev2 forecasts is presented in Figs. 12 and 13. The new verification (Fig. 13) 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 have affected verification of the two cycles unequally. Apparently, assimilation of TAMDAR RH observations improve RUC RH forecasts in cases with large errors in the middle-troposphere where RAOB values were being flagged using the old verification method. Note that the spacing on the vertical axis is equal, even though the magnitude of the error is larger with the new verification.

To see why this is so, we look at a particular case. Table 1 shows 500-hPa RH values for RAOB observations and the 3-h dev and dev2 RUC forecasts, all valid at 0000 UTC 1 July 2006. The old verification did not use the 500-hPa RH RAOBs at PIT (Pittsburgh, PA) and ILX (Lincoln, IL). In both cases (see soundings in Figs. 14 and 15), strong subsidence layers were evident, with very dry air with bases just below 500 hPa, accompanied by 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 operational 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 14 shows the observed RAOB and 3-h forecasts for RUC dev and dev2 soundings for ILX. The dev2 forecast sounding suggests that TAMDAR had detected a dry layer at 500 hPa. Nearby RAOBs (not shown) also suggest that the observed dry layer at and above 500 hPa was real.

Figure 15 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. Apparently, the much stronger TAMDAR impact shown in Fig. 13 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.

In fact, the TAMDAR impact on RH forecasts is potentially larger than this: In section 5.1, we describe that a change in the RH error characteristic used in the dev2 assimilation of TAMDAR data—not implemented until 26 April 2007—increases TAMDAR RH impact.

This new verification system also provides much finer vertical resolution than the old, and provides data below 850 hPa. Fig. 16 shows a vertical profile of RH bias for dev and dev2. Note that the RH bias of both models starts positive (more moist than RAOBs) near the surface, becomes negative between approximately 900 and 700 hPa, then becomes increasingly positive with increasing altitude. The old verification system produced data on only three levels at and below 500 hPa (500, 700, and 850 hPa), thereby obscuring vertical variations such as these.

Since some of the finer resolution results from interpolating linearly in log-p between significant levels, we investigated the extent to which this interpolation might differ from actual atmospheric values. One-second resolution data now available from the Radiosonde Replacement System (Facundo, 2004) allowed us to study this. In order to test the effect of interpolation over relatively large pressure ranges, we chose a sounding with relatively few significant levels (Grand Junction on 0000 UTC 29 June 2009, Fig. 17). In this case, the interpolation extended over pressure ranges up to 120 hPa (between 820 and 700 hPa). For this sounding we calculated the average and RMS difference for temperature, relative humidity, and wind, between the one-second data and the 10-mb interpolated sounding. Results are shown in table 2 for various pressure bands, and are lower by a factor of 3 to 10 than the RMS values in the various data deprivation experiments we discuss below, particularly for temperature. Thus, we are confident that our interpolation scheme is not obscuring or skewing our forecast impact results and that the linear approximation between RAOB significant levels agrees well with the one-second data, especially for temperature.

4.2 Effect of TAMDAR assimilation on RUC forecast skill

4.2.1 Temperature

TAMDAR impact on 3-h RUC temperature forecasts averaged over the 1000-500 hPa layer for the 2006-2008 period is shown in Fig. 18. The temperature RMS errors for both RUC dev (without TAMDAR) and dev2 (including TAMDAR) 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. We consider only 0000 UTC RAOBs because this is the time when we expect to see the maximum TAMDAR impact, given the schedule (1200-0300 UTC, primarily daylight hours) of the Mesaba TAMDAR fleet.

The TAMDAR impact (black line in Fig. 18) is always positive, and is largest in winter, when the temperature forecast errors are themselves largest. In winter, TAMDAR reduces the 3-h temperature forecast error by an average of 0.2 K over the entire 1000-500 hPa depth.

This figure can help put the results discussed in section 3.2 in climatological perspective. Note that October 2006—the period over which TAMDAR's errors were evaluated in section 3.2—is a transition period between the relatively lower RUC RMS errors and TAMDAR

impact of summer and the larger errors and impact of winter, but is otherwise generally consistent with RUC behavior and TAMDAR impact over the entire three- year period, and is consistent with the behavior in the autumns of 2007 and 2008. Thus, we are confident that the results in 3.2 are reasonably representative of any fall period.

A vertical profile of temperature RMS error for RUC dev and dev2 3-h forecasts for March 2008 in shown in Fig. 19. Figure 18 suggests that this is a typical spring period in terms of RUC temperature error and TAMDAR impact. Inaccuracy in forecast temperatures associated with errors in PBL (planetary boundary layer) depth results in a maximum from 950-800 hPa in the vertical profile for temperature errors in the RUC dev model forecasts (without TAMDAR). The dev2 has lower errors for all levels between the surface and 320 hPa but especially between 850-950 hPa. We interpret this as TAMDAR's ascent/descent profiles being particularly important in defining PBL depth more accurately. The maximum RMS error difference between dev and dev2 occurs at 900 hPa and is about 0.4 K.

To put this TAMDAR impact in perspective, we present profiles of 3-h temperature forecast errors (Fig. 20) from the Nov-Dec 2006 retrospective period (see section 5) for 1) all-AMDAR data (including

TAMDAR), equivalent to the dev2; 2) no-TAMDAR data, equivalent to the dev; and 3) no-AMDAR data at all.

The TAMDAR impact (the black curve) peaks at 0.4 K at 900 hPa, just as it does in Fig. 19. The AMDAR impact also peaks at 900 hPa and has a value of nearly 1.1 K. AMDAR impact also has an additional peak at 500 hPa, above the region where Mesaba turboprop aircraft (carrying TAMDAR) fly most of the time.

4.2.2 Wind

TAMDAR impact on 3-h wind forecasts, also averaged over the surface-500 hPa layer (Fig. 21) was consistently positive, although small. This indicates that, even though TAMDAR wind errors are greater than those of the traditional AMDAR jet fleet, as discussed in section 3, they nonetheless provide additional value for wind forecasts in the RUC.

In the vertical profile for 3-h wind forecast error (RMS of the vector wind difference between model and RAOBs) for March 2008 (Fig. 22) , TAMDAR impact on winds shows a double peak, with a maximum at

700 hPa. At this level, the RMS reduction due to TAMDAR is about 0.25 m/s.

The vertical profile for 3-h wind forecast error (Fig. 23) from the Nov-Dec 2006 retrospective period (see section 5) compares the TAMDAR wind impact with the impact of all aircraft (AMDAR, which includes TAMDAR). The heavy gold curve shows the maximum AMDAR wind impact to be at 450-500 hPa, with an RMS error reduction of 0.7 m/s. The TAMDAR impact peaks at about 600 hPa and is about 0.2 m/s. Below 550 hPa, the similarity of the TAMDAR and the AMDAR impact curves (heavy) indicates that TAMDAR is responsible for most of the (small) AMDAR wind impact in this altitude range. Above 550 hPa, AMDAR jets provide most of the impact on RUC 3-h wind forecasts.

4.2.3 Relative humidity

A 3-year history for TAMDAR impact on lower-tropospheric RH forecasts (RUC dev vs. RUC dev2) is shown in Fig. 24. The impact is generally between 1% and 2% when averaged between the surface and 500 hPa. A change was made on 26 April 2007 to the specific observation error for TAMDAR RH (see section 5.1). Although we know from reprocessing a 10-day period that the new RH observation error

increases TAMDAR's RH impact, the increase is small enough that it is not clearly evident compared with the seasonal variations shown in Fig. 24.

The corresponding vertical profile for RH forecast impact from TAMDAR (Fig. 25) is relatively uniform from the surface to 700 hPa, from 1-3%. An enhancement in RH impact from TAMDAR around 600 hPa is also evident. This enhancement is consistent over seasons (not shown). We speculate that surface observations limit the impact of TAMDAR at altitudes below this level, and there are relatively few TAMDAR observations above.

4.2.4 TAMDAR impact as a fraction of estimated maximum potential improvement (EMPI)

To put these error reductions in perspective, it is worth considering what the minimum model-RAOB differences ("errors") might be, given a perfect model. RAOBs have instrument errors, and also exhibit representativeness errors because they provide *in-situ* point observations, whereas a model provides an average over the area of a grid cell (20 km^2 in the case of the dev and dev2). To account for these inherent differences between the model and verifying

observations, we can take the *analysis* error as an approximate measure of the minimum forecast error to be expected, similar to the normalization of forecast impact shown by Benjamin et al. (2004c, eqn. 3).

As a specific example, Fig. 26 shows profiles of the dev2 and dev 3-h RH forecast error along with the dev2 *analysis* error. The RMS for the analysis varies between 6%RH at 950 hPa to about 14%RH at 700 hPa. The *difference between* the dev and dev2 3-h RH forecast error, i.e., the TAMDAR impact, varies between 1%RH and 3%RH. At 600 hPa, the TAMDAR impact is 2.8%RH, and the difference between the dev 3-h forecast curve and the dev2 analysis curve is 5.7%RH. Assuming that this 5.7%RH error reduction at 600 hPa is the best we can hope for (the EMPI), TAMDAR impact is about 50% of the EMPI. Over all altitudes, TAMDAR provides 15%-50% of the estimated maximum potential improvement (EMPI).

For temperature, we reason similarly. 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. 19 at 900 hPa and the 0.5 K analysis fit).

Therefore, TAMDAR's impact is about 35% of the EMPI for 3-h temperature forecast error at 900 hPa (35% ≈ 0.4/(1.6 – 0.5)).

For wind, the analysis fit to RAOBs is about 2.2 ms^{-1} near 600 hPa (not shown). Thus, TAMDAR's impact on 3-h wind forecasts in this altitude range is about 15% of the EMPI.

5. Further applications of retrospective runs

To study TAMDAR's impact in more detail, and determine how these new data are best assimilated in the RUC, we saved all data for two 10-day periods: 1200 UTC 26 November to 1200 UTC 5 December 2006 and 0000 UTC 15 August to 0000 UTC 25 August 2007, and reran the RUC with a variety of different assimilation schemes and TAMDAR data variations over these periods.

We chose these periods because they included intense weather events: The 2006 period included a potent early winter storm that featured a 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. The August 2007 period included a variety of weather as well.

Since results from this summer period generally corroborate the winter results, we do not include them here.

These periods were chosen primarily in support of our TAMDAR investigations. However, they have served as a basis for additional experiments denying other data sources and are discussed in detail by Benjamin et al. (2010)

5.1 Relative humidity observation error specification for assimilation

Because high temporal and spatial resolution RH measurements have been unavailable in the past, we had no firm guidance for choosing the appropriate error for these observation measurements other than from engineering-based estimates by manufacturers. 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. Estimating an RH observation error that is too large will result in less-than-optimal TAMDAR impact. Choosing a value that is too small will result in over fitting, causing numerical noise that will degrade forecasts.

We experienced over fitting when, during the fall of 2005, the TAMDAR RH error was inadvertently set to 1%RH. During this period, TAMDAR's impact of 3-h RH forecasts was negative (Benjamin et al. 2007, Figs 9 and 10). However, for most of the time we have assimilated TAMDAR's data, we have run with RH observation errors for TAMDAR between 3% and 12%. With these errors, TAMDAR has had a positive impact of reducing subsequent RUC RH forecast errors by 1-3 %RH (see section 4.3).

In April 2007, we discovered that the observation errors for all RH observations (TAMDAR, surface observations, RAOBs, and integrated precipitable water data from GPS-Met (Smith et al. 2007)) had been inadvertently set too low since the start of our TAMDAR experiments. We corrected this in a retrospective run, and found that the correction (called "new RH processing" below) resulted in slightly increased model skill (decreased RMS) for RH forecasts at nearly all levels, as Fig. 27 shows, even in the absence of TAMDAR.

When TAMDAR data are included, the new processing increased TAMDAR impact, as shown in Fig. 28.

Each curve in Fig. 28 indicates the difference between the RMS errors of the TAMDAR and no-TAMDAR runs (with respect to 0000 UTC RAOBs in the Great Lakes verification region shown in Fig. 5). The blue curve shows the impact under the old RH processing; the red curve shows the impact with the new RH processing. The larger values for the red curve demonstrate that the TAMDAR impact in RH forecasts increases substantially at levels between 850 and 450 hPa with the new processing using a more appropriate observation error for TAMDAR RH observations.

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. Although TAMDAR's RH impact was less than it might have been before this date, our long time series show that TAMDAR's impact on RH forecasts was notable even before this change was implemented.

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.)

