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P2.20 NEW TAMDAR FLEETS AND THEIR IMPACT ON RAPID UPDATE CYCLE (RUC) FORECASTS

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1. INTRODUCTION

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

Two shortfalls of the current AMDAR data set are the absence of data below 25,000 ft between major airline hubs and the almost complete absence of water vapor data at any altitude. To address these deficiencies, a sensor called TAMDAR (Tropospheric AMDAR) was developed by AirDat, LLC, under NASA sponsorship (Daniels et al. 2006). The sensor has been deployed on approximately 50 regional turboprop aircraft flying over the central United States. These turboprops are operated by Mesaba Airlines (doing business as “Northwest Airlink”). Recently, PenAir airlines in Alaska has also begun to provide TAMDAR data. These TAMDAR-equipped aircraft generally cruise at lower altitudes than traditional AMDAR jets, and into regional airports not serviced by AMDAR jets. Like the rest of the AMDAR fleet, TAMDAR measures winds and temperature. But unlike most of the rest of the fleet, TAMDAR also measures humidity, turbulence, and icing.

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 three years that TAMDAR has been in operation. Our evaluation system relies primarily on the Rapid Update Cycle (RUC) numerical model and data assimilation system (Benjamin et al. 2004a,b, 2006a) over the contiguous U.S., and the NCEP GFS (Global Forecast System) model elsewhere.

Mesaba flies within the RUC domain, and so we are able to evaluate improvements in RUC forecasts due to TAMDAR Mesaba data. We have reported on this impact in the past (Moninger, 2007a,b) and provide an update here. We had expected new TAMDAR fleets to be providing data in the CONUS by January 2008, but this has not occurred. However, PenAir has been reporting TAMDAR data for several months. PenAir flies in southwest Alaska, which is outside of the RUC domain. We therefore report here on the quality of PenAir data by comparing them with 3-h forecasts from the Global Forecast System (GFS).

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

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

- ‘Dev’ (or ‘development version 1’) assimilates all hourly non-TAMDAR observations.
- ‘Dev2’ is the same as dev but assimilates, in addition, TAMDAR wind, temperature, and relative humidity observations in the RUC domain.
- The same lateral boundary conditions, from NCEP’s North American Model (NAM), are used for both dev and dev2 experiments.
- These RUC experiments are run at 20-km resolution, but using latest 13-km-version code, with the exception that dev and dev2 do not ingest radar reflectivity data.

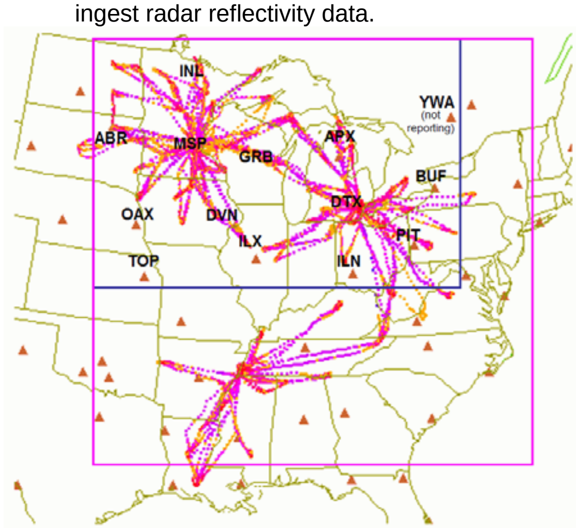

Fig. 1. TAMDAR-Mesaba observations typical for a 24-h period in 2007. Verification areas are shown for blue rectangle (Great Lakes area – 13 RAOBs) and violet rectangle (Eastern US area – 38 RAOBs)

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

The RUC version used for the TAMDAR experiments includes complete assimilation of nearly all observation types (as used in the RUC13, including cloud analysis (GOES and METAR), full METAR assimilation, GPS precipitable water, GOES precipitable water, all other aircraft, profiler, mesonet, and RAOB. (It does not, however, use radar data, which was added to GSD's experimental 13-km RUC cycles in spring 2007.) A summary of the characteristics of the June 2006 operational RUC13 is available at http://ruc.noaa.gov/ruc13_docs/RUC-testing-Jun06.htm. More details on the RUC assimilation cycle and the RUC model are available in Benjamin et al. (2004a,b, 2008). Other details on RUC TAMDAR experimental design are described in Benjamin et al. (2006a,b).

