Evaluation of Regional Aircraft Observations using TAMDAR

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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; 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 operate.

1. Introduction

Commercial aircraft now provide more than 240,000 observations per day of wind and temperature aloft worldwide (figure 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 are 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, 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. 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 winds and temperature. But unlike most of the rest of the fleet, TAMDAR also measures humidity, turbulence, and icing. By 2010, 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 four 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 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 cycles 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’) 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 runs.
- These RUC experiments are run at 20-km resolution, but using the 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 into the operational-NCEP 13-km, with the exception that dev and dev2 do not ingest radar data.

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.

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, 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).

3. TAMDAR data quality

To evaluate the *quality* (as opposed to the *model forecast impact*) of TAMDAR, GSD maintains a database of AMDAR and TAMDAR observations, and 1-h forecasts interpolated to the AMDAR observation point from the dev and dev2 cycle (and more recently from the Bak13 and NoTAM13 cycles). This enables us to compute mean and RMS differences between RUC 1-h forecasts and aircraft-observed temperature, wind, and relative humidity.

Model data are interpolated vertically (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 was stored between December 2005 and December 2008, as well as which variable(s) were actually used in the RUC analysis. Examples of recorded reject information include:

- The aircraft is on a reject list for T, RH, or Wind.
- A variable was flagged as bad by “front-end” (non-model-based) QC checks (e.g., due to track checking or climatological consistency).

- A wind observation was taken during descent by TAMDAR-equipped aircraft (these observations are of lower quality than other aircraft observations, as will be argued in sec. 3).
- Data were taken by Canadian AMDAR aircraft -some of these data are currently of uncertain quality (Zaitseva et al. 2006).
- The observation is a duplicate.
- The difference between the observation and the model background is unacceptably large to be considered reliable for use in the RUC data assimilation.
- The location of the observation is out of the RUC horizontal domain.
- The altitude of the observation is out of range.
- The observation time is not within the analysis time window.
- The dewpoint is greater than the temperature.
- The observation is taken by an aircraft that has had too many other errors in the analysis time window.
- The QC disposition is unknown. (This can happen if the analysis did not run.)

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 dev2 cycle. We do not consider the dev2 to be “truth”; rather we use it as a common benchmark with which to compare the error characteristics of various aircraft fleets. We focus on 1-30 October 2006. This is 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 (12 UTC to 03 UTC) when TAMDAR-equipped aircraft generally fly. Moreover, data are stratified by phase of flight. Data taken during descent are shown in blue; data taken during ascent or en route are shown in red. All data points are 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.

Figure 6 shows temperature bias relative to the dev2 1-h forecast for traditional AMDAR jets and TAMDAR turboprops. The jets show a small warm bias at most altitudes, and descents show a cooler bias than en route/ascent data above 600 hPa. Below 800 hPa, descents show a slightly warmer bias than ascents for this time period.

TAMDAR shows a slightly cooler bias than AMDAR at most levels.

In general, both AMDAR and TAMDAR temperature biases are small, mostly less than 0.25ºK in absolute magnitude.

Figure 7 shows temperature RMS difference for TAMDAR and AMDAR. For both fleets, temperature RMS is small at most levels, with TAMDAR RMS being generally equivalent to that of AMDAR jets.

Figure 8 shows RMS of the vector wind difference between aircraft-measured winds and RUC 1-h forecast winds. In this case, TAMDAR departures from the RUC are considerably larger than those of 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.

Figure 9 shows relative humidity bias relative to the dev2 for TAMDAR only, because most traditional AMDAR jets do not measure moisture. The humidity bias is generally below 5 %RH. This is a substantial improvement since January 2006, when RH biases for data taken during ascent were substantially higher. (In fact, the improvement in TAMDAR's RH bias occurred by April 2006, and has persisted since that time.)

Figure 10 shows relative humidity RMS difference for TAMDAR. The RMS difference is generally similar on ascent/en-route and descent, 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 the National Centers for Environmental Prediction (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 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 and RUC 1-h forecast error).

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, Region 1 – Eastern US, and Region 2 – the Great Lakes.

In studying TAMDAR's impact, we take a two-pronged approach. First, we consider the two real-time 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.

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.)

For most of the verified variables and 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 (TAMDAR) over dev 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.

Figures 12 and 13 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.

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 00 UTC 1 July 2006.

The old verification did not use the 500-hPa RH RAOBs at PIT and ILX. 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 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 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 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.

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. Properly initializing the sharp moisture gradients can lead to improved cloud forecasts in subsequent hours.

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 negative near the surface, increases to positive between approximately 900 and 700 hPa, then becomes increasingly negative 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 this.

4.2 RUC forecast skill

4.2.1 Temperature

Figure 17 shows TAMDAR's impact on temperature forecasts for the period indicated. The RMS temperature difference 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. We consider only 00 UTC RAOBs because this is the time when we expect to see the maximum TAMDAR impact, given the schedule (12-03 UTC, primarily daylight hours) of the Mesaba TAMDAR fleet.

The TAMDAR impact 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.

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.

Figure 18 shows a vertical profile of temperature RMS for dev and dev2 3-h forecasts for March 2008. Figure 17 suggests that this is a typical spring period in terms of RUC temperature error and TAMDAR impact. Inaccuracy in PBL depth results in a maximum in the vertical profile for temperature errors in the dev model forecasts. 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.

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. 18 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.

To put this TAMDAR impact in perspective, we present here a result from our fall 2006 retrospective period (see section 5) in which we ran a 10-day period with 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.

Figure 19 shows this. The TAMDAR impact (the black curve) peaks at 0.4 K at 900 hPa, just as it does in Figure 18. The AMDAR impact also peaks at 900 hPa and has a value of nearly 1.1 K. AMDAR also has an additional peak in impact at 500 mb, above the region where Mesaba aircraft fly most of the time. These results indicate that TAMDAR is responsible for approximately 40% of the total AMDAR impact on 3-h temperature forecasts in the altitude range where TAMDAR is flying.

4.2.2 Wind

Figure 20 shows TAMDAR's impact on winds for the period indicated, averaged over the surface-500 hPa layer. Although TAMDAR wind errors are greater than those of the traditional AMDAR jet fleet, as discussed in section 3, the impact of TAMDAR on dev2 forecasts is consistently positive, albeit small.

Figure 21 shows the corresponding vertical profile. The 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. 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.

Figure 22 compares the TAMDAR wind impact with the impact of all aircraft (AMDAR, which includes TAMDAR) for the period 27 November through 6 December 2006 (see section 5). 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 AMDAR 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

Figure 23 shows TAMDAR's impact on RH. 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 RH error characteristic used in dev2 assimilation of TAMDAR data (see section 5.1). Although we know from reprocessing a 10-day period that the new RH error characteristic increases TAMDAR's RH impact, the increase is small enough that is not clearly evident compared with the seasonal variations shown in Fig. 23.

Figure 24 shows the corresponding vertical profile and shows RH impact to be relatively uniform from the surface to 700 hPa, and is 1-3%. An enhancement in RH impact around 600 hPa is evident in the figure. 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.

Figure 25 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. 24. The RMS for the analysis varies between 6 %RH at 950 hPa and about 13 %RH between 750 and 400 hPa. Thus, the 1-3% reduction in RMS due to TAMDAR moves the 3-h RMS about 15-40% of the way to the analysis fit, and so represents a reduction in 3-h RH forecast error of 15-40%.

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: 12 UTC 26 November to 12 UTC 5 December 2006 and 0 UTC 15 August to 0 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. These additional experiments are discussed in detail by Benjamin et al. (2009)

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'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 errors between 3% and 12%. With these errors, TAMDAR has had a positive impact of 10-40% (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. 26 shows, even in the absence of TAMDAR.

When TAMDAR data are included, the new processing increased TAMDAR impact, as shown in Fig. 27.

Figure 27 shows two impact curves. Each curve indicates 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 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.

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.)

Figure 28 shows that, for 3-h forecasts of RH, TAMDAR has virtually no impact when its RH data are excluded. However, Fig. 29, 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 of our

RUC model runs. However, at longer forecast projections such as 9-h, some improvement in RH forecasts is apparent. We attribute this to the increased spatial resolution of wind and temperature observations provided by TAMDAR aircraft flying into regional airports.

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. 30 may be compared to the black curve in Fig. 18. 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 for temperature below 700 hPa. This is, on average, about 10% of the maximum TAMDAR impact on 900-hPa, 3-h temperature forecasts, growing 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—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 GSD. Currently, the four fleets providing TAMDAR data are:

- Mesaba – Data first received in 2004, and reported on above.
- PenAir – Data first received in late 2007. PenAir covers the Aleutian Peninsula in Alaska—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.

Figure 31 shows TAMDAR data reported to GSD in April 2009. The PenAir fleet may be seen in Alaska. Horizon covers the Western US; Chautauqua covers 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 32 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 that was not densely covered by the Mesaba fleet alone, as shown in Fig. 5. The increased

TAMDAR impact on RH forecasts since late April 2008 is evident in the difference curve.

Figure 33 shows a vertical profile of TAMDAR's impact on RH 3-h forecasts. The effect of the Chautauqua fleet becomes evident if this is compared with Fig. 24, which shows vertical RH impact for the Great Lakes region in March 2008, before TAMDAR sensors started reporting from the Chautauqua fleet. In Fig. 33 we see that the TAMDAR impact now extends 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 regular aircraft profiles were not available. 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 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 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 3-h forecast errors are reduced by up to 35%, dependent on vertical level.
- Wind forecast errors are reduced by up to 15%.
- Relative humidity forecast errors are reduced by up to 25%.
- Retrospective runs have revealed the following:
- The optimal RH error to use for assimilating TAMDAR's RH observations is 12%. Lower values than this result in overfitting; higher values result in a gradual drop off of TAMDAR's 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 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.

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Fig. 4. As for fig 3, but with TAMDAR observations included.
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Figure 20. As for Fig. 17, but for wind forecasts.
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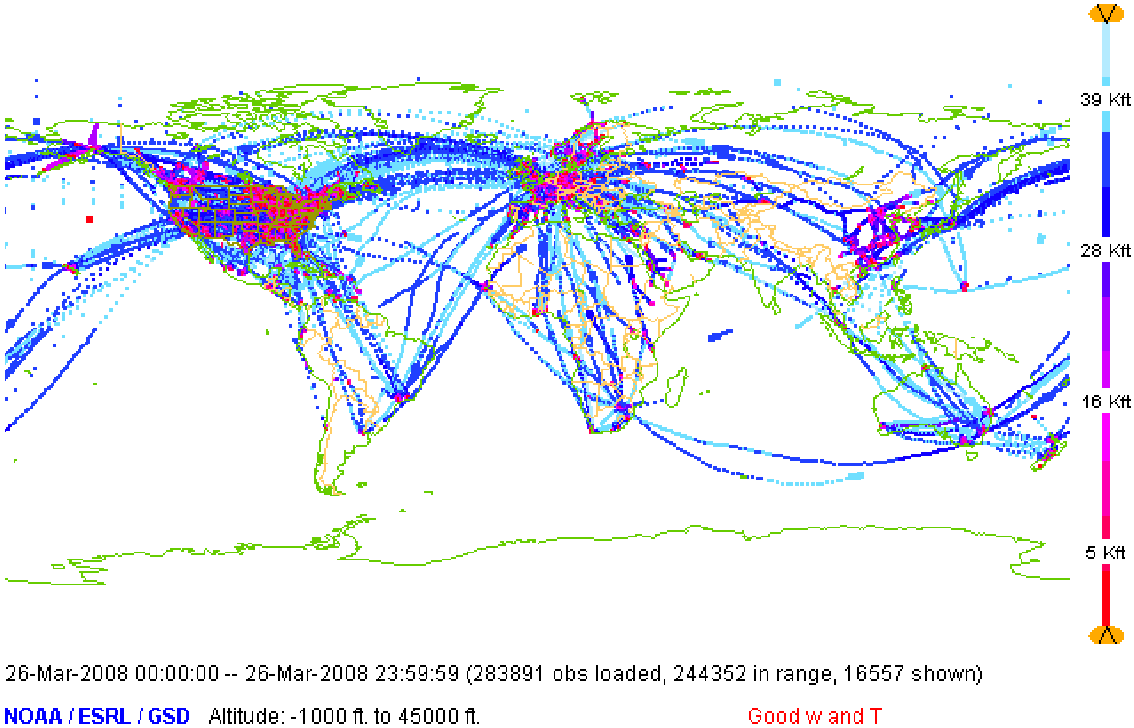
Figures