When TAMDAR RH observations are excluded, TAMDAR has virtually no impact on 3-h forecasts of RH (Fig. 29). However, TAMDAR wind and temperature data alone do have some impact on longer range forecasts, such as the 9-h RH forecasts shown in Fig 30. In that case, the blue curve between 500 and 450 hPa 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 subsequent RH forecasts.

Thus, we can conclude that for 3-h forecasts, RH observations are needed to improve RH forecasts, at least on the 20-km scale of our RUC model runs. However, at longer forecast projections such as 9-h,

a small improvement in RH forecasts is apparent solely from the TAMDAR temperature and wind observations.

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. 31 may be compared to the black curve in Fig. 19. 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's impact on 3-h temperature forecasts below 700 hPa. TAMDAR's impact is reduced by about 10% at 900 hPa, growing to a 30% reduction at 750 hPa. For RH forecasts, reducing the vertical resolution had little consistent impact (not shown). However, for all variables, the impact

of reduced vertical resolution is certainly larger in certain situations—often 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 (Szoke et al. 2006).

6. Recent developments

Recently, additional TAMDAR fleets have started reporting to ESRL/GSD. Currently (fall 2009), the four commercial air carrier fleets providing TAMDAR data are:

- Mesaba – Data first received in 2004, and reported on above.
- PenAir – Data first received in late 2007. PenAir flights connect Anchorage with smaller cities in southwestern Alaska and the Aleutian Islands—a generally data-poor region.
- Chautauqua – Data first received in April 2008. This fleet of regional jets flies higher and faster than the turboprops in the other fleets, and therefore can potentially provide valuable data at higher altitudes than available from turboprops.
- Horizon – Data first received in December 2008.

A more recent (April 2009) horizontal distribution of TAMDAR data reported to ESRL/GSD for a 24h-h period is shown in Fig. 32. Reports

from the PenAir fleet are evident over Alaska. Horizon reports are over the western US; Chautauqua reports are now made over Mexico, the lower Midwest, and the East Coast. Note the data points coded in light blue, representing data taken above 28,000 ft by Chautauqua jets.

Our initial studies of data from the Chautauqua jets indicate that the quality of the temperature, wind, and relative humidity data is as good or better than that produced by the Mesaba turboprops (not shown). We started ingesting Chautauqua data into the dev2 on 30 April 2008 and have seen a notable increased TAMDAR impact—particularly on relative humidity forecasts—since that time.

Figure 33 shows TAMDAR's impact on 3-h relative humidity forecasts for the entire Eastern U.S. region (the violet rectangle in Fig. 5). This geographic and altitude (up to 400 hPa) region was not densely covered by the initial TAMDAR Mesaba fleet alone (Fig. 5). The increased TAMDAR impact on RH forecasts for this region since late April 2008 is evident in the difference curve.

A December 2008 vertical profile of TAMDAR impact on RH 3-h forecasts (Fig. 34) in the Eastern U.S. region includes the effect of the Chautauqua fleet. Comparing this with Fig. 25, which shows the

corresponding pre-Chautauqua vertical RH impact for the Great Lakes region, reveals that TAMDAR impact now extends higher—to above 300 hPa.

7. Summary and a look ahead

The TAMDAR sensor provides meteorological data on a regional scale over the US Midwest (and now over most of the U.S.). By equipping regional aircraft, TAMDAR provides ascent/descent profiles at regional airports for which traditional AMDAR profiles were not available. Moreover, TAMDAR also reports relative humidity, a variable not generally or reliably available previously from commercial aircraft. We have evaluated the impact of TAMDAR's wind, temperature, and relative humidity data on the RUC model/assimilation system with 1) real-time matched TAMDAR and no-TAMDAR runs for the past three years, and 2) retrospective runs over two 10-day active weather periods during the winter of 2006 and summer of 2007.

We have shown that assimilation of TAMDAR observations improves 3-h RUC forecasts in the region and altitude range in which TAMDAR flies. We estimate the TAMDAR impact as follows:

- Temperature 3-h forecast errors are reduced by up to 0.4 K, dependent on vertical level.
- Wind 3-h forecast errors are reduced by up to 0.25 m s^{-1}.
- Relative humidity 3-h forecast errors are reduced by up to 3 %RH.

As discussed in section 4.2.4, we can cast these error reductions into fractions of the *estimated maximum potential improvement* (EMPI). In these terms, TAMDAR results in these impacts.

- Temperature 3-h forecast errors are reduced by 15% - 50% of the EMPI.
- Wind 3-h forecast errors are reduced by up to 15% of the EMPI.
- Relative humidity 3-h forecast errors are reduced by up to 35% of the EMPI.

Retrospective runs have revealed the following:

- The optimal TAMDAR RH observational error specification is 12% for assimilation impact. Both lower and higher values resulted in lower RH forecast impact. The 12% RH error is now being used in real-time RUC cycles.
- RH observations are generally required to improve 3-h forecast skill. However, for longer forecasts, wind and temperature

observations alone, on sufficiently fine resolution, can improve RH forecasts indirectly.

- Lowered vertical resolution reduces TAMDAR-related forecast improvement from 10-30% for temperature forecasts, but in individual cases, this reduced accuracy may cause important meteorological conditions to be unobserved or inadequately resolved.

8. 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 Bradley Ballish (NWS/NCEP), John M. Brown (ESRL/GSD), and an anonymous reviewer for their very helpful comments and suggestions. We also thank Annie Reiser (ESRL/GSD) for her careful editing.

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Tables

Table 1. RH values at 500 hPa – 0000 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	**<--**

Table 2. Bias and RMS differences between 10-hPa interpolated and one-second RAOB data from GJT sounding, 0000 UTC 29 Jun 2009

Pressure (hPa)	N/N-RH	T bias/rms (°C)	RH bias/rms (%)	Speed bias / vector wind rms (m/s)
1000 to 800	122	-0.02/0.02	-0.00/0.24	-0.24/0.7
800 to 700	260	-0.02/0.02	-0.52/0.84	0.10/0.93
700 to 600	278	-0.02/0.02	0.37/0.95	-0.44/0.80
600 to 500	338	-0.00/0.01	-0.57/2.52	0.10/1.26
500 to 400	398	0.00/0.01	-0.30/0.95	-1.09/2.85
400 to 300	521	-0.00/0.01	0.09/0.10	0.04/0.87
300 to 200	633	-0.02/0.03	-0.18/0.34	-0.62/1.28
200 to 100	935	0.03/0.06	0.07/0.57	-0.08/2.7
100 to 0	1960	-0.01/0.08	-0.01/0.59	-1.35/3.94

Figure Captions

Fig. 1. Worldwide AMDAR reports, Tuesday 16 Oct 2009. 239,865 observations of wind and temperature.

Fig. 2. Traditional AMDAR (i.e., non-TAMDAR) reports over the contiguous United States, Tuesday 13 Oct 2009, 126,665 observations.

Fig. 3. As for Fig. 2, but below 20,000 ft. 78754 observations.

Fig. 4. As for Fig 3, but with TAMDAR observations included.93207 observations.

Fig. 5. TAMDAR observations typical for a 24-h period in 2007. Verification areas are shown for blue rectangle (Great Lakes region – 13 RAOBs) and magenta rectangle (Eastern US area – 38 RAOBs)

Fig. 6. TAMDAR (open circles) and AMDAR (solid circles) temperature "bias" (aircraft minus RUC dev2 1-h forecasts) for Oct 2006. Observations taken during descent are shown in blue and labeled with the suffix "_dn"; observations taken during ascent and en-route are shown in red and labeled with the suffix "_erup".

Fig. 7. As in Fig. 6, but for temperature RMS difference from RUC dev2 1-h forecasts for Oct 2006.

Fig 8. As in Fig. 6 but for RMS wind vector differences.

Fig. 9. As in Fig. 6 but for relative humidity, for TAMDAR only.

Fig. 10. TAMDAR (open circles) relative humidity RMS with respect to RUC dev2 1-h forecasts for Oct 2006. Solid black circles show the RAOB RH error assumed by the operational NAM model run at NCEP.

Fig. 11. 850-hPa temperature 3-h forecast (valid at 0000 UTC, Great Lakes Region) RMS difference between model and RAOBs for 3-h RUC dev(blue) and RUC dev2 (red). a) old verification, b) new verification. 30-day running averages.

Fig. 12. RMS RH 500 hPa 3-h forecast error for RUC forecasts (blue – dev, red – dev2 with TAMDAR assimilation) against RAOBs for the old verification system (centered at 15% RH). 30-day running averages.

Fig. 13. As in Fig. 12 but for the new verification system (centered at 20% RH).

Fig. 14. Soundings at ILX (Lincoln, IL) for 0000 UTC 1 July 2006. RAOB in black, RUC dev 3-h forecast in orange, RUC dev2 3-h forecast in magenta.

Fig. 15. As for Fig. 15 but for PIT (Pittsburgh, PA).

Fig. 16. Vertical profile for RH bias (model-minus-RAOB) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red) 3-h forecasts with respect to RAOBS at 00 UTC in the Great Lakes region for the Apr–Aug 2006 period.

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Fig. 19. Vertical profile of 3-h temperature forecast errors (RMS difference from 0000 UTC RAOBs) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red), and dev-dev2 difference (black). For the Great Lakes Region, March 2008.

Fig. 20. As in Fig. 19, but for 27 November through 5 December 2006. All-data run (light red), no-TAMDAR run (light blue), no-aircraft run (gold). TAMDAR impact (black), Aircraft impact (heavy gold).

Fig. 21. As in Fig. 18, but for wind forecasts (RMS vector difference from 0000 UTC RAOBs).

Fig. 22. As for Fig. 19, but for 3-h wind forecasts.

Fig. 23. As in Fig. 20, but for 3-h wind forecasts. All- data run (light red), no-TAMDAR run (light blue), no-aircraft run (light gold). TAMDAR impact (heavy blue), Aircraft impact (heavy gold).

Fig. 24. As for Fig. 18, but for relative humidity forecasts.

Fig. 25. As for Fig. 19, but for 3-h relative humidity forecasts.

Fig. 26. RMS difference between RUC grids and RAOBs in the Great Lakes Region at 00z for dev2 RH analysis (black), dev 3-h forecast (blue) and dev2 (red) 3-h forecasts. March, 2008.

Fig. 27. Vertical profile of 3-h RH forecast errors (RMS difference from 0000 UTC RAOBs) for "old RH processing" (blue—RH errors divided by 4), and "new RH processing" (RH errors corrected), without TAMDAR data, for the Great Lakes Region. The black curve shows the difference; negative values indicate that the new processing has lower RMS errors.

Fig. 28. TAMDAR's impact for 3-h RH forecasts (see text for explanation) for "new RH processing" (12% TAMDAR RH error, red) and "old RH processing" (12/4 = 3% TAMDAR RH error, blue) for the retrospective time period.

Fig. 29. 3-h RH forecast errors (RMS difference from 0000 UTC RAOBs) for the Great Lakes region, for the retrospective period, for three cases: Red: all-TAMDAR data, Black: no-TAMDAR data, Blue: TAMDAR wind and temperature data only.

Fig. 30. As in Fig. 29 but for 9-h RH forecasts.

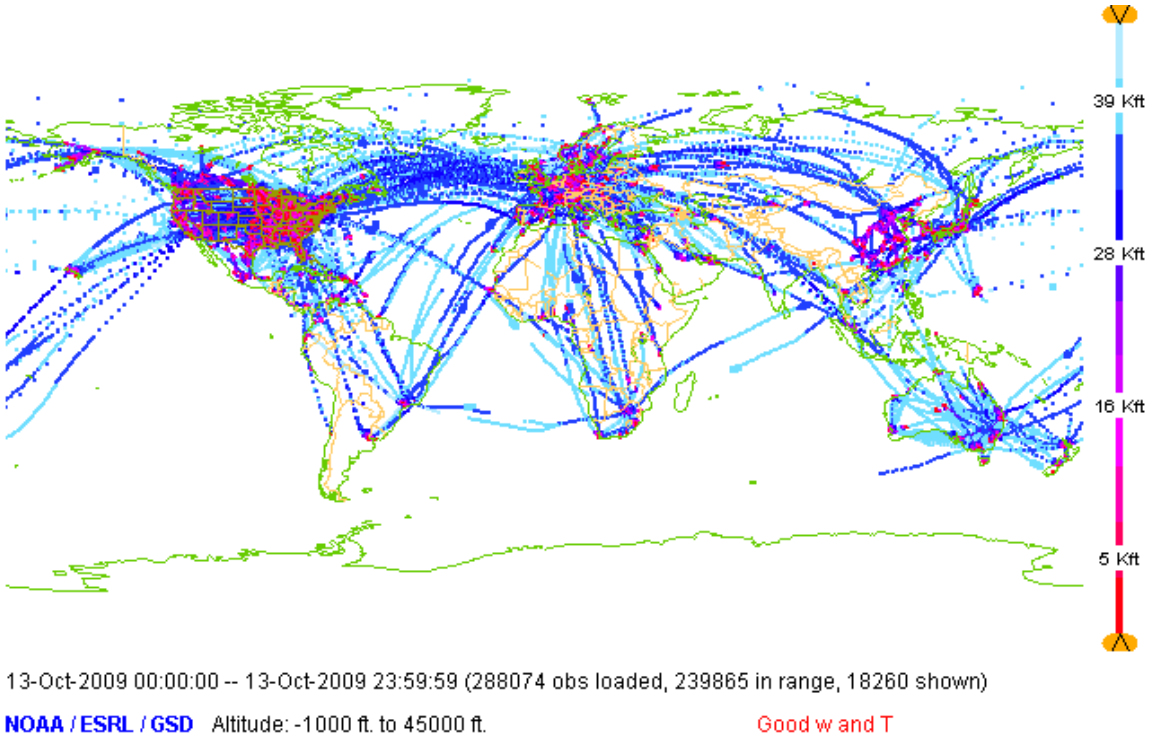
Fig. 31. TAMDAR 3-h temperature forecast impact (see text for explanation) for the full-vertical resolution run (red) and the low-vertical resolution run (blue), for the retrospective period.