3. REAL-TIME RUC FORECAST SKILL WITH AND WITHOUT TAMDAR-MESABA DATA

In this section we present an update of TAMDAR impact on forecasts of temperature, wind, and relative humidity. A related paper by Szoke et al. (2008) describes the effect of TAMDAR on RUC short-term forecasts of aviation-impact fields such as ceiling, visibility, reflectivity, and precipitation.

3.1 Temperature

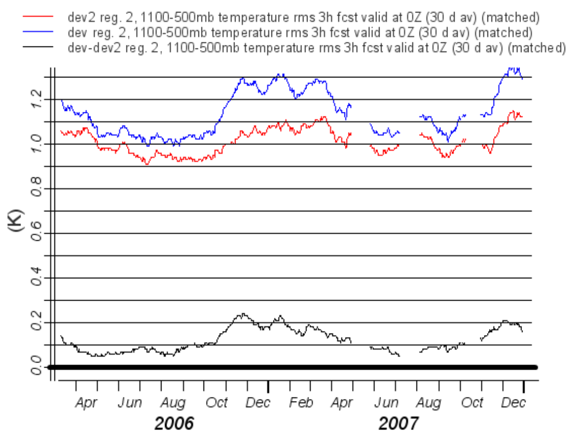

Fig. 2. Time series of 3-h temperature forecast errors (RMS difference from 00 UTC RAOBs) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red), and dev-dev2 difference (black). For the Great Lakes region, in the layer between the surface and 500 hPa. Mid-Mar 2006 – Dec 2007; 30 day running averages. Positive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

Figure 2 shows TAMDAR impact on temperature forecasts. The RMS temperature shows the common seasonal variation with larger values in winter and smaller in summer when the lower troposphere is more commonly well mixed with a deeper boundary layer (also seen in the fall-winter of 2005/06). TAMDAR impact is greatest during winter, when RUC (and other model) temperature errors in the lower troposphere are larger. We consider only 00 UTC RAOBs because this is the time when we expect to see the maximum TAMDAR impact, given the schedule (11-03 UTC, primarily daylight hours) of the TAMDAR Mesaba fleet.

Figure 3 shows a vertical profile of temperature RMS for dev and dev2 3-h forecasts for the time period indicated. The dev2 RUC has lower errors for all levels between the surface and 450 hPa. The maximum RMS error difference between dev and dev2 occurs at 950 hPa and is about 0.5 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 1.3 K (the difference between the ~1.8 K RMS shown for dev in Fig. 3 at 900 hPa and the 0.5 K analysis fit). Thus **TAMDAR data result in about a 35% reduction in 3-h temperature forecast error at 900 hPa**.

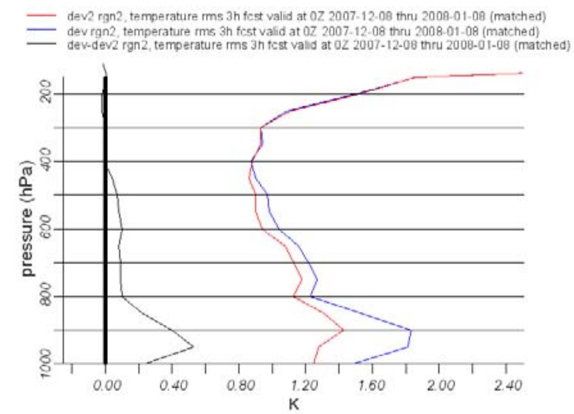

Fig. 3. Vertical profile of 3-h temperature forecast errors (RMS difference from 00 UTC RAOBs) for dev (no TAMDAR, blue) and dev2 (TAMDAR, red), and dev-dev2 difference (black). For Region 2 (Great Lakes), 8 Dec 2007 to 8 Jan 2008.

3.2 *Wind*

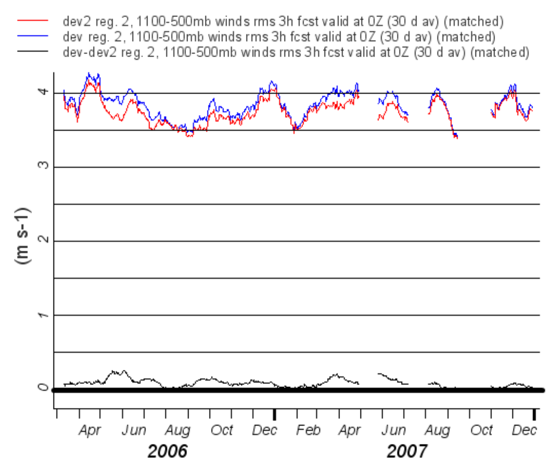

Fig. 4. as for Fig. 2, but for 3-h wind forecasts

Figure 4 shows TAMDAR impact on winds for the 21 months, averaged over the surface-500 hPa layer. The impact is small but consistently positive. TAMDAR-Mesaba wind errors are greater than those of the traditional AMDAR jet fleet because the quality of the heading information from the Mesaba turboprop aircraft is lower than that found on jets flown by most major airlines (Moninger et al. 2007a). Heading information is a critical variable for calculating winds aloft.