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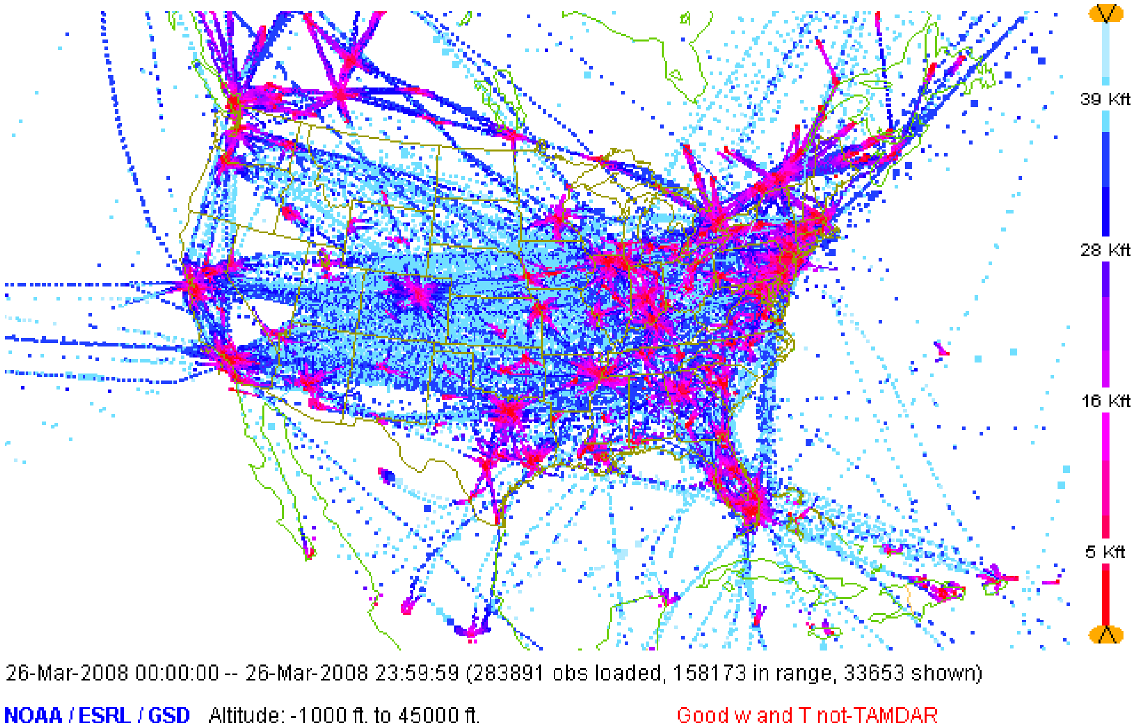

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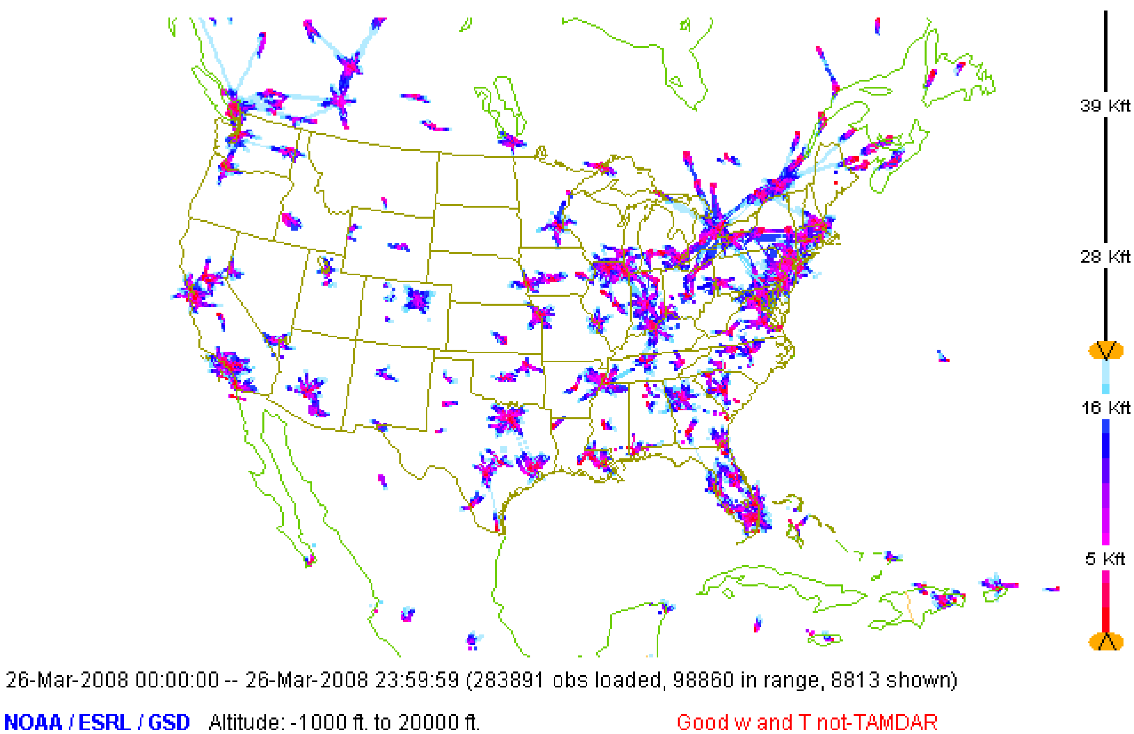

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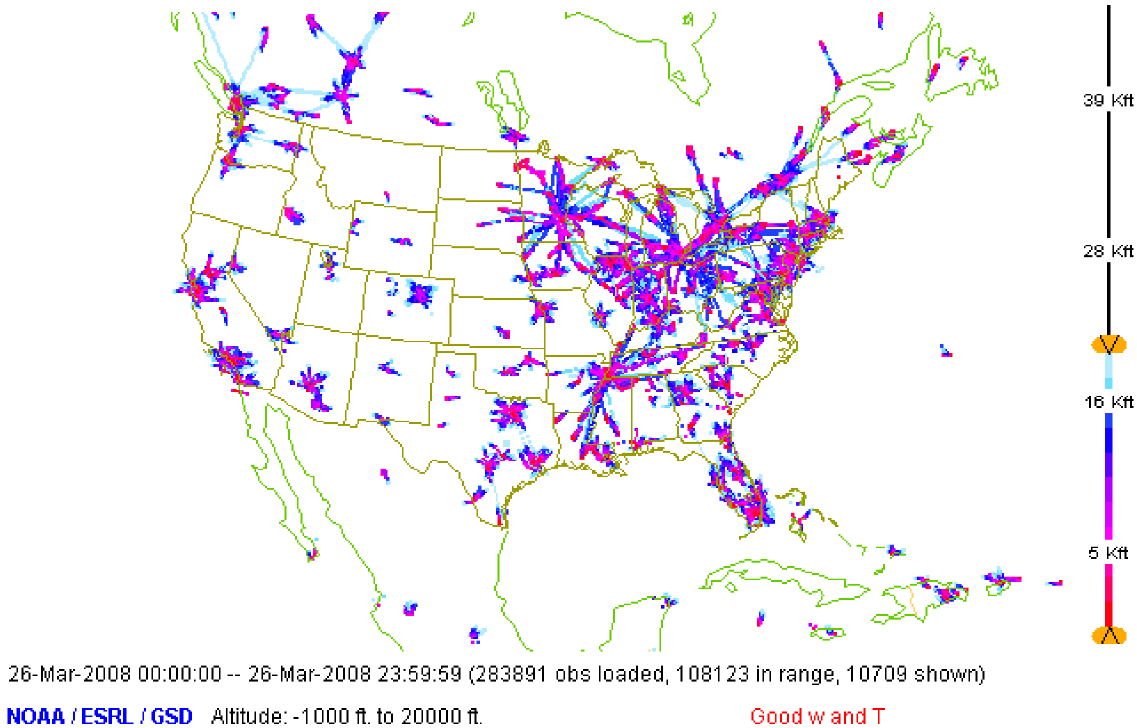

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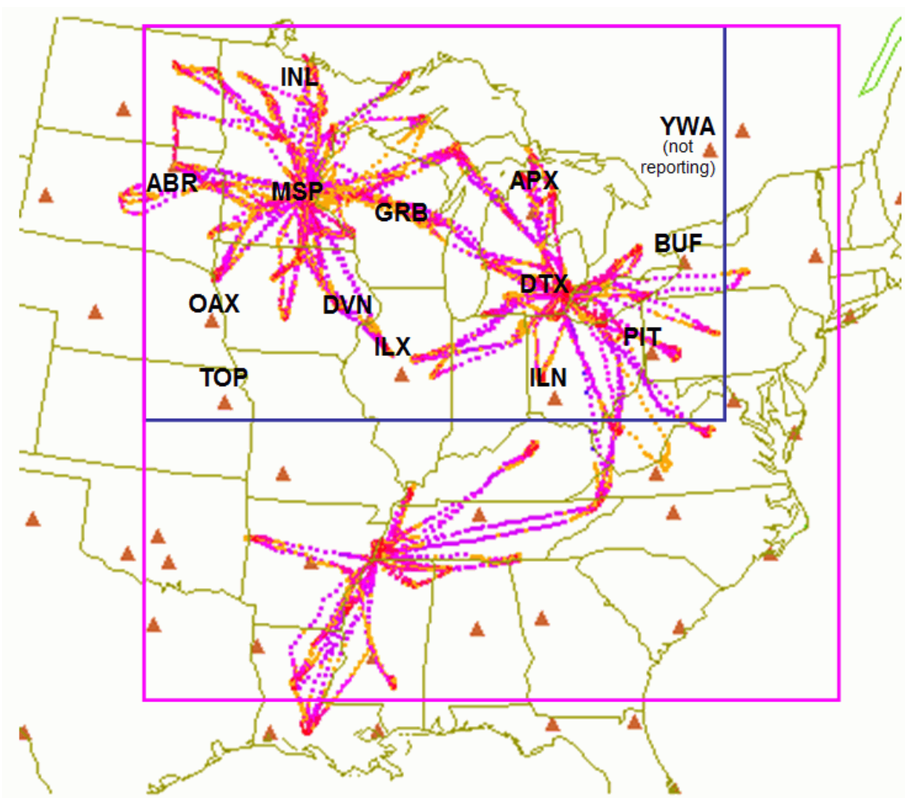

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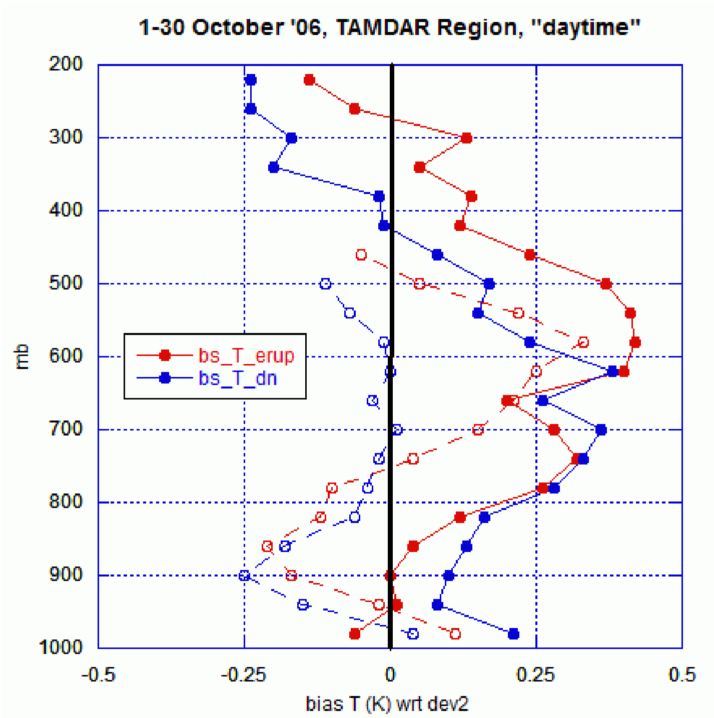
Verification areas are shown for blue rectangle (Great Lakes region – 13 RAOBs) and magenta rectangle (Eastern US area – 38 RAOBs)