Fig. 32. TAMDAR observation reports received over a 24-h period at ESRL/GSD on 29 April 2009. 30877 reports.

Fig. 33. Time series of 3-h relative humidity forecast errors (RMS difference from 0000 UTC RAOBs) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red), and dev-dev2 difference (black). For the Eastern U.S. region, in the layer between the surface and 400 hPa. 30-day running averages. Positive differences indicate a positive TAMDAR impact.

Fig. 34. Vertical profile of 3-h relative humidity forecast errors (RMS difference from 0000 UTC RAOBs) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red), and dev-dev2 difference (black). For the Eastern U.S. region, December 2008.

Figures



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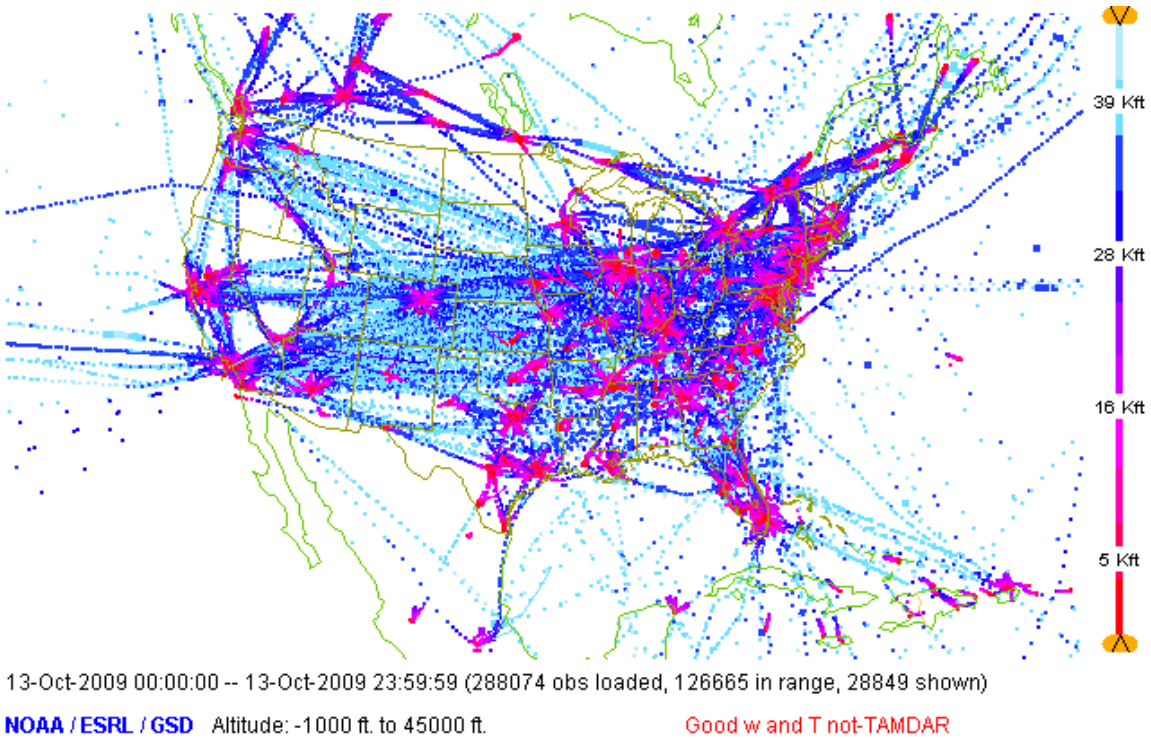

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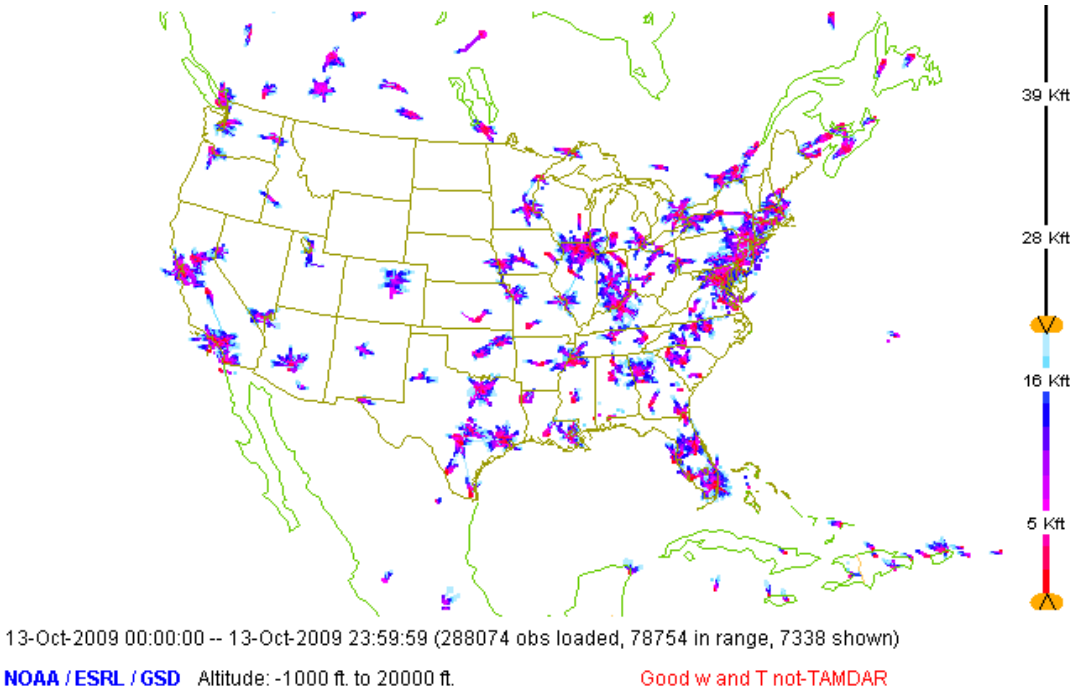

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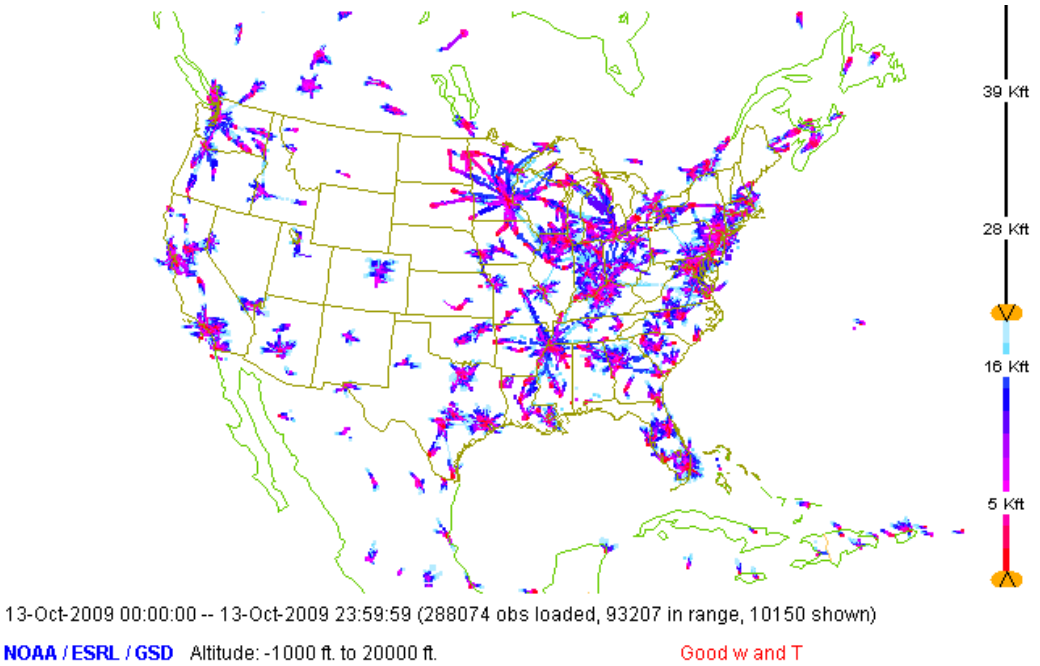

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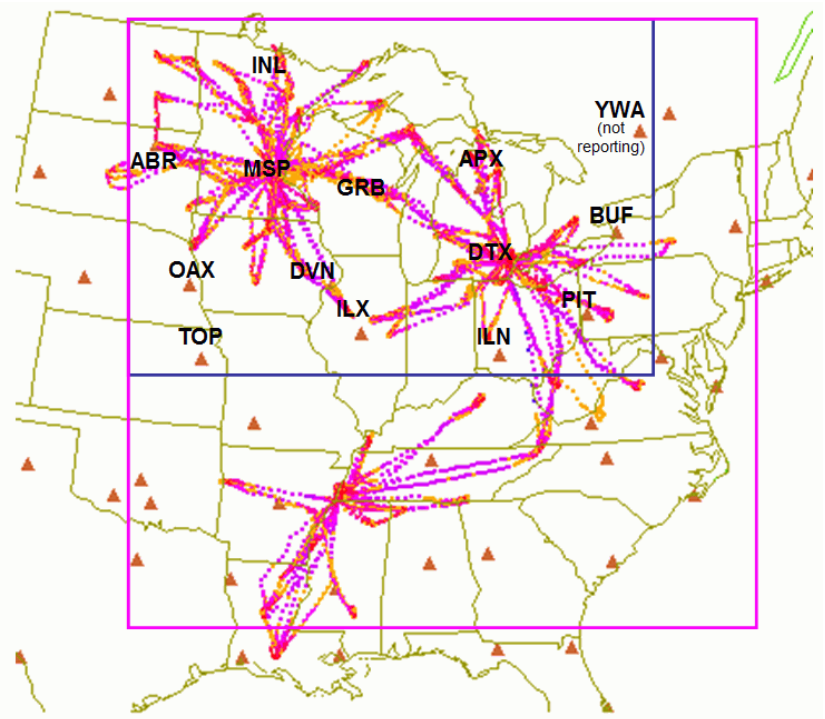

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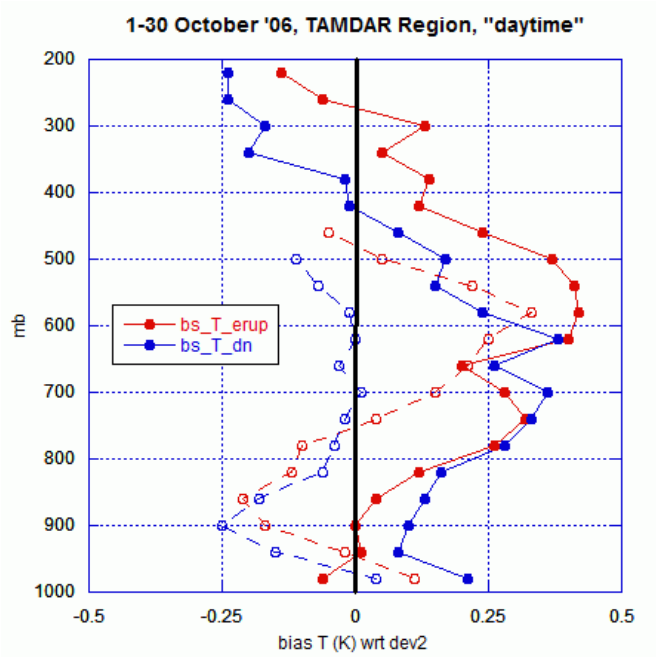