Figure 5 shows the corresponding vertical profile. The TAMDAR impact on winds shows a broad peak between 700-950 hPa, with a maximum at 950 hPa. At this level, the RMS reduction due to TAMDAR is about 0.25 m/s. This represents about **a 15% reduction in 3-h wind forecast error due to TAMDAR** since the analysis fit to RAOB winds is about 2.2 m/s in this altitude range.

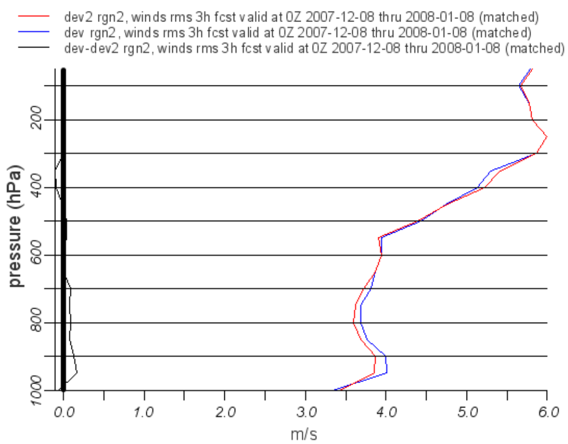

Fig. 5. as for Fig. 3, but for 3-h wind forecasts.

3.3 *Relative Humidity*

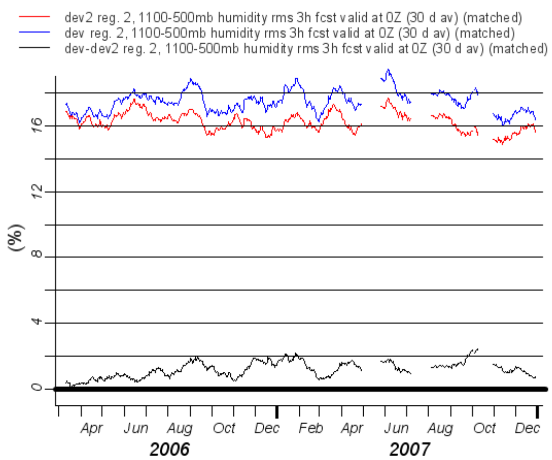

Fig. 6. as for Fig. 2, but for 3-h Relative Humidity forecasts.

Figure 6 shows TAMDAR impact on RH for the past 21 months. The impact is generally between 1 and 2 %RH when averaged between the surface and 500 hPa. We note that the recent RH impact is somewhat less than it was in September 2007, and so we look at two vertical profiles, one for September 2007 and one for a month starting 8 December 2007.

Figure 7 shows the September vertical profile. The RH impact is seen to be relatively uniform between 850 and 550 hPa—the general altitude range in which TAMDAR flies, and is 1-2%.

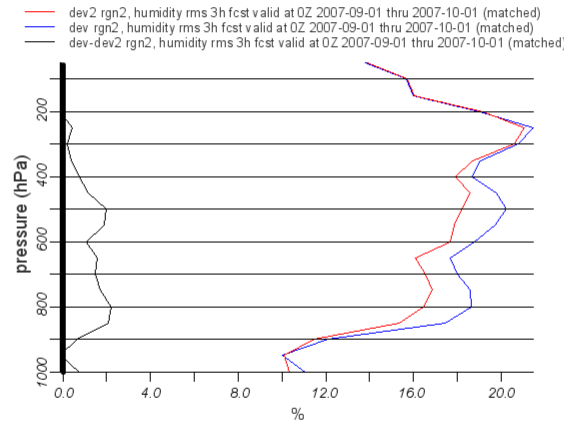

Fig. 7. as for Fig. 3, but for 3-h Relative Humidity forecasts, and for 1 Sep – 1 Oct 2007.