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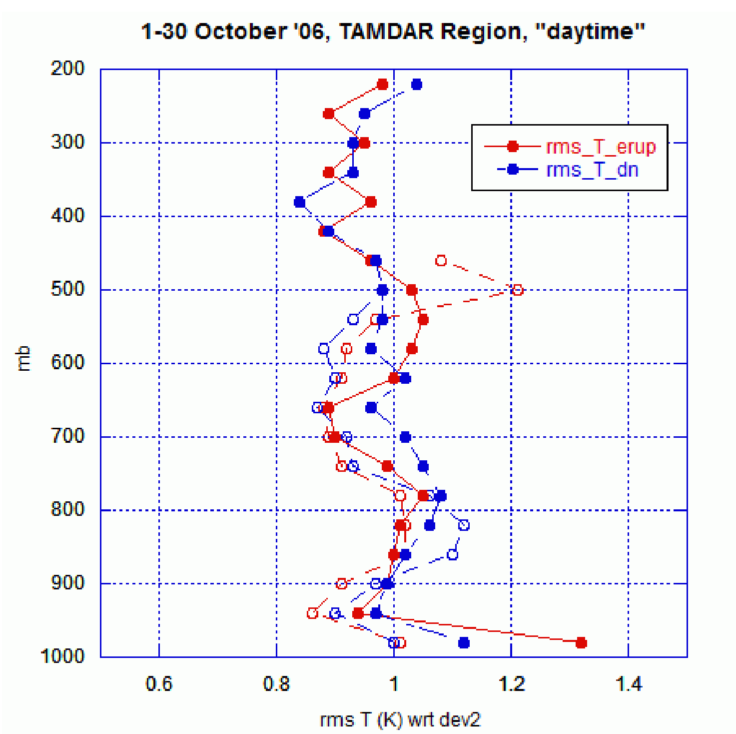
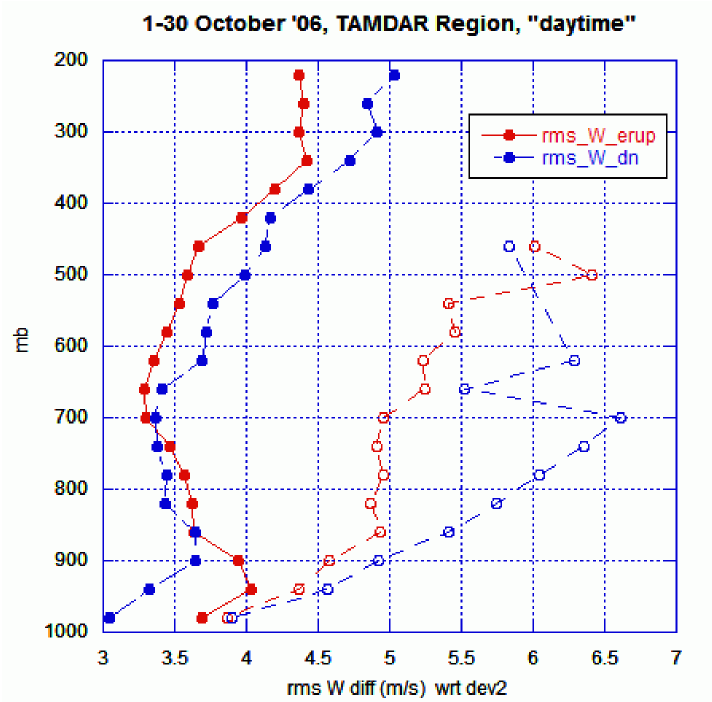


Figure 7. TAMDAR (open circles) and AMDAR (solid circles) temperature RMS for Oct '06 with respect to dev2 1-h forecasts.



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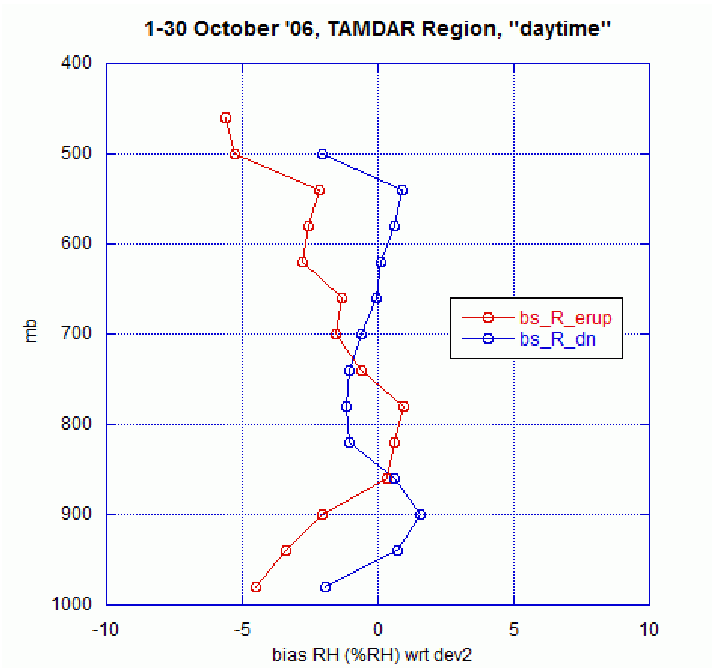

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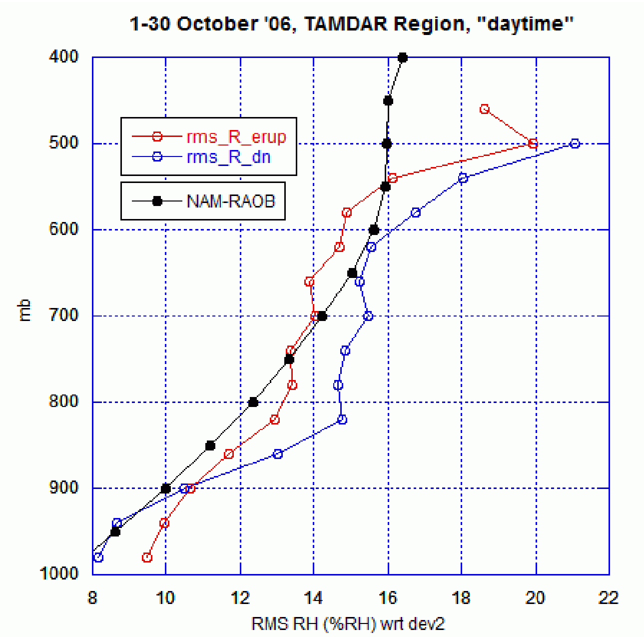

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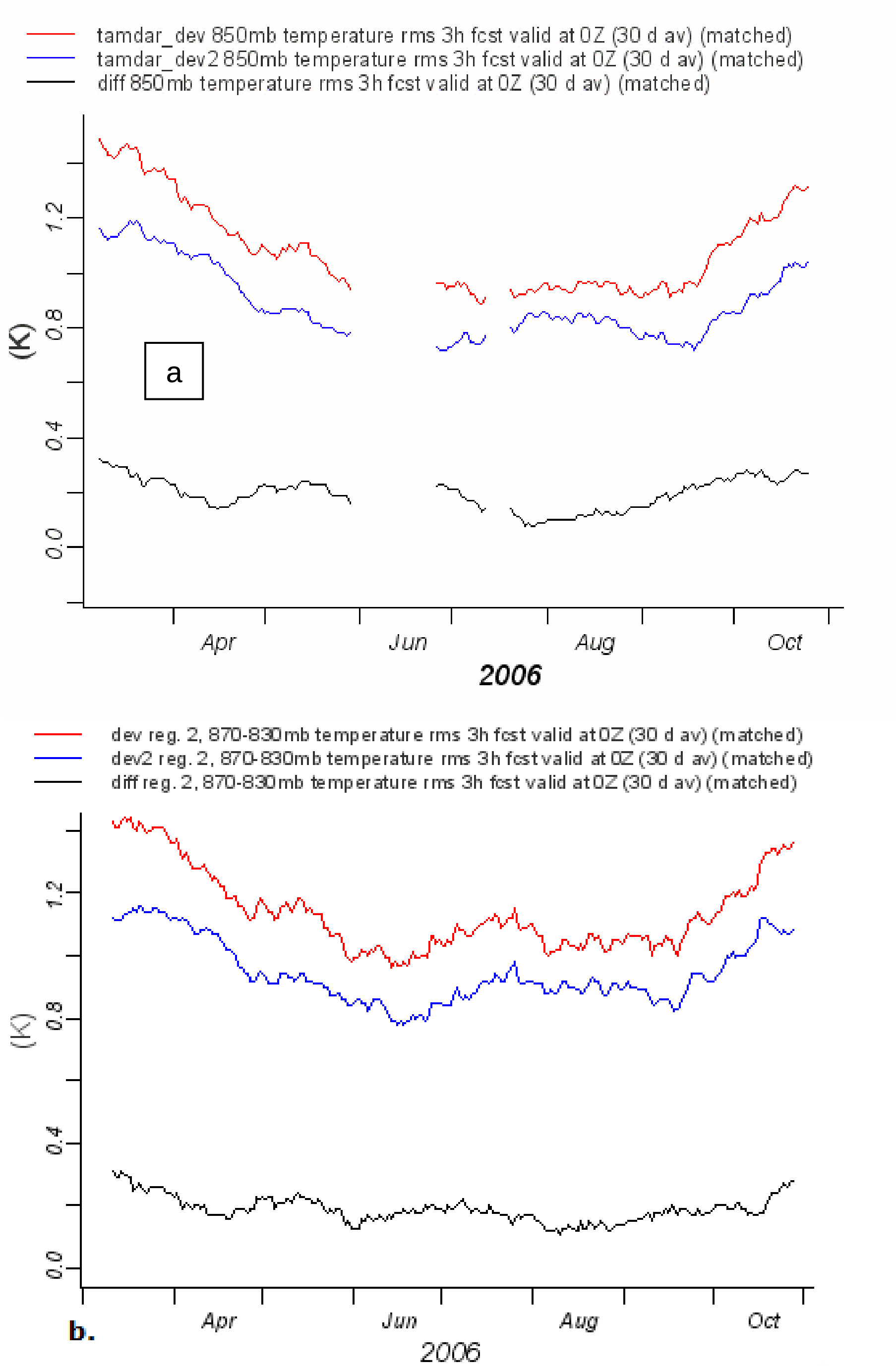

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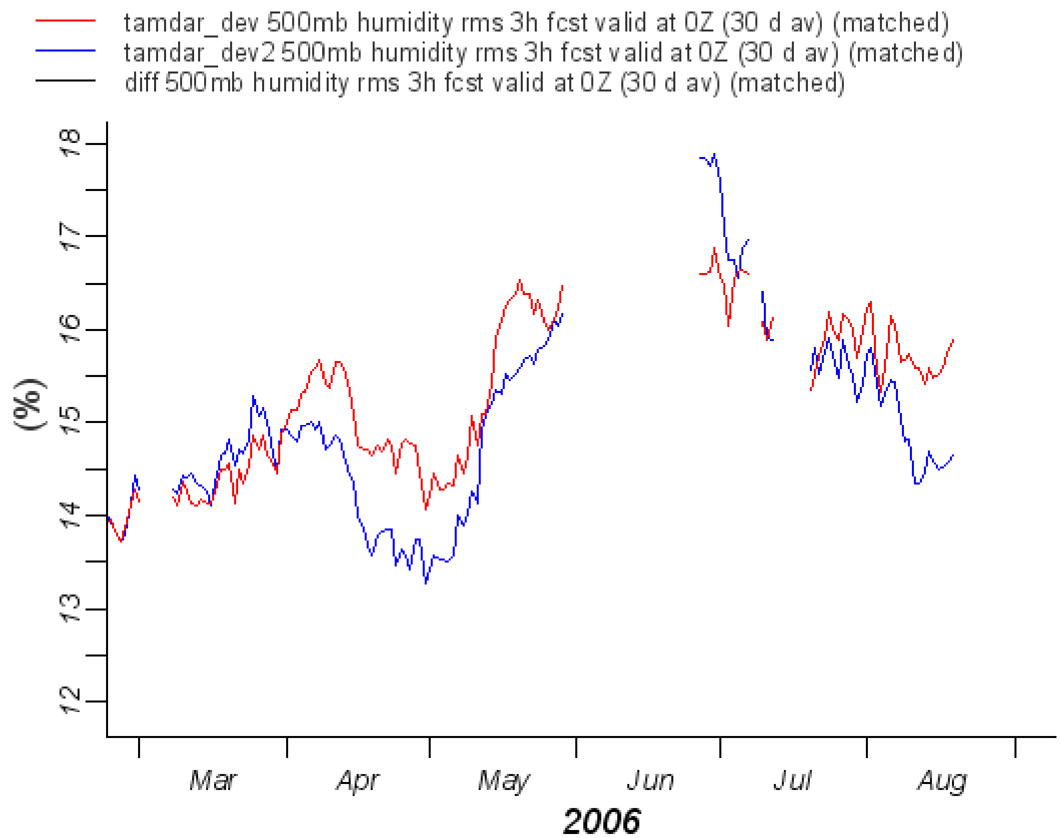