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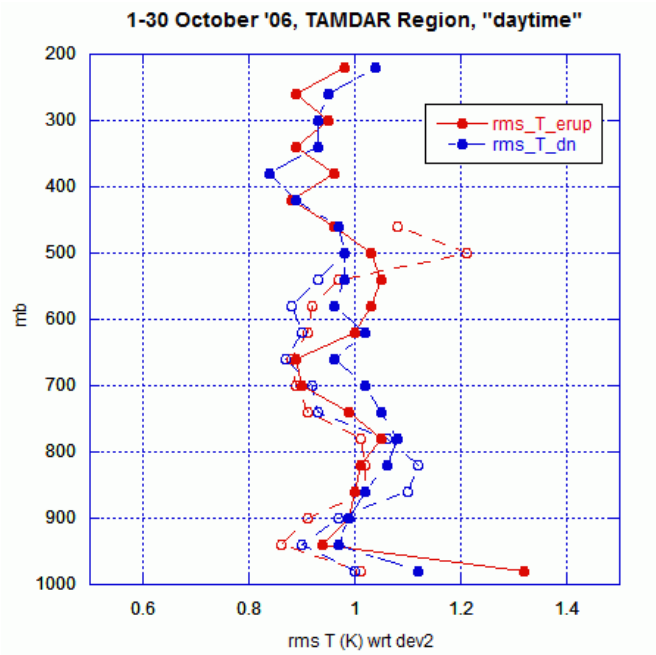

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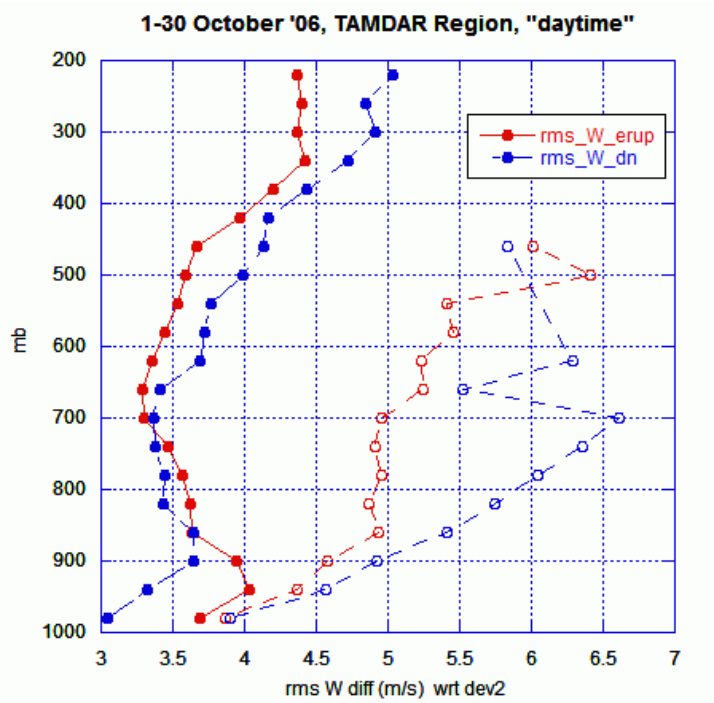

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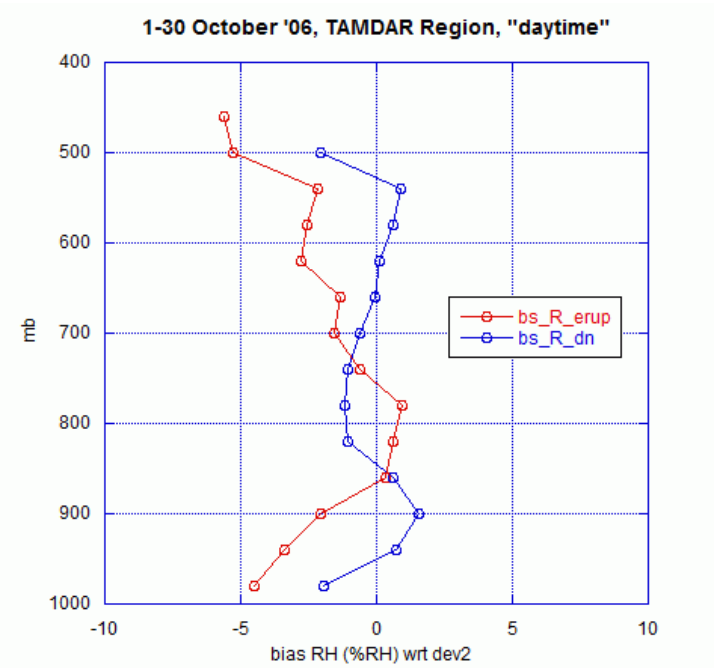

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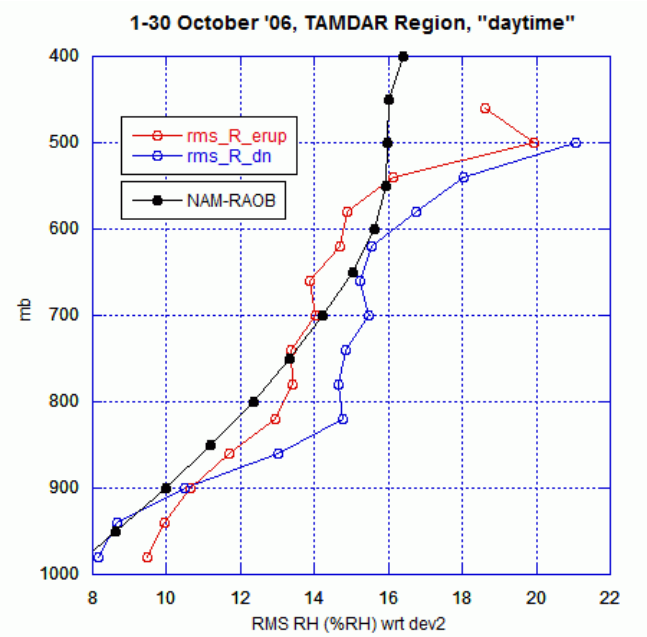

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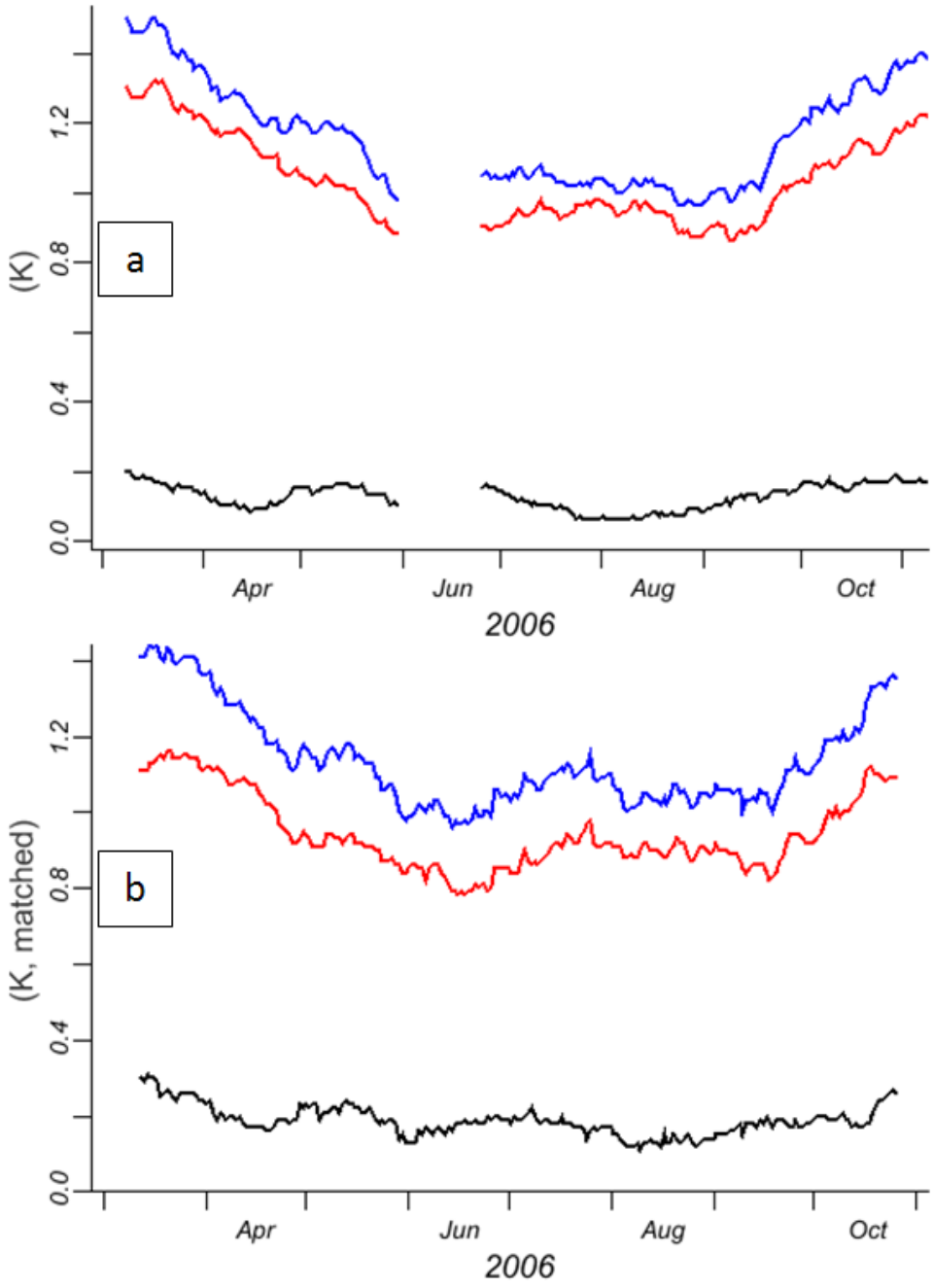

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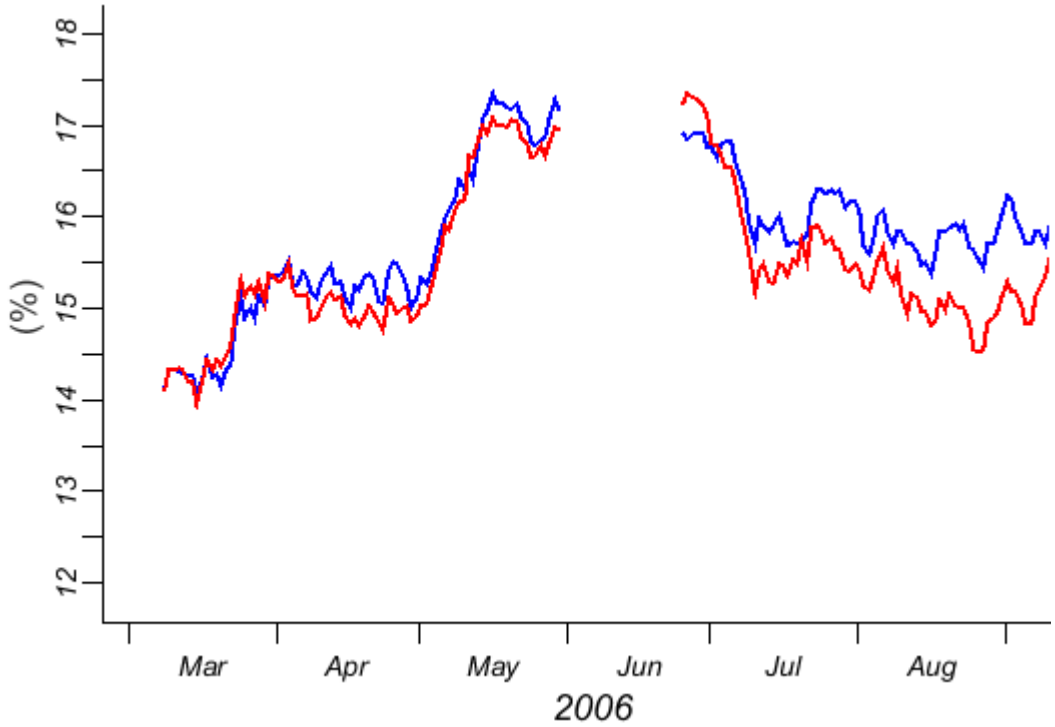