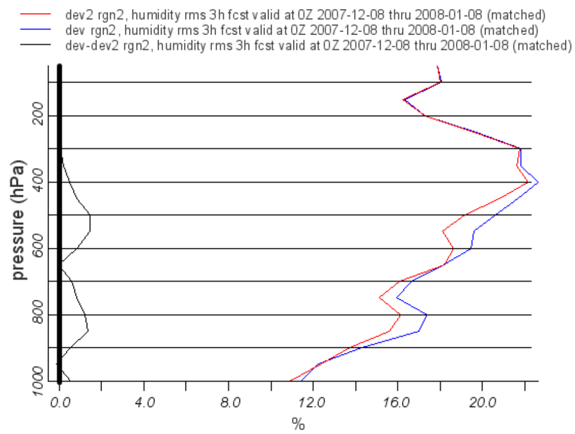

Fig. 8. as for Fig. 7, but for 8 Dec 2007 — 8 Jan 2008.

Comparing Fig. 7 with Fig. 8 shows that the RH impact is somewhat less in December 2007 than in September 2007 (as seen in Fig. 6), and less uniform with altitude. Nonetheless, even the December impact is notable.

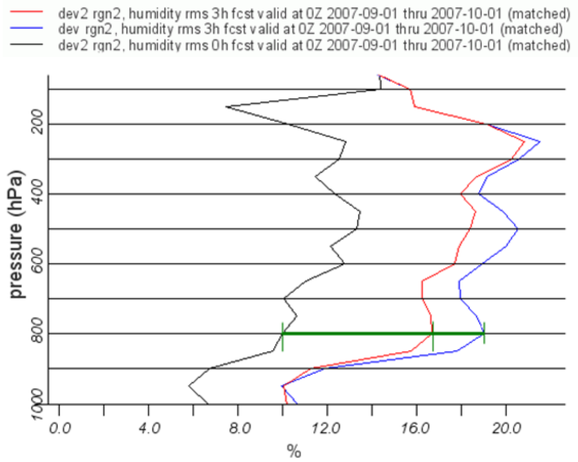

Fig. 9. dev2 RH *analysis* RMS difference (black) with 0 UTC RAOBs in the Great Lakes region, 21-Jan through 21-May 2007, along with dev (blue) and dev2 (red) 3-h RH forecasts. The green line indicates the differences between dev 3-h fcst, dev2 3-h fcst., and dev2 analysis errors at 800 mb.

Figure 9 shows the *analysis* fit for RH for the same temporal and spatial region, along with the same dev and dev2 3-h forecast errors shown in Fig. 7. The RMS for the analysis varies between 5 %RH at 950 hPa and about 11 %RH between 750 and 400 hPa. Thus, the 1-2% reduction in RMS due to TAMDAR moves the 3-h RMS about 15-25% of the way to the analysis fit (as indicated by the green line), so represents **a reduction in 3h RH forecast error of 15-25%**.

4. TAMDAR-PENAIR ERROR CHARACTERISTICS

GSD has been receiving TAMDAR-PenAir data since early October 2007. These aircraft are Saab-340 turboprops—the same platform used by the TAMDAR-Mesaba fleet. However, the avionics may not be identical between the two fleets and, because PenAir flies at higher latitudes than Mesaba, which can potentially affect the accuracy of heading information, we expect error characteristics to differ between the two fleets.

Because Alaska is outside of the current RUC domain, until recently we have had to rely on RAOBs for comparison with the TAMDAR-PenAir fleet. Section 4.1 discusses some of these comparisons. Recently, we have developed the capability to compare TAMDAR (and other AMDAR observations) with GFS forecasts. We discuss these comparisons in section 4.2.

Figure 10 shows TAMDAR-PenAir flights for a typical day.

. 4.1 *TAMDAR-PenAir comparisons with RAOBs*

We have performed several comparisons between TAMDAR soundings and RAOBs since October 2007, mostly with the Anchorage RAOB (ANC), but also with the RAOBs at King Salmon (AKN), Dutch Harbor (DUT), and Prudhoe Bay (PDU). We present a small subset of these comparisons here. More may be found at http://amdar.noaa.gov/docs/.

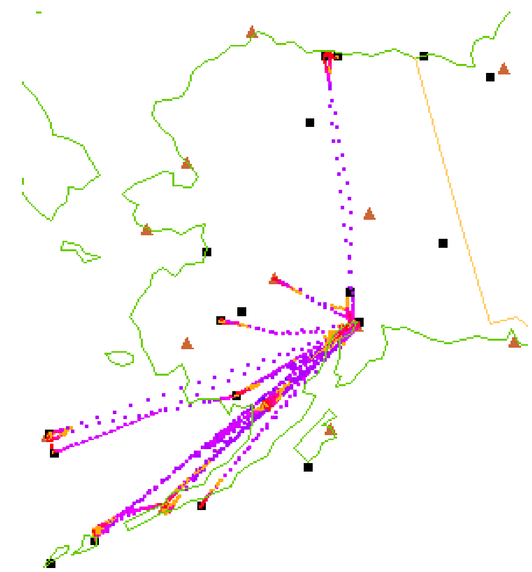

Fig. 10. TAMDAR-PenAir observations for 9 Jan 2008. Airports are indicated by black squares; RAOB sites by gold triangles.