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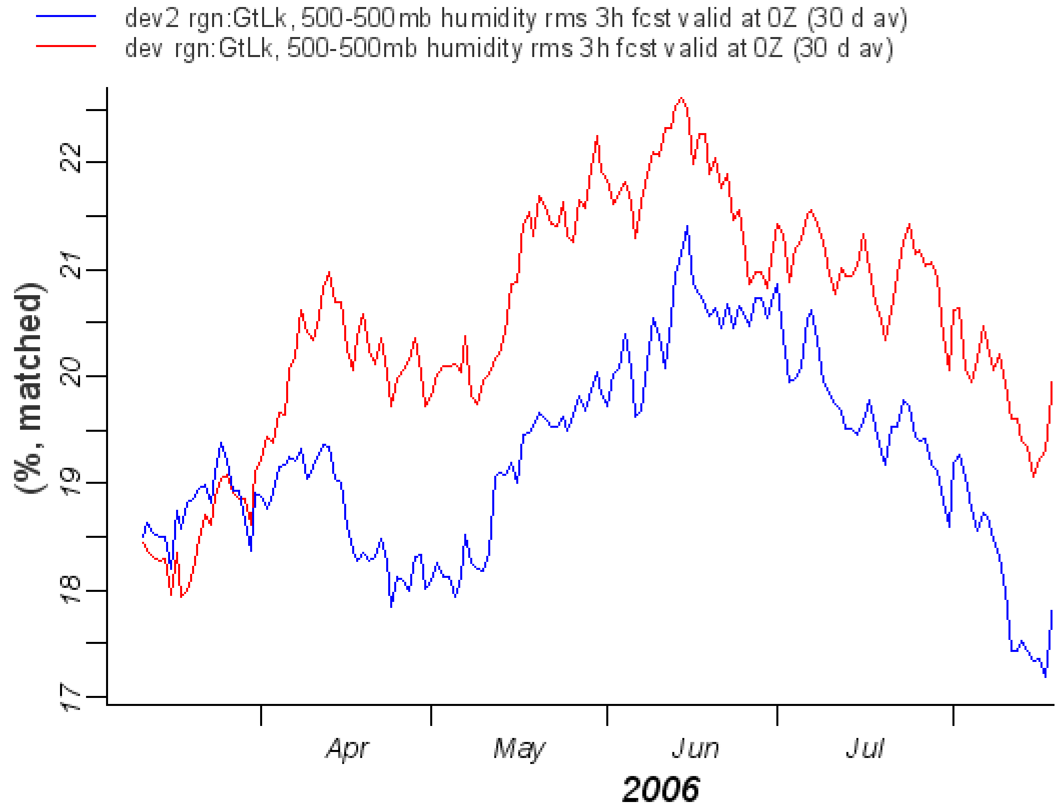

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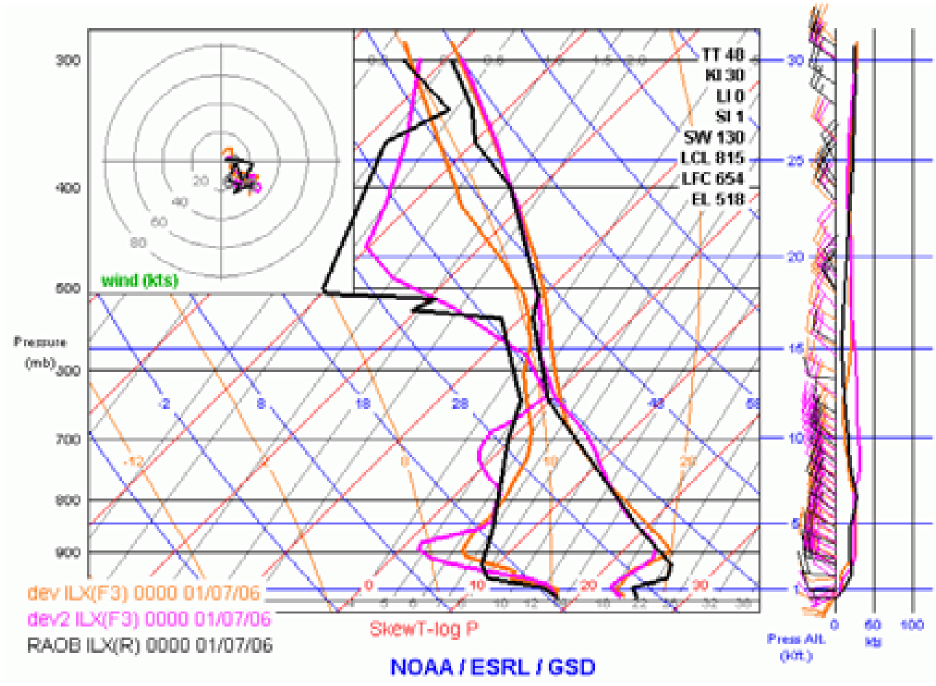

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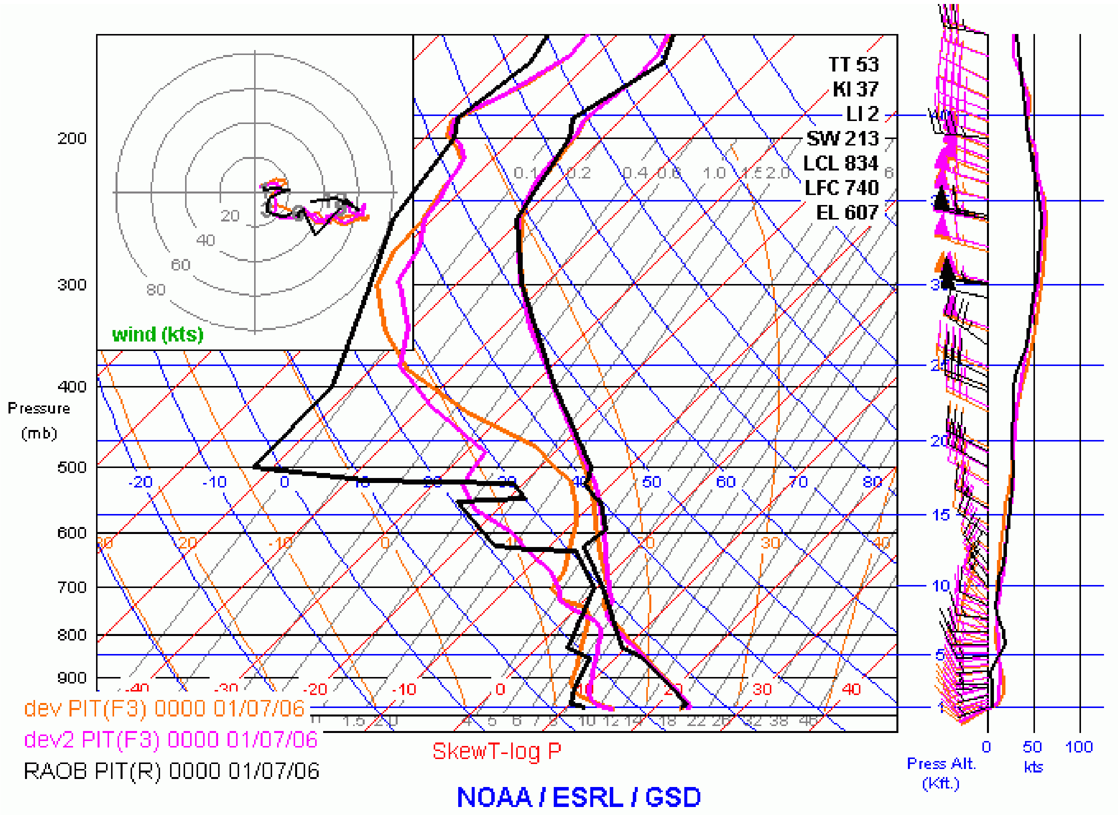

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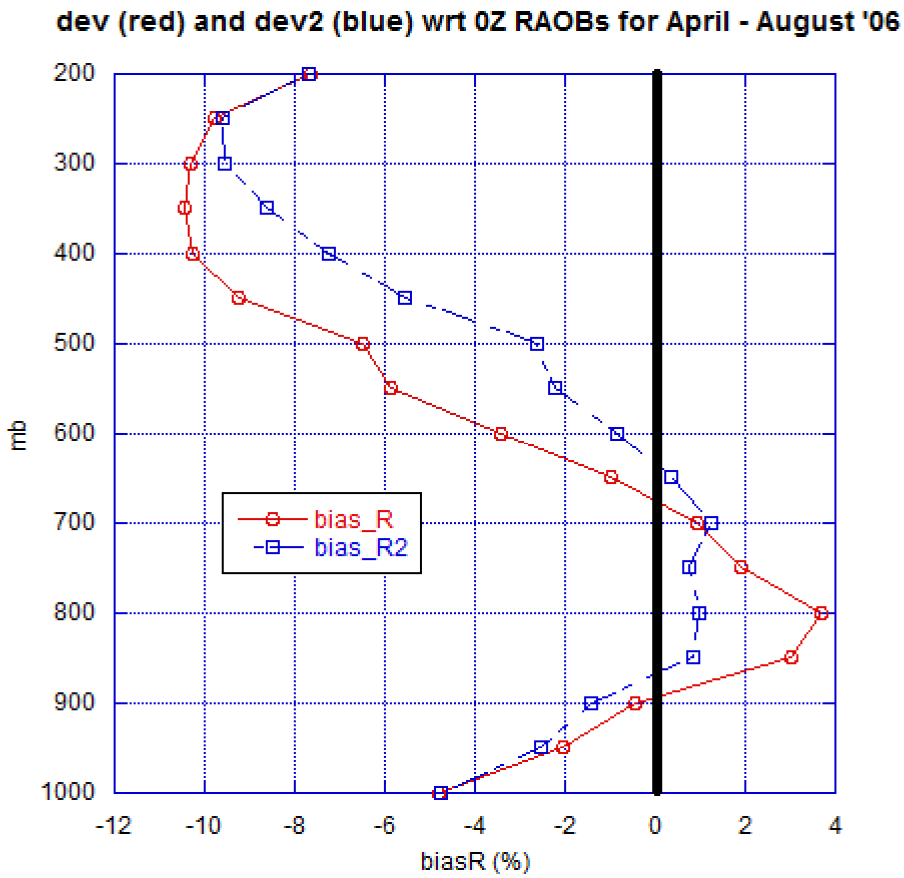

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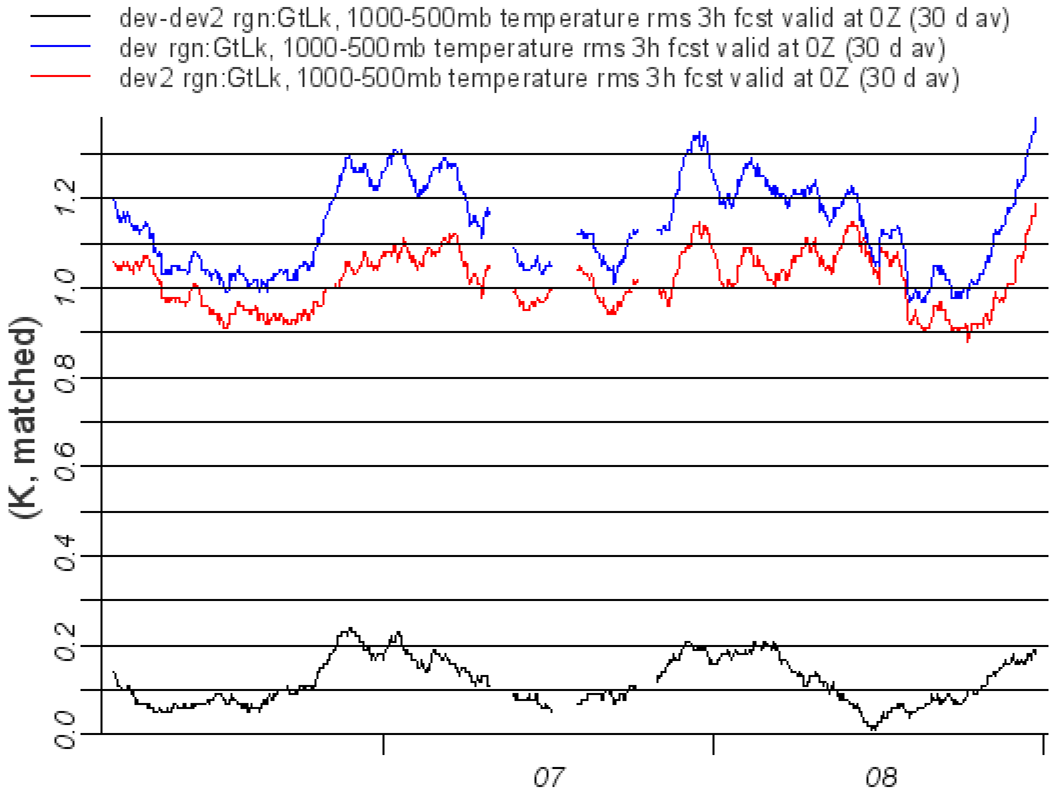