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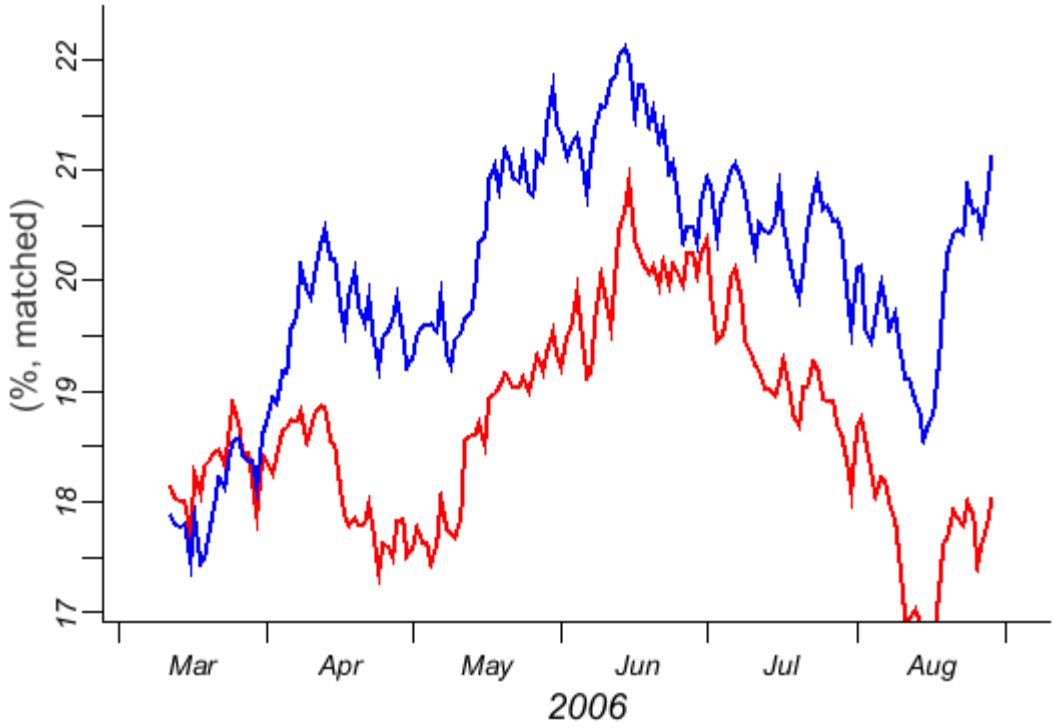

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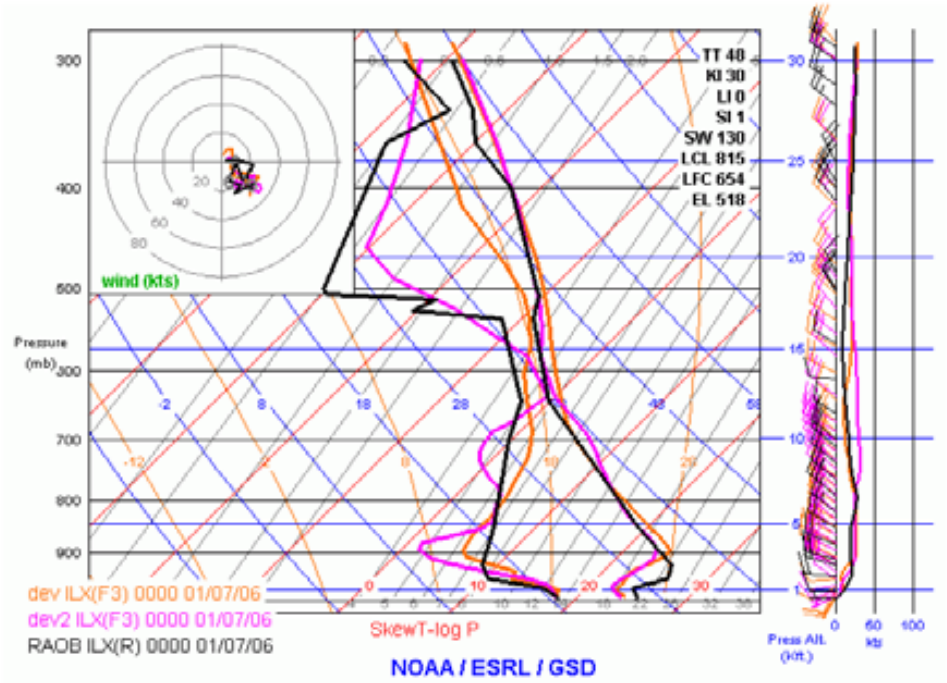

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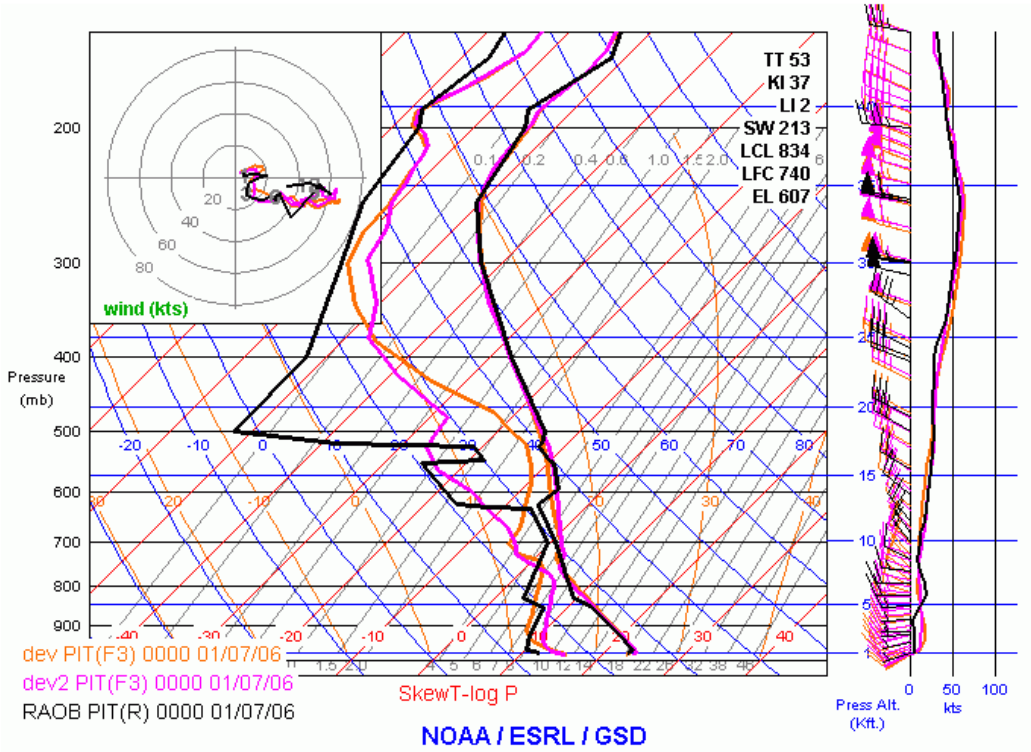

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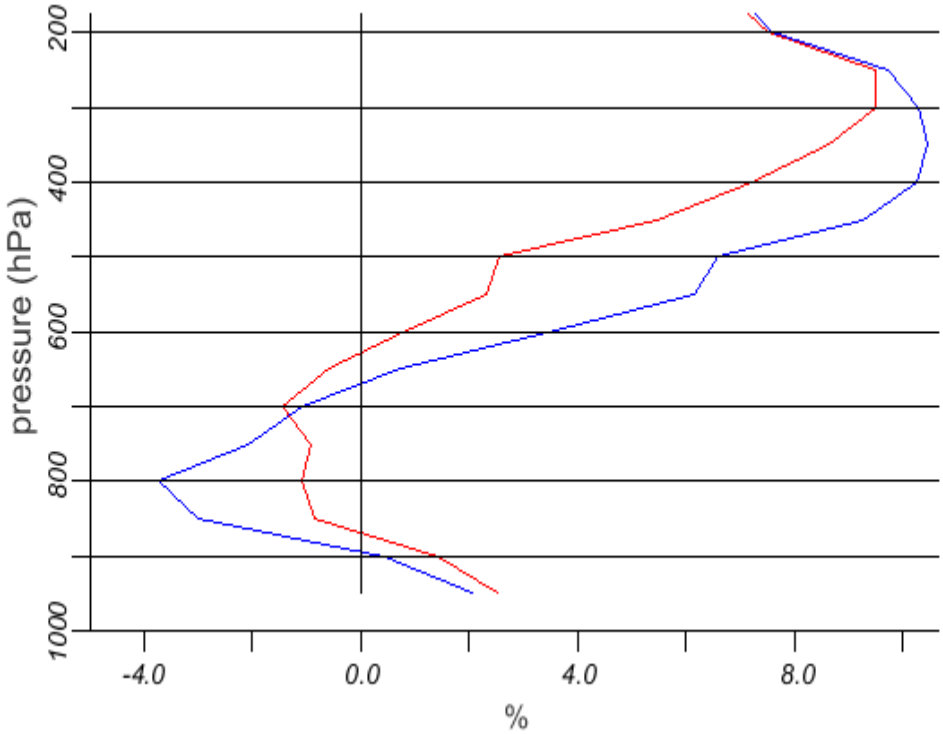

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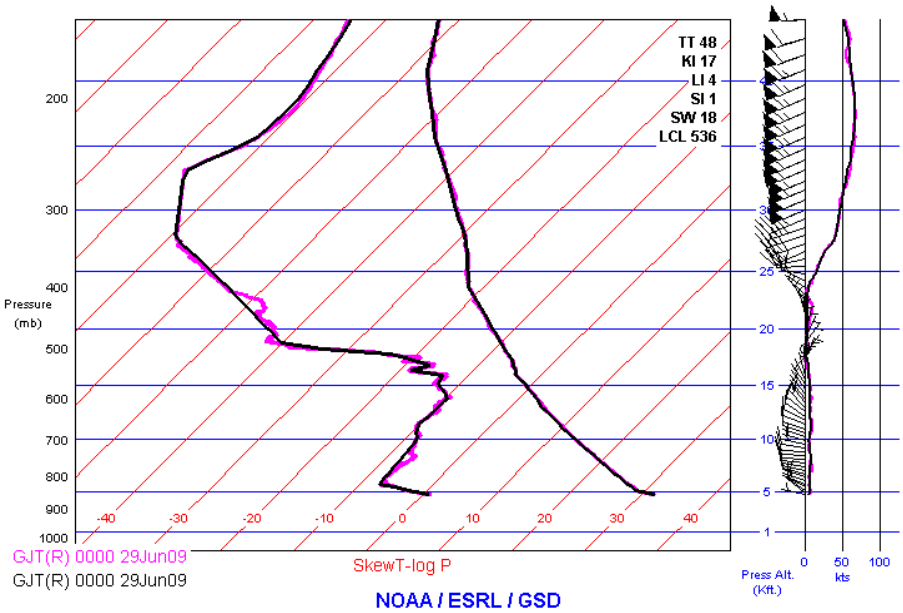

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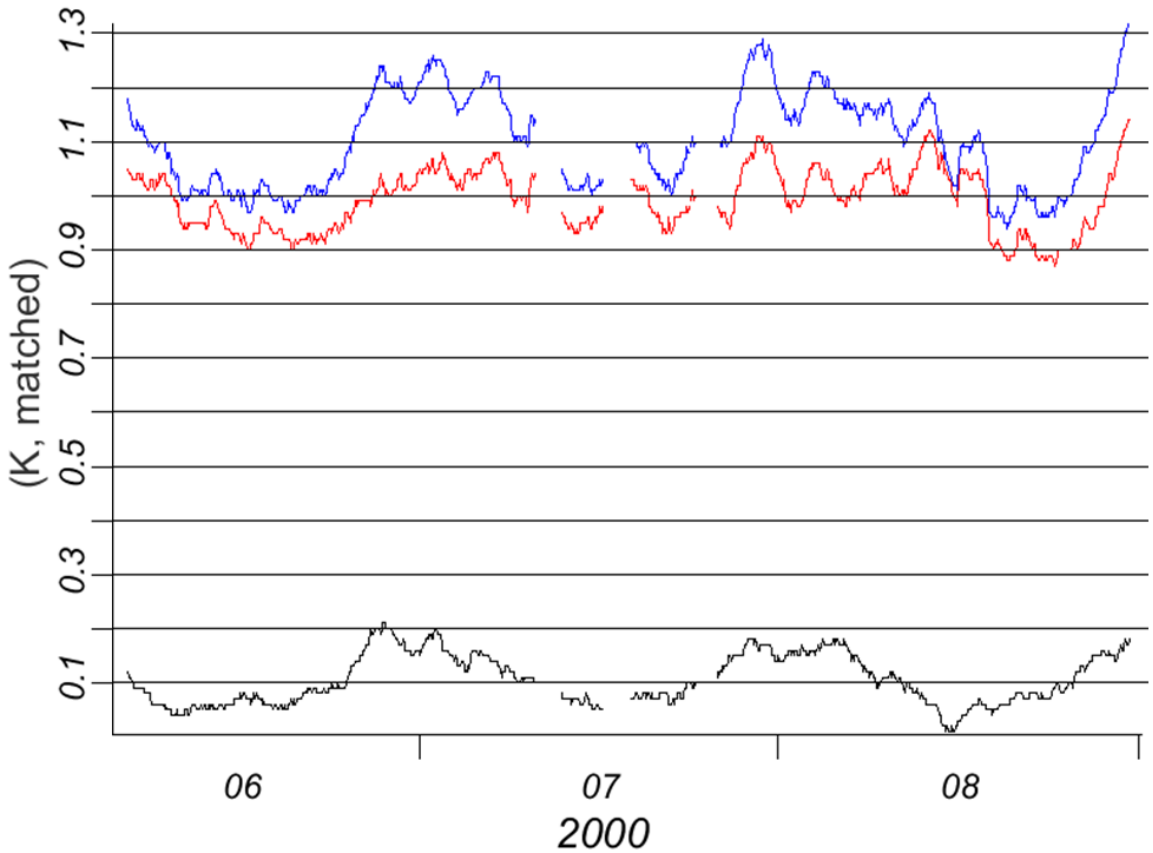

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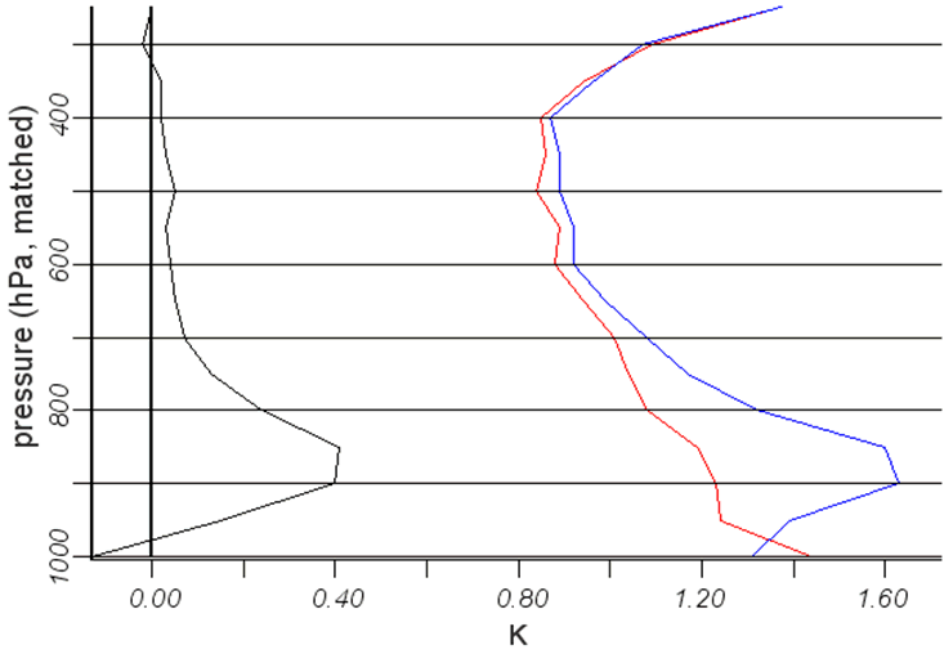

Fig. 19. Vertical profile of 3-h temperature forecast errors (RMS difference from 0000 UTC RAOBs) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red), and dev-dev2 difference (black). For the Great Lakes Region, March 2008.

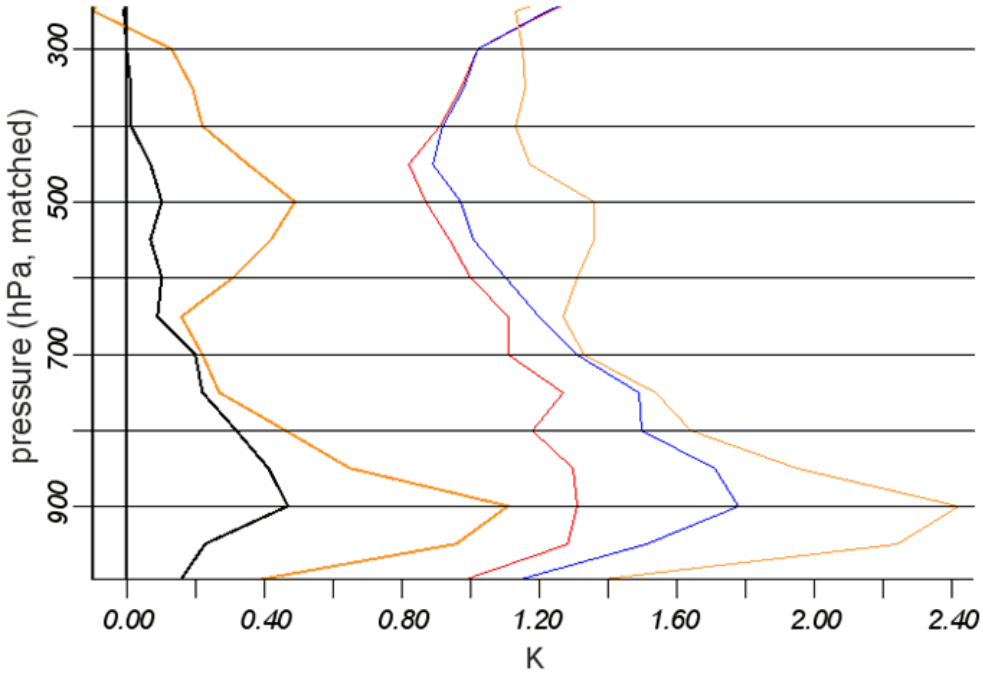

Fig. 20. As in Fig. 19, but for 27 November through 5 December 2006. All-data run (light red), no-TAMDAR run (light blue), no-aircraft run (gold). TAMDAR impact (black), Aircraft impact (heavy gold).

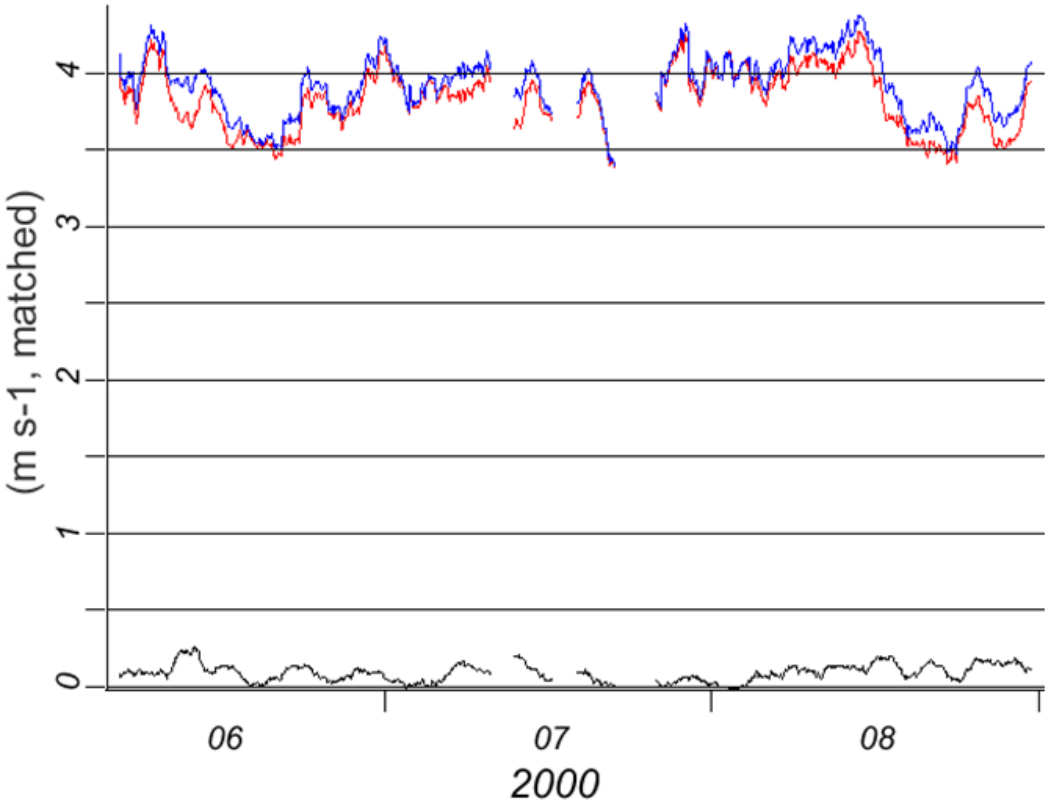

Fig. 21. As in Fig. 18, but for wind forecasts (RMS vector difference from 0000 UTC RAOBs).

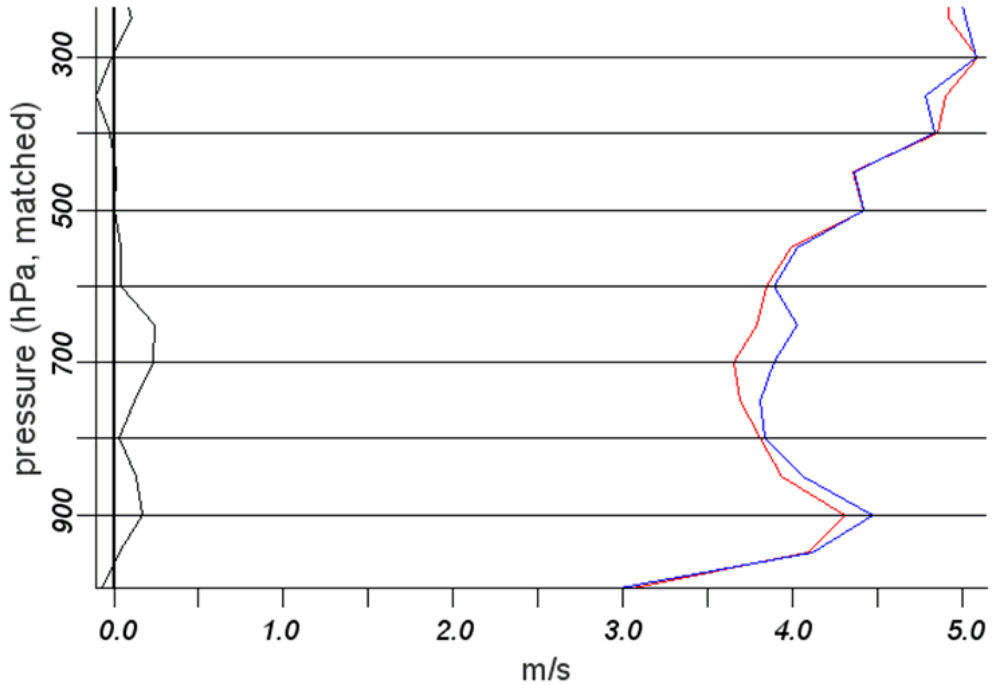

Fig. 22. As for Fig. 19, but for 3-h wind forecasts.