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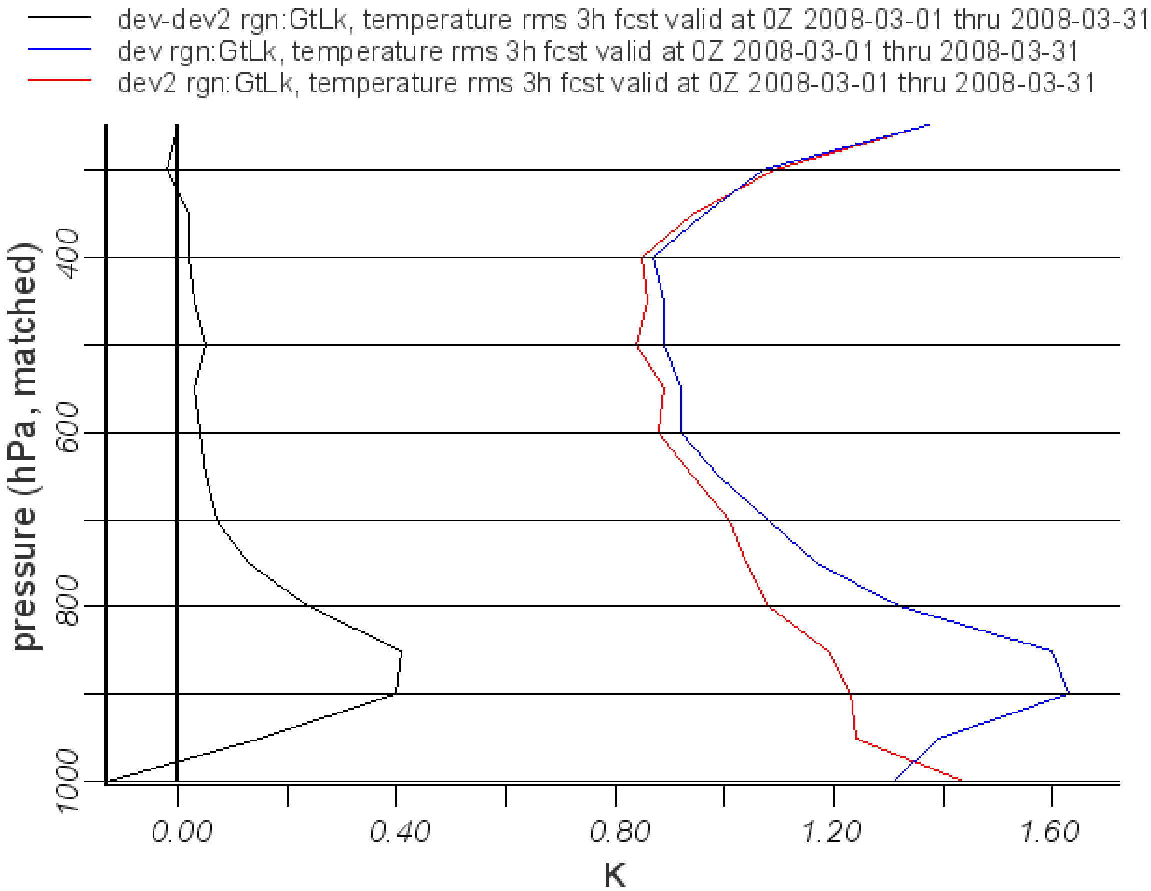

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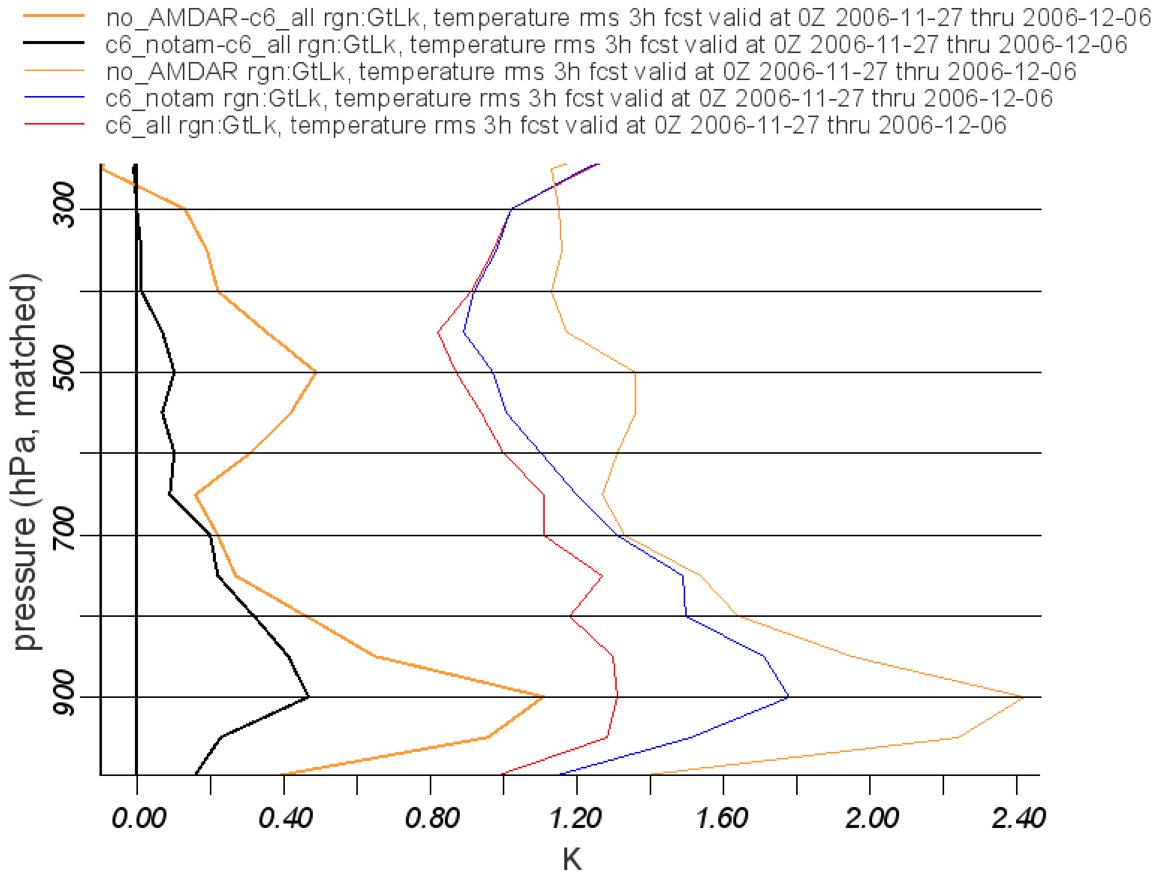

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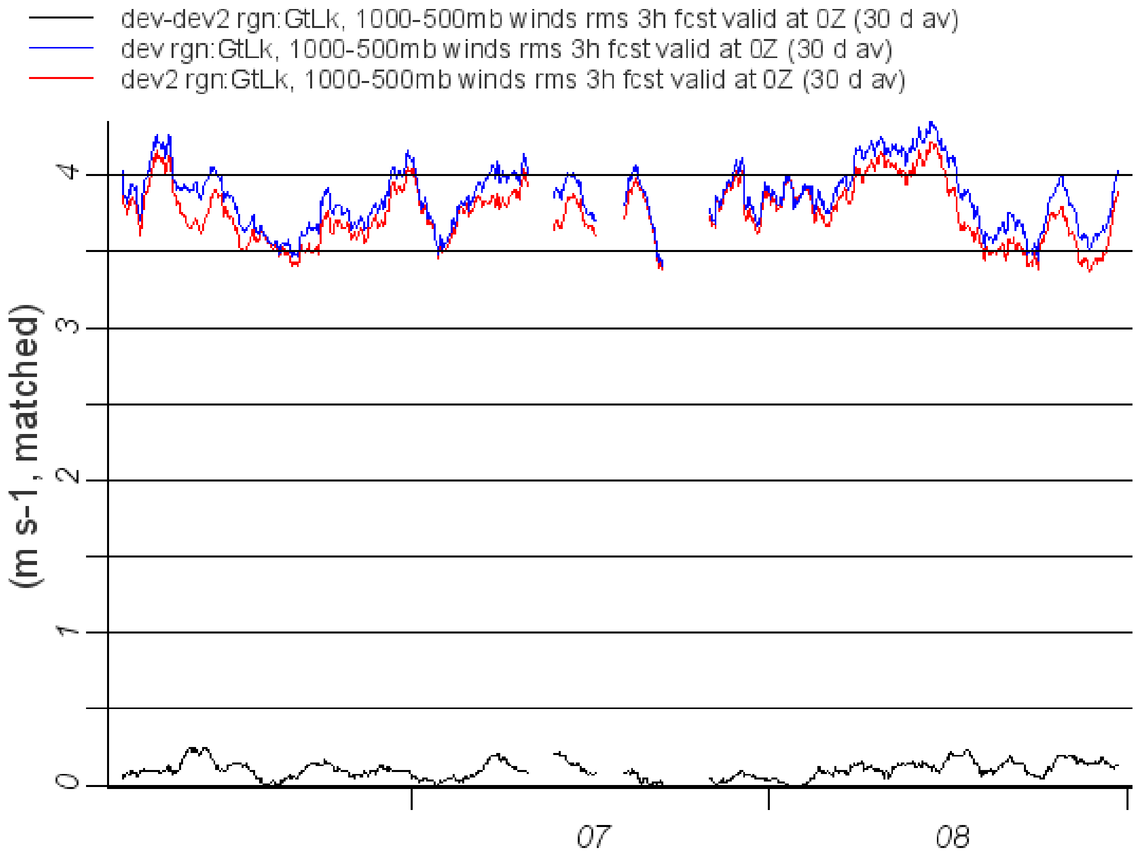

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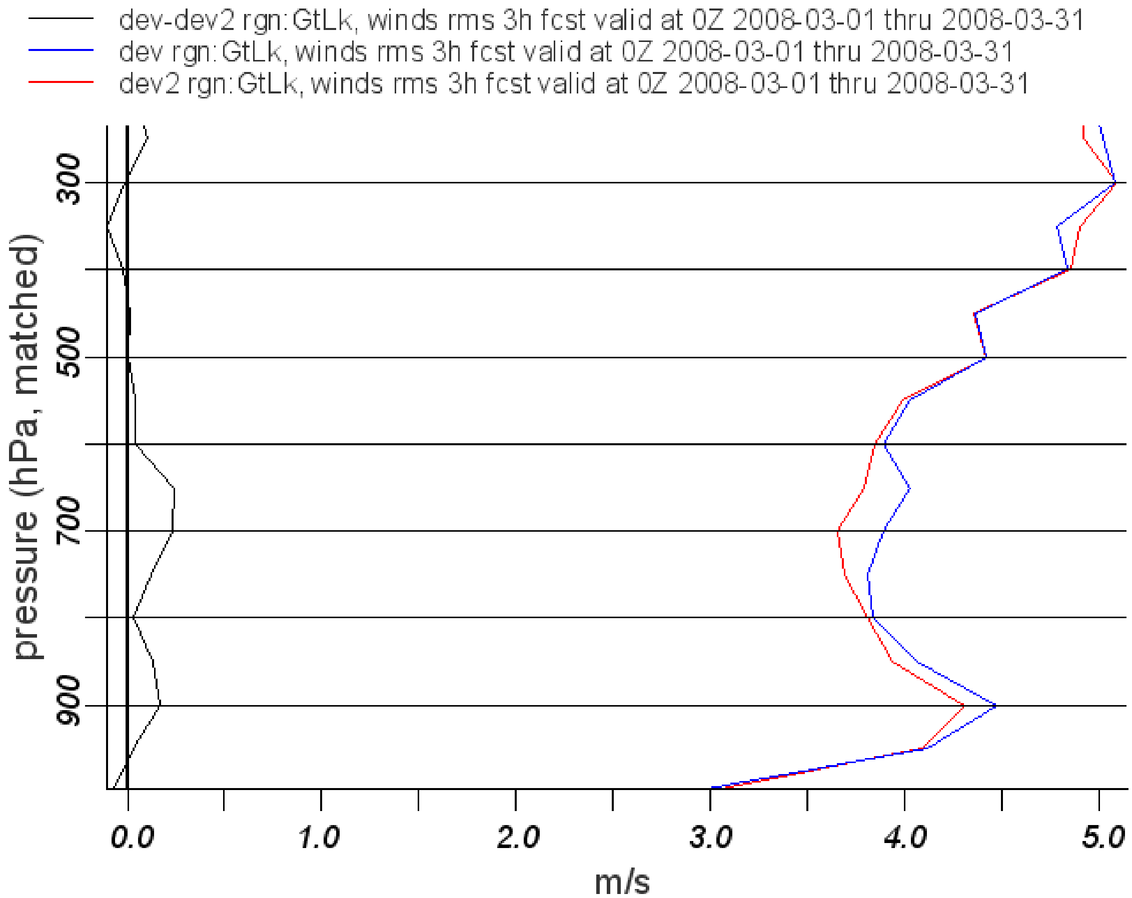