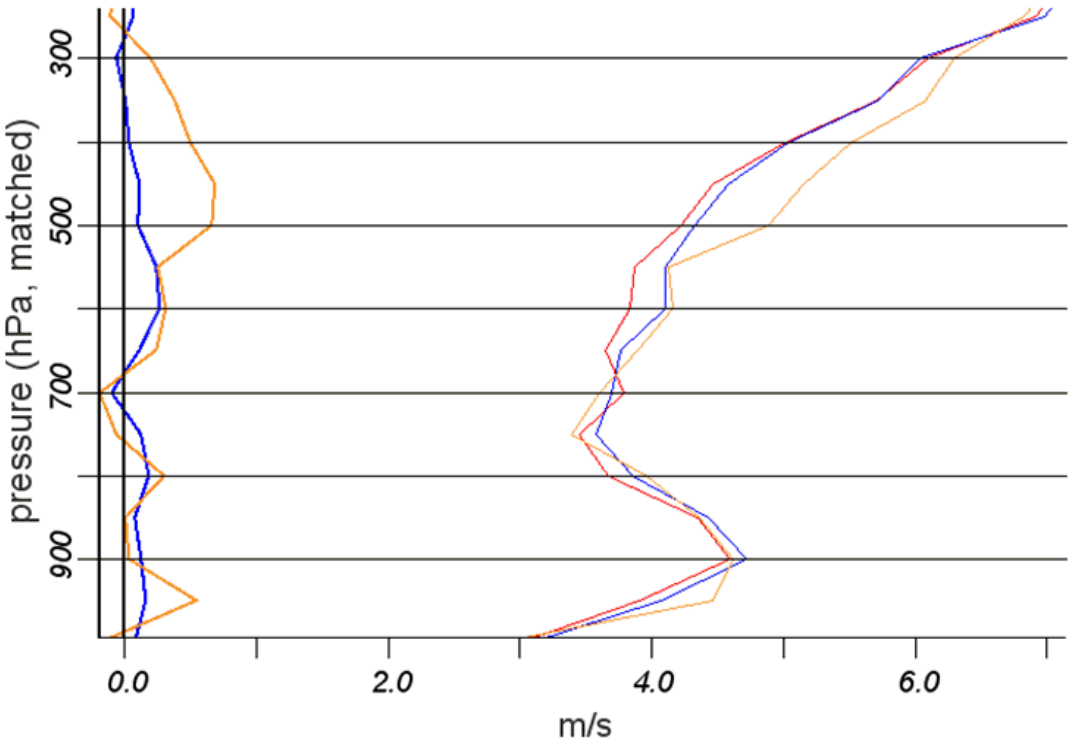

Fig. 23. As in Fig. 20, but for 3-h wind forecasts. All- data run (light red), no-TAMDAR run (light blue), no-aircraft run (light gold). TAMDAR impact (heavy blue), Aircraft impact (heavy gold).

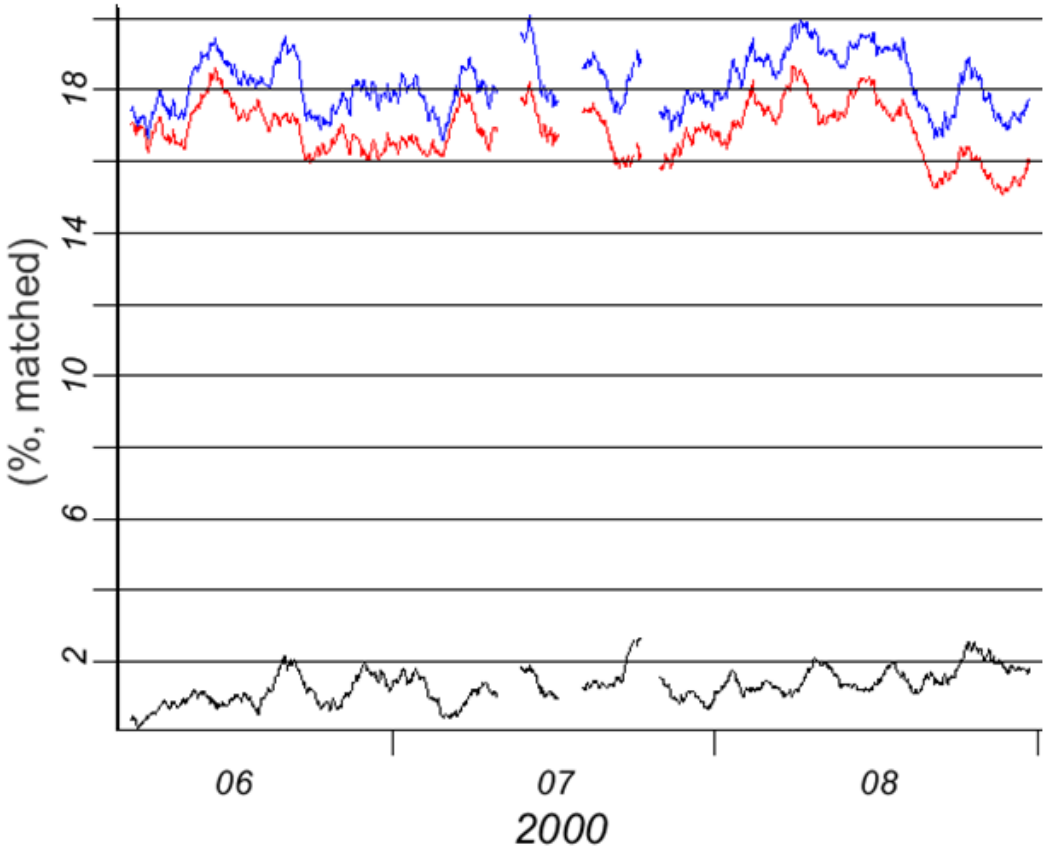

Fig. 24. As for Fig. 18, but for relative humidity forecasts.

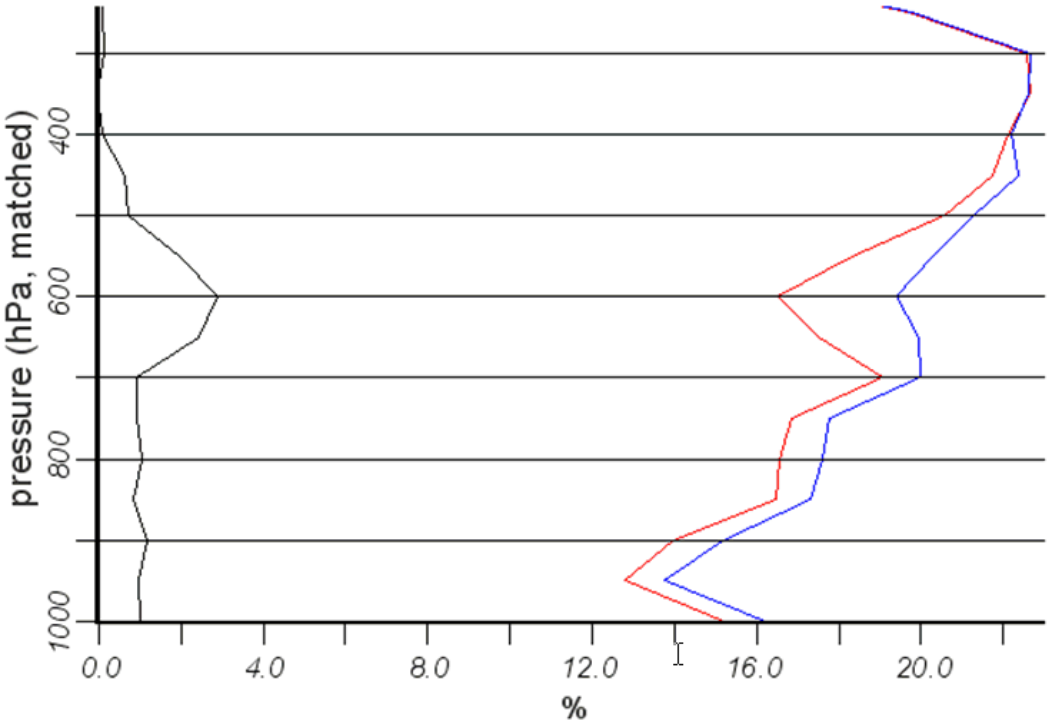

Fig. 25. As for Fig. 19, but for 3-h relative humidity forecasts.

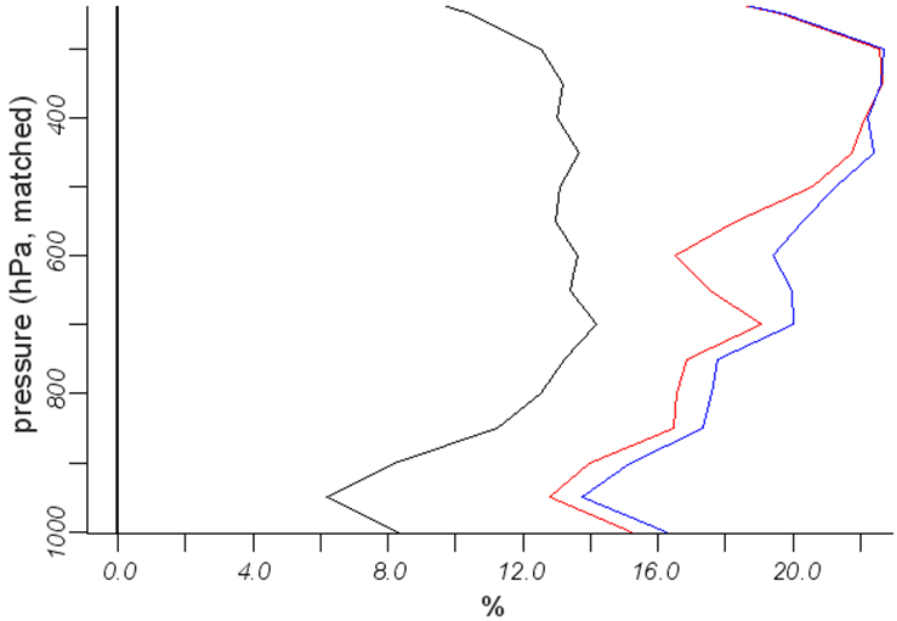

Fig. 26. RMS difference between RUC grids and RAOBs in the Great Lakes Region at 00z for dev2 RH analysis (black), dev 3-h forecast (blue) and dev2 (red) 3-h forecasts. March, 2008.

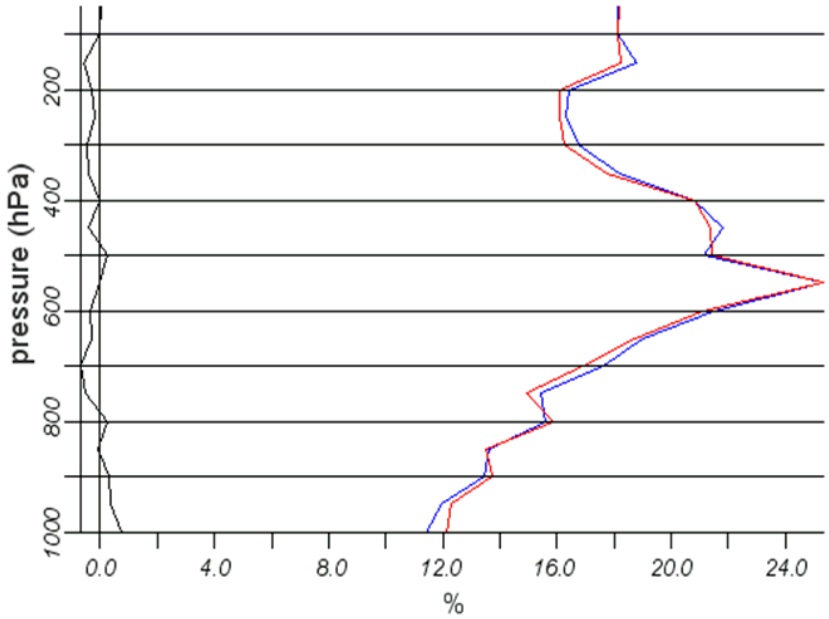

Fig. 27. Vertical profile of 3-h RH forecast errors (RMS difference from 0000 UTC RAOBs) for "old RH processing" (blue—RH errors divided by 4), and "new RH processing" (RH errors corrected), without TAMDAR data, for the Great Lakes Region. The black curve shows the difference; negative values indicate that the new processing has lower RMS errors.

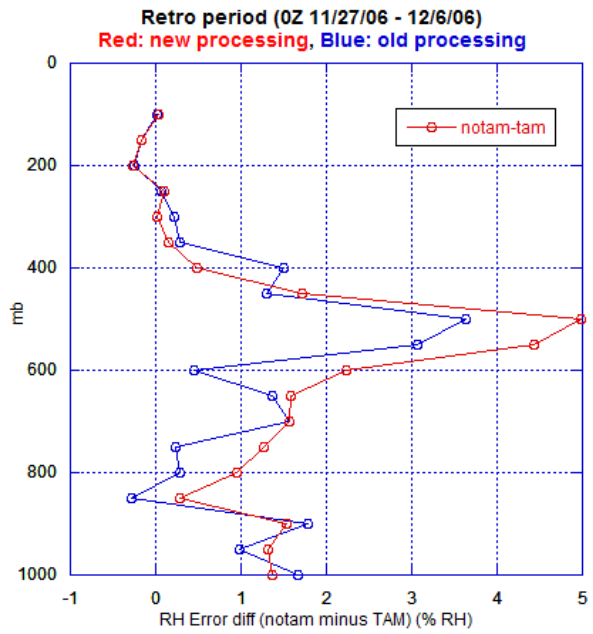

Fig. 28. TAMDAR's impact for 3-h RH forecasts (see text for explanation) for "new RH processing" (12% TAMDAR RH error, red) and "old RH processing" (12/4 = 3% TAMDAR RH error, blue) for the retrospective time period.