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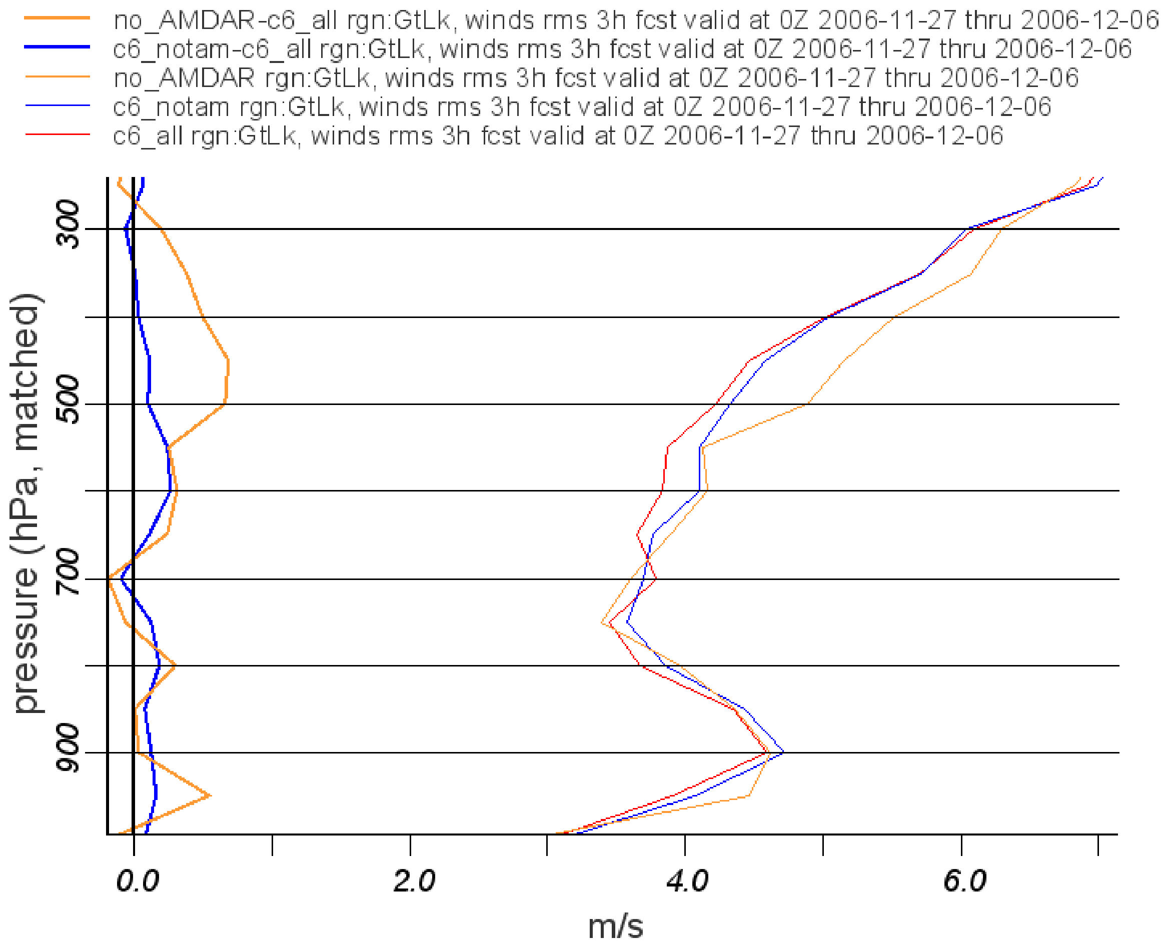

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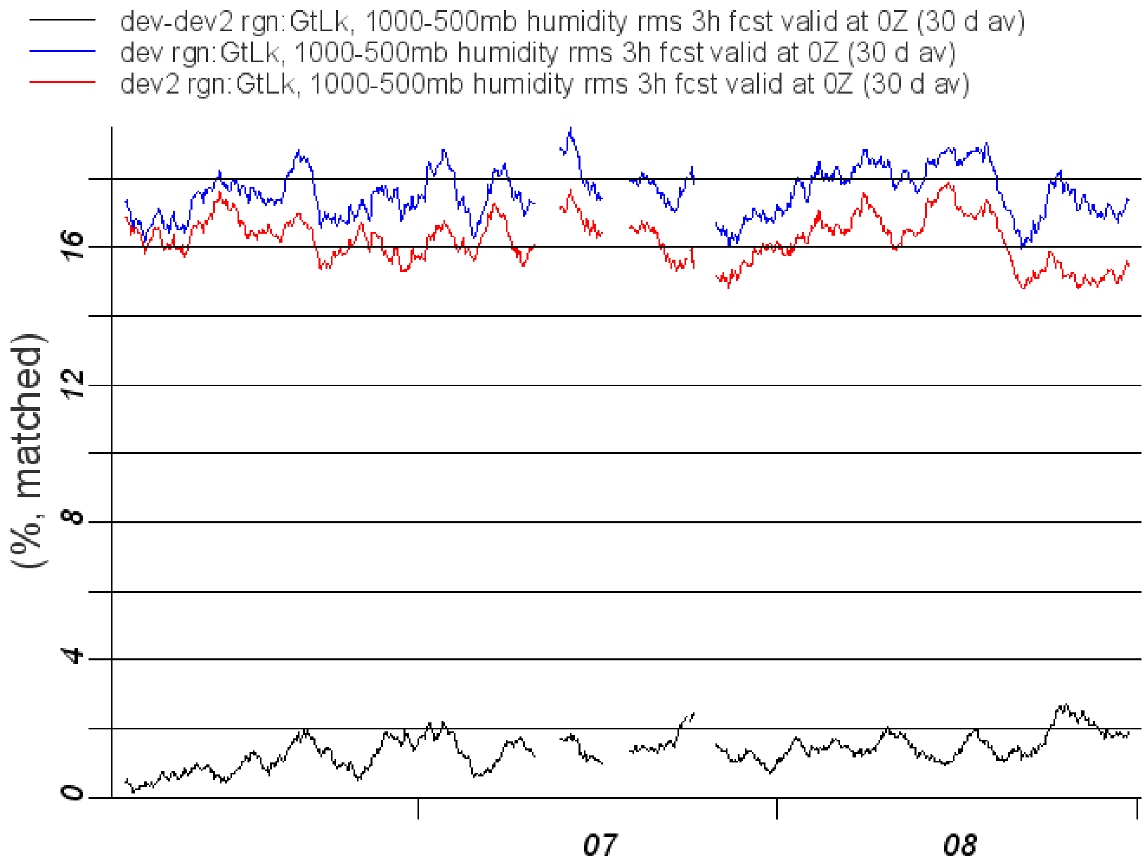

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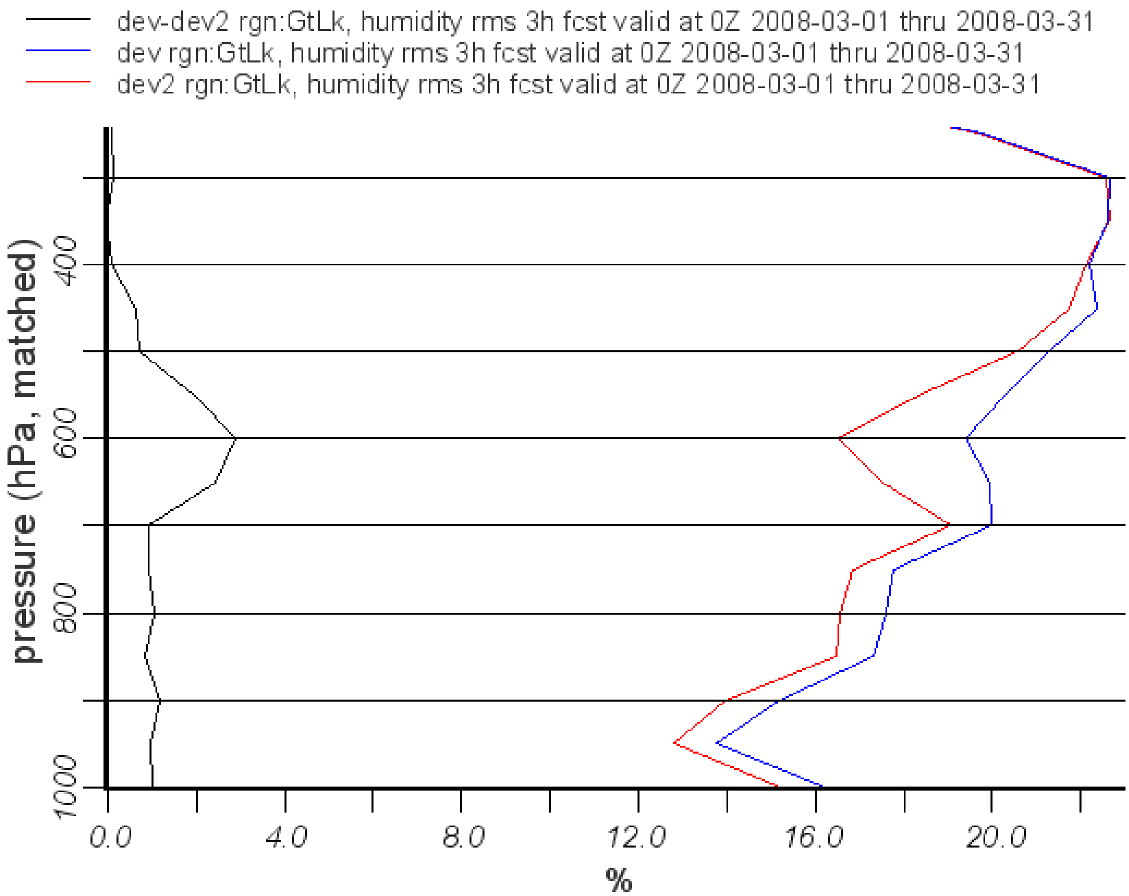

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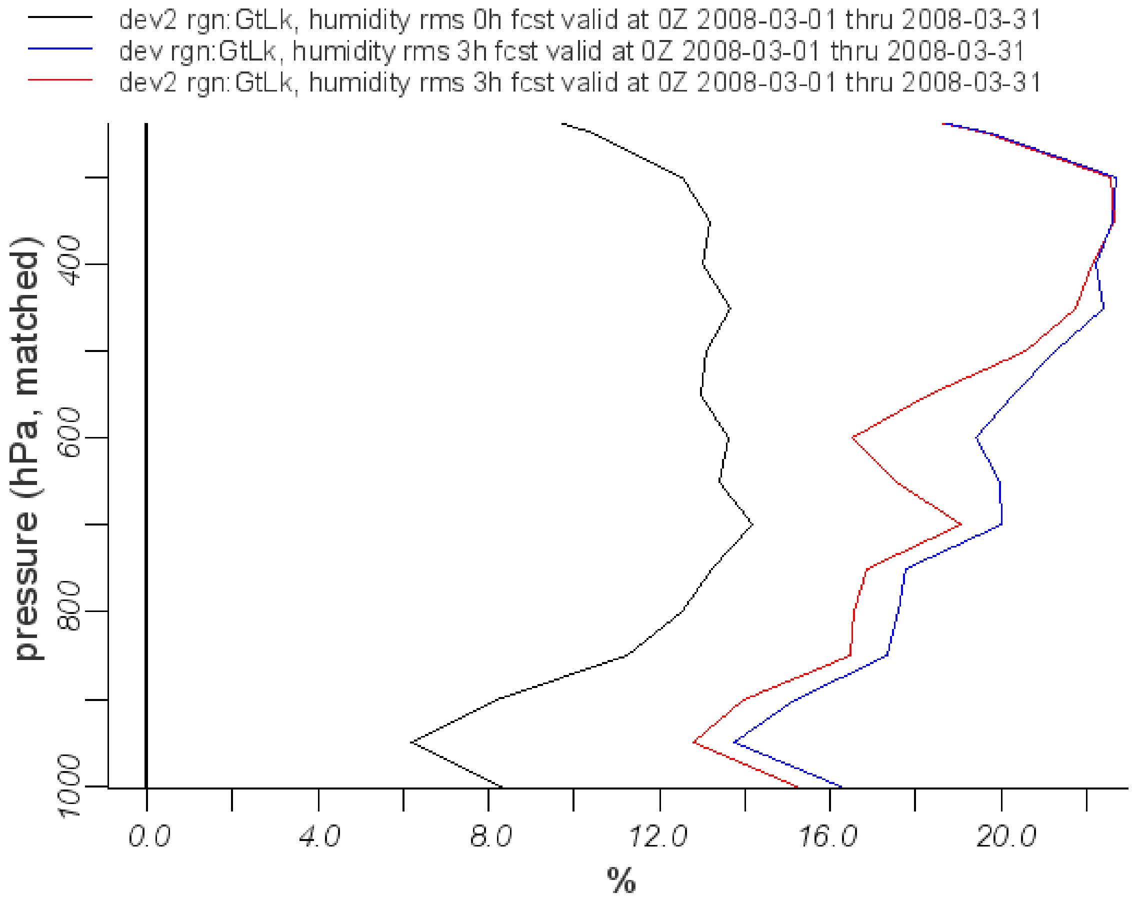