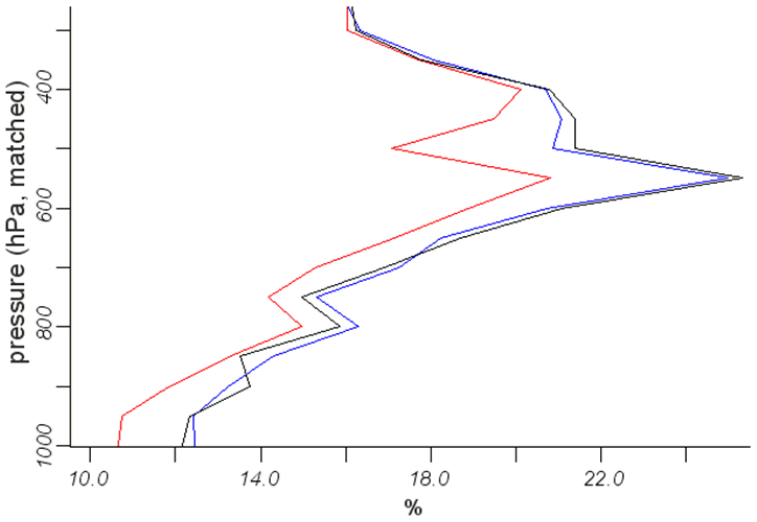

Fig. 29. 3-h RH forecast errors (RMS difference from 0000 UTC RAOBs) for the Great Lakes region, for the retrospective period, for three cases: Red: all-TAMDAR data, Black: no-TAMDAR data, Blue: TAMDAR wind and temperature data only.

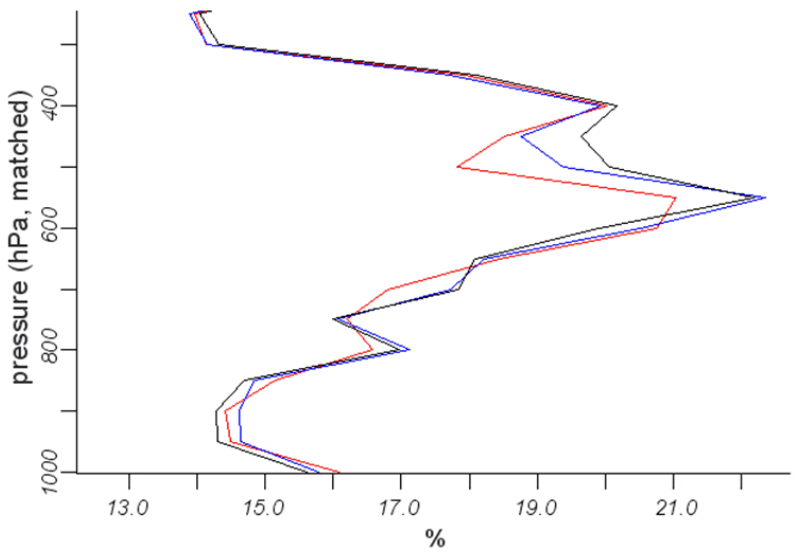

Fig. 30. As in Fig. 29 but for 9-h RH forecasts.

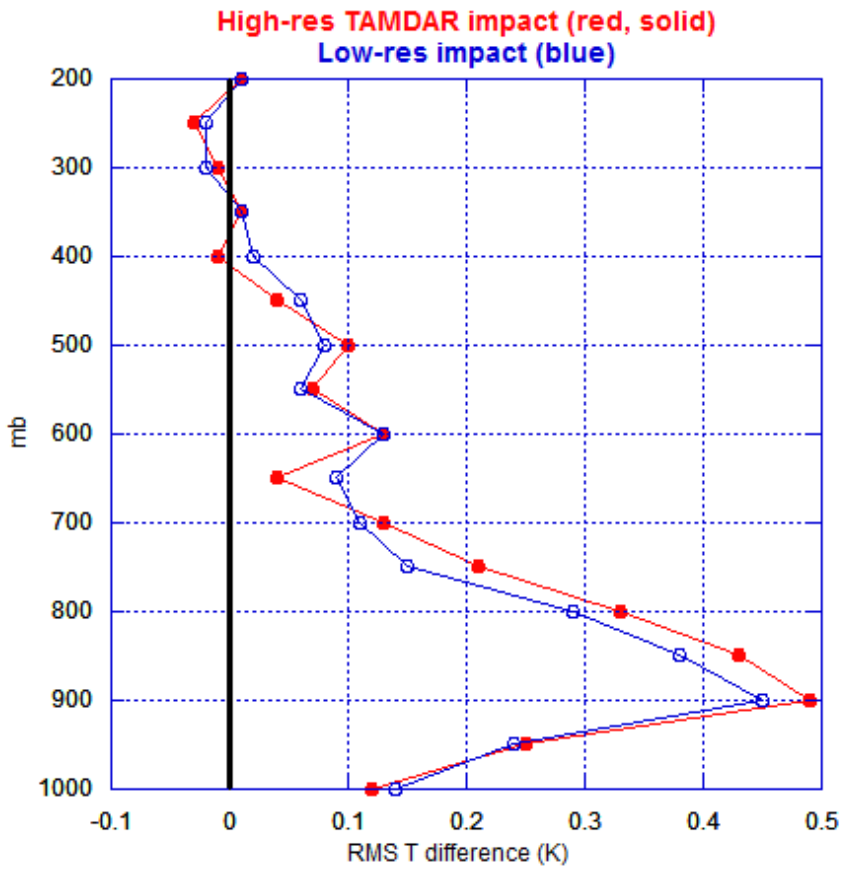

Fig. 31. TAMDAR 3-h temperature forecast impact (see text for explanation) for the full-vertical resolution run (red) and the low-vertical resolution run (blue), for the retrospective period.

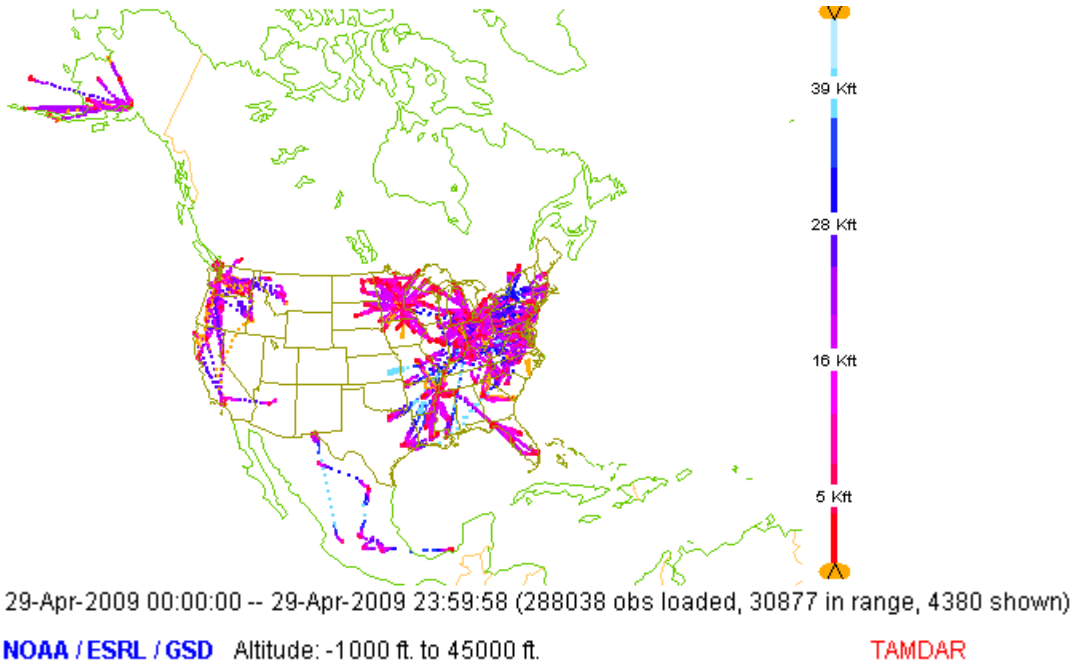

Fig. 32. TAMDAR observation reports received over a 24-h period at ESRL/GSD on 29 April 2009. 30877 reports.

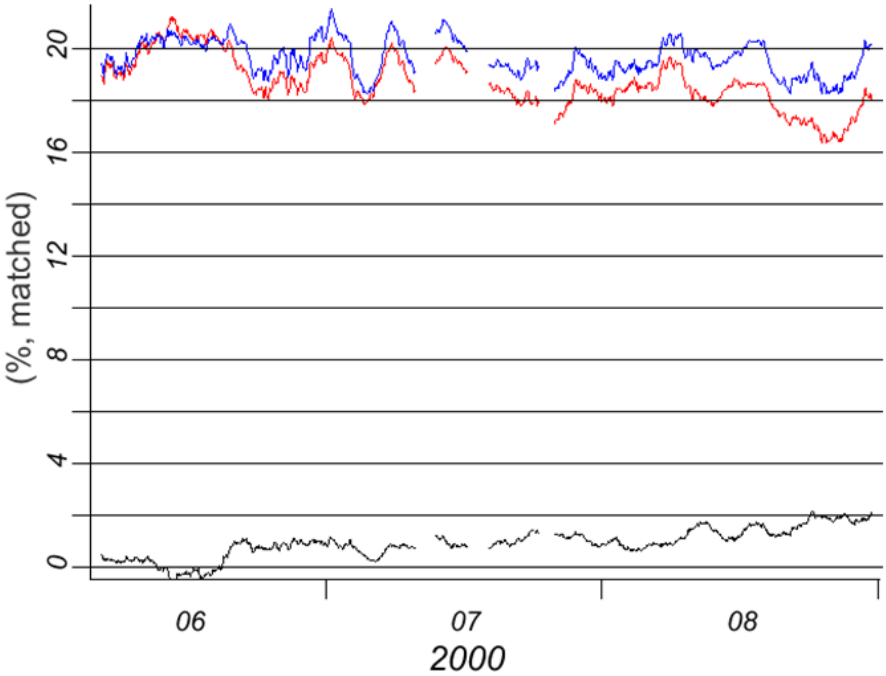

Fig. 33. Time series of 3-h relative humidity forecast errors (RMS difference from 0000 UTC RAOBs) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red), and dev-dev2 difference (black). For the Eastern U.S. region, in the layer between the surface and 400 hPa. 30-day running averages. Positive differences indicate a positive TAMDAR impact.

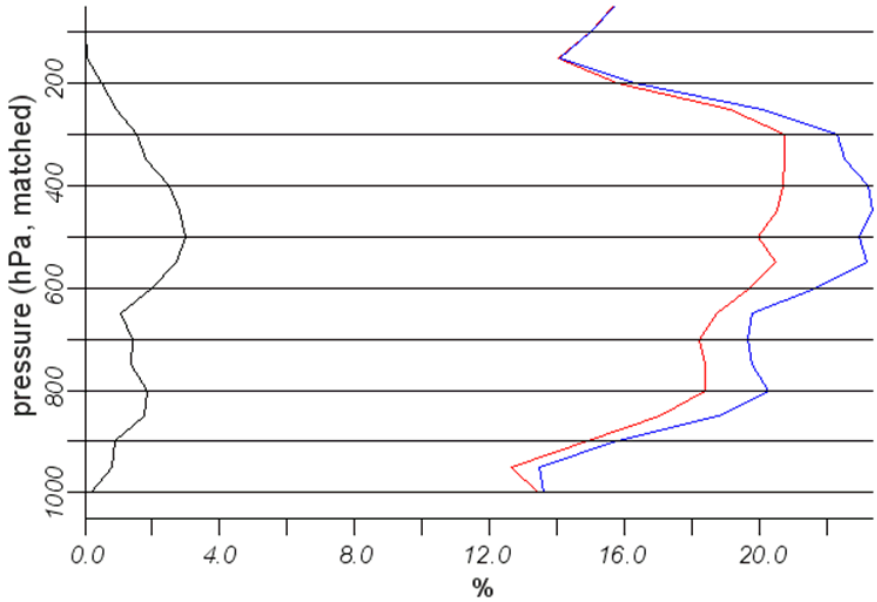

Fig. 34. Vertical profile of 3-h relative humidity forecast errors (RMS difference from 0000 UTC RAOBs) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red), and dev-dev2 difference (black). For the Eastern U.S. region, December 2008.