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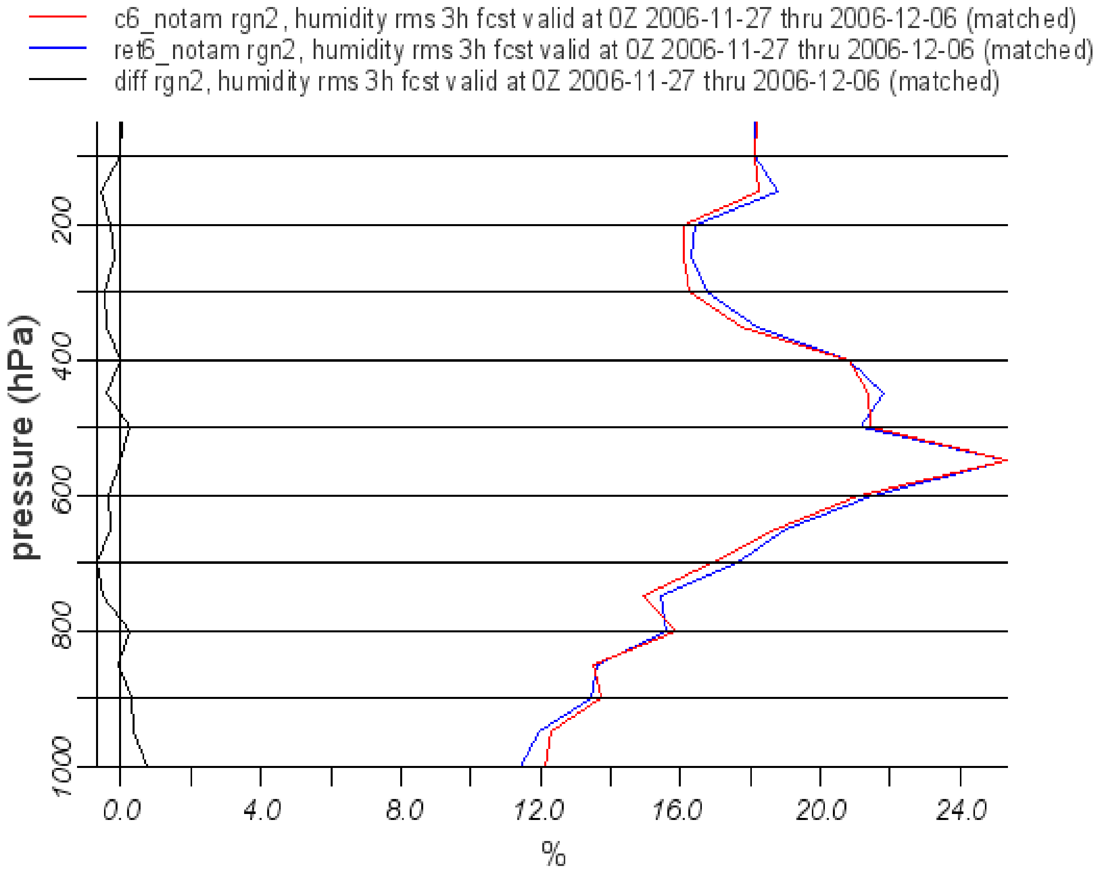

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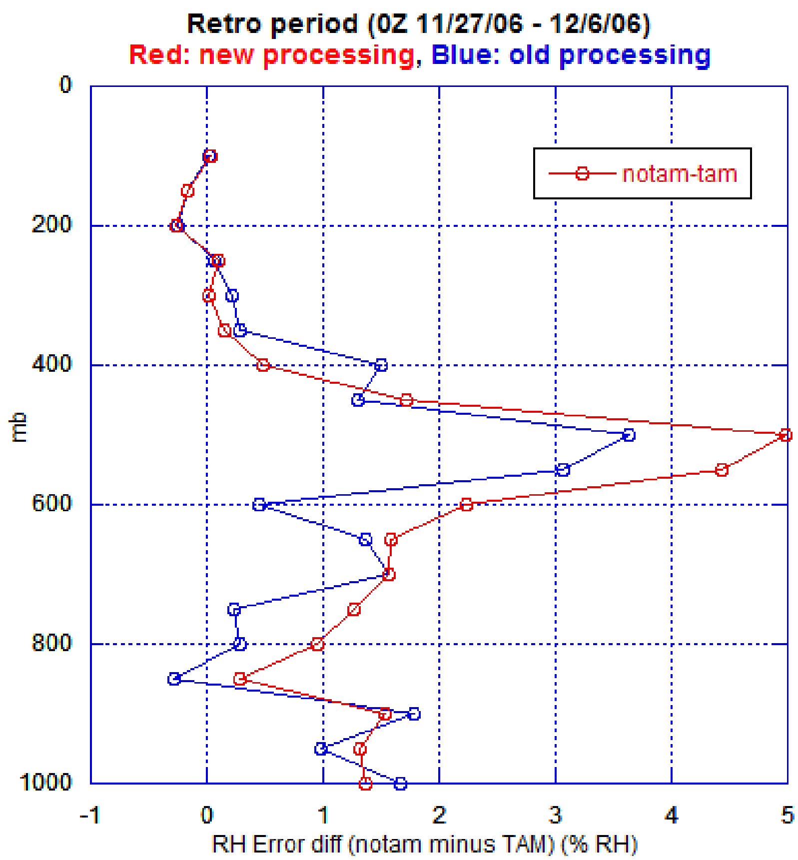

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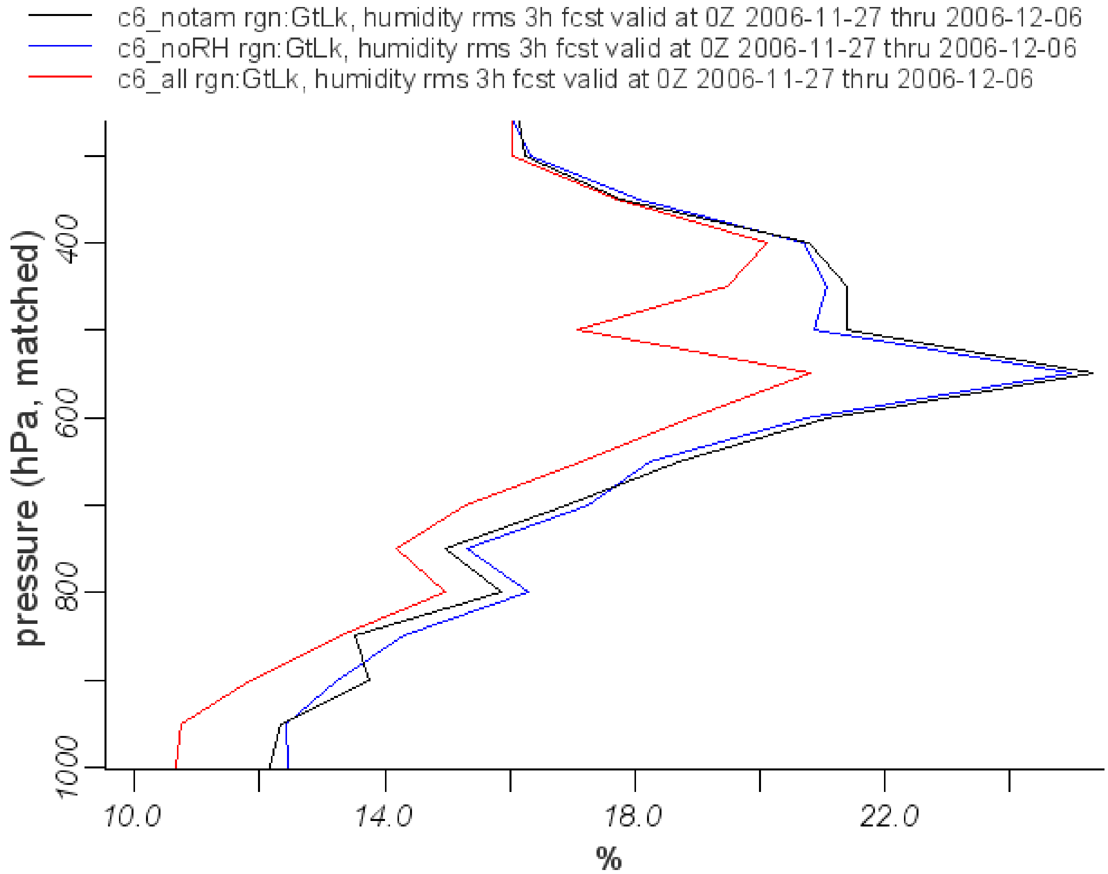

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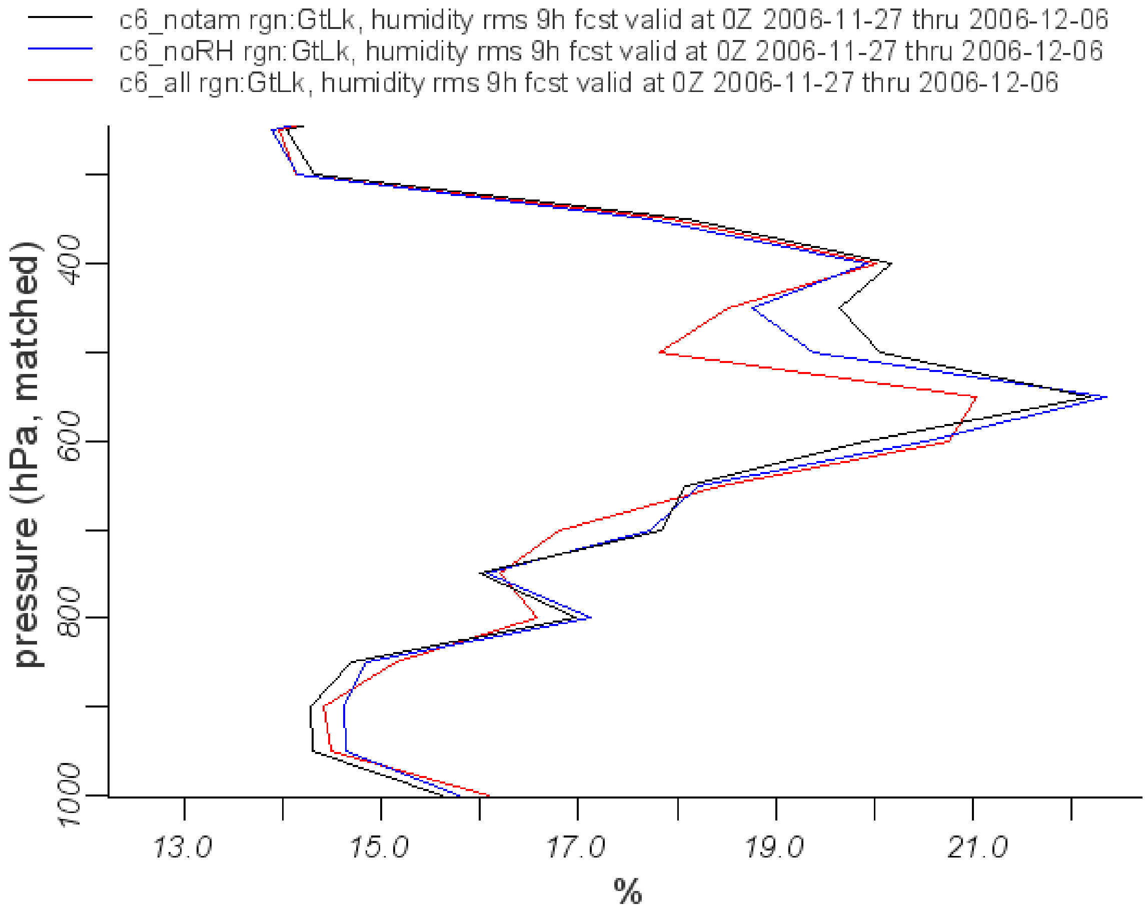

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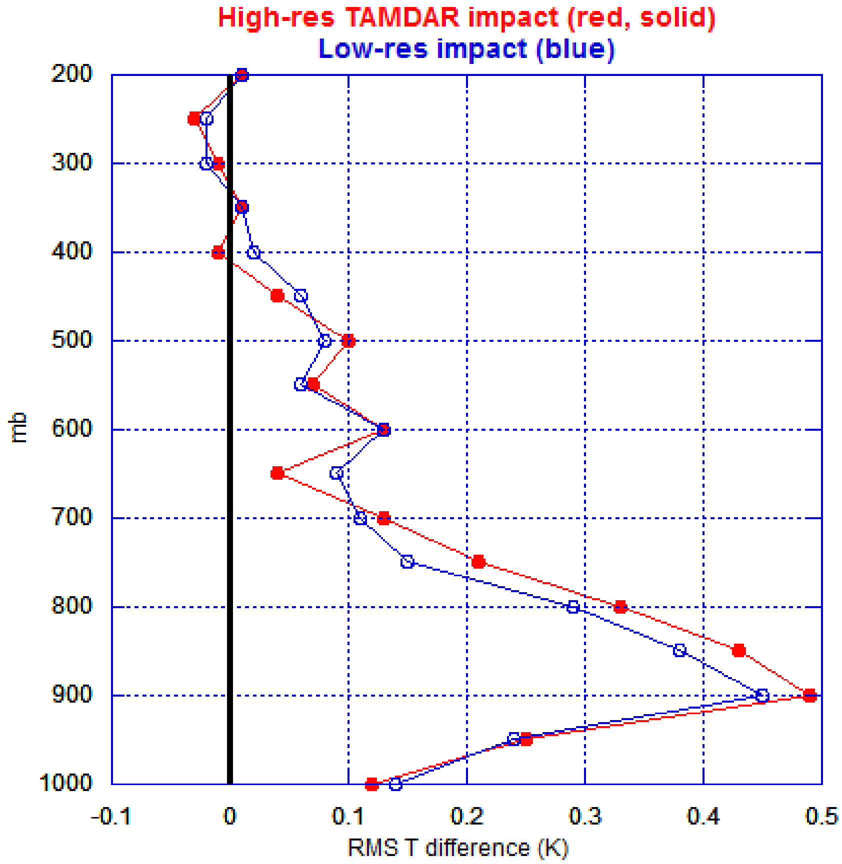

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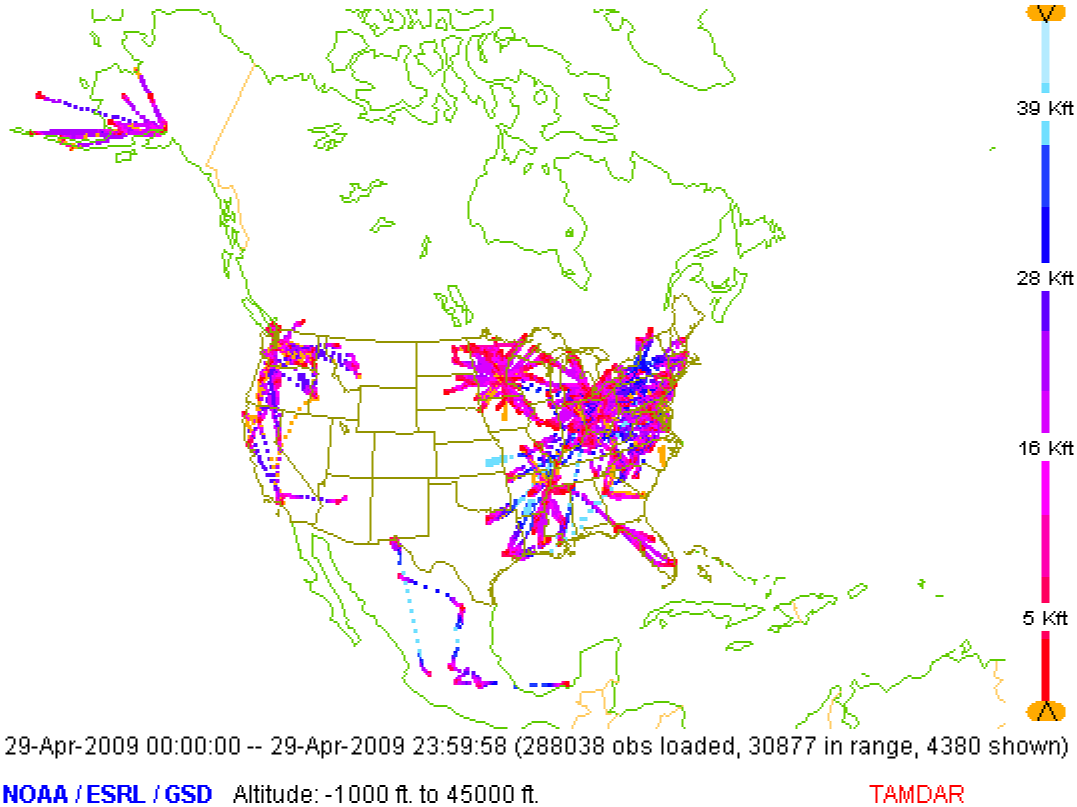

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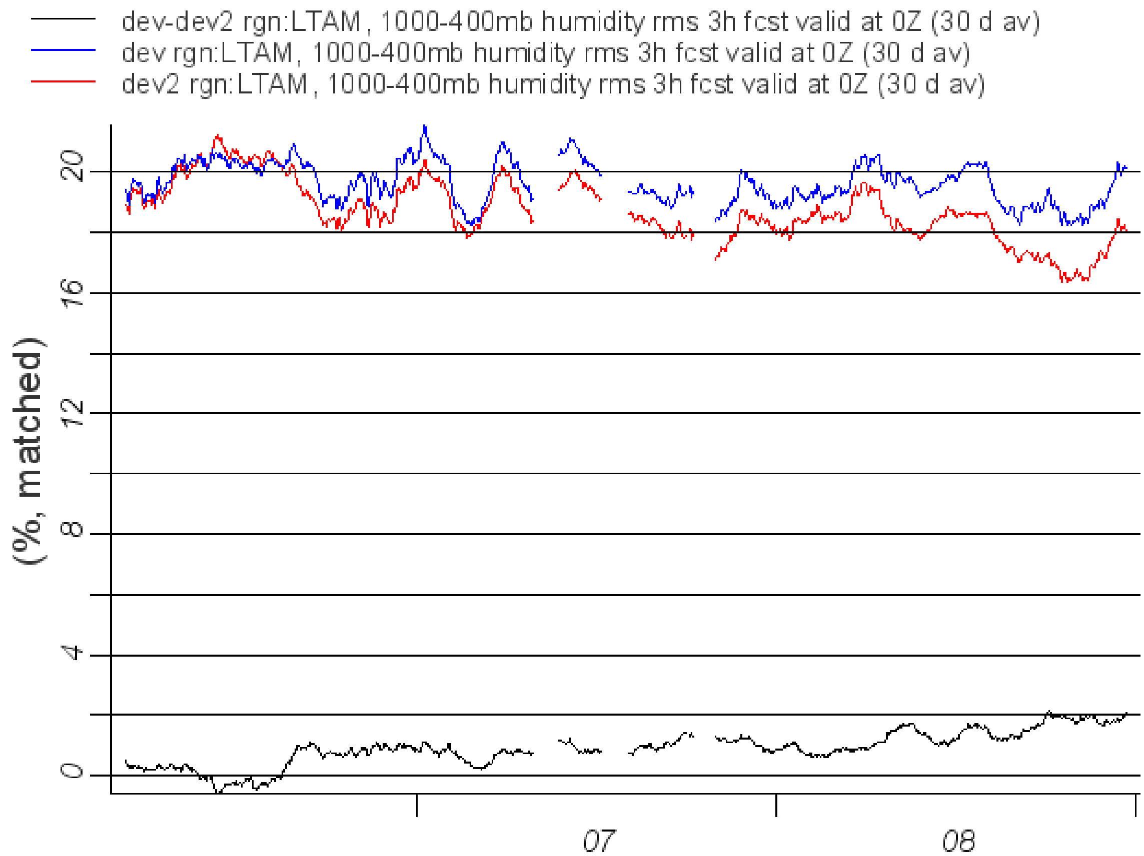

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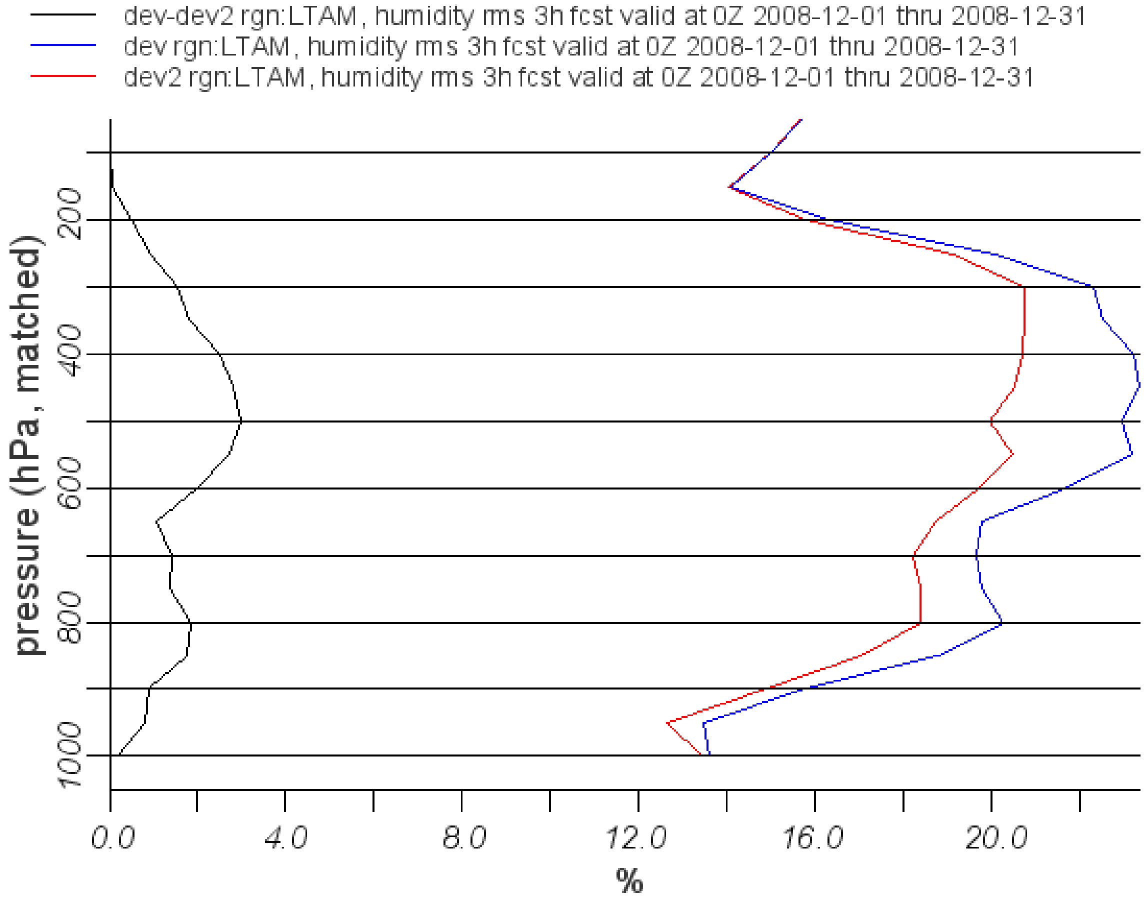

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Tables

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	**<--**