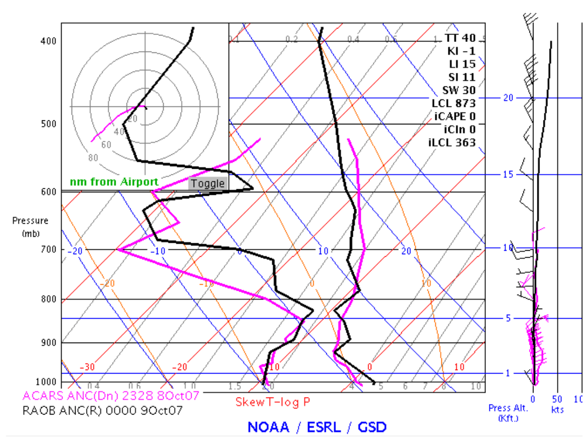

Fig. 11. TAMDAR descent sounding at Anchorage (violet), and the 00 UTC 9 Oct 2007 RAOB (black). Flight tracks for aircraft and the balloon are shown in the upper left.

Figure 11 shows a TAMDAR descent into Anchorage that landed at 2328 UTC 8 October 2007, along with the 00 UCT 9 October 2007 RAOB (launched at about the time the aircraft landed). The flight track of both the aircraft and the RAOB are shown in the upper left (though the RAOB dewpoint trace crosses over this). The RAOB flight track is very short (in the horizontal) and shows up as a black dot near the origin because winds were light.

Agreement between TAMDAR and the RAOB is generally good for both temperature and dewpoint, although the RAOB reports somewhat more moist conditions between 780 and 680 hPa, and a slightly higher surface temperature. TAMDAR shows higher winds (20 kts) at 950 hPa than is reported by the RAOB (0 kts). At least in this case, differences can easily be attributed to mesoscale atmospheric variability.

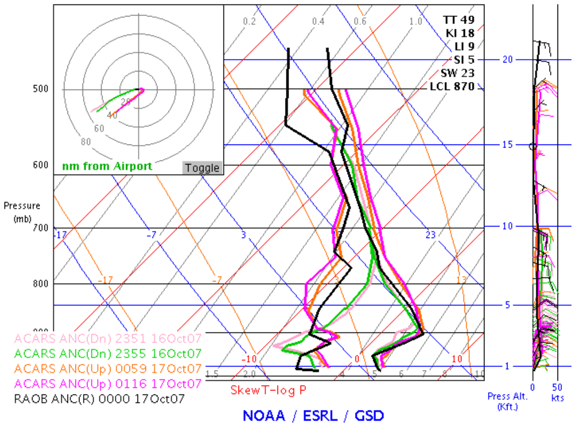

Fig. 12. TAMDAR ascent and descent soundings at Anchorage, and the ANC 00 UTC RAOB; 17 Oct 2007. Flight tracks for aircraft and the balloon are shown in the upper left.

Figure 12 shows soundings for several TAMDAR ascents and descents at Anchorage, along with the RAOB. All soundings occur within +/- 1¼ hour of the 00 UTC RAOB time.

All of the TAMDAR soundings agree reasonably well with the RAOB temperature. There is less agreement in the dewpoints. The descent ("Dn") soundings (green and pink) have higher RH than the RAOB or the ascent ("Up") soundings (gold and violet) at mid levels. Both descents show near saturation above 750 hPa. We cannot tell if these soundings are more moist because of instrument errors during the descent, or because of true meteorological differences. The descent soundings are 64 to 85 minutes earlier than the ascent soundings. The ANC METAR station was reporting broken clouds at this time; certainly passage through a cloud during the descents could account for this difference.

Figure 13 shows a case from King Salmon, (AKN) in which a TAMDAR aircraft—which provided both a descent and ascent sounding—corrected the RAOB surface temperature. (The low-level temperature/dewpoint reported by the aircraft (3-4/2.1-2.2 ºC) agrees far more closely with the METAR report (3.8/2.2 ºC) than does the RAOB (8.6/8.6 ºC).

In general, the great majority of the TAMDAR soundings we compared with RAOBs in Alaska agree well with RAOBs, or have differences that are likely due to mesoscale spatial and temporal variations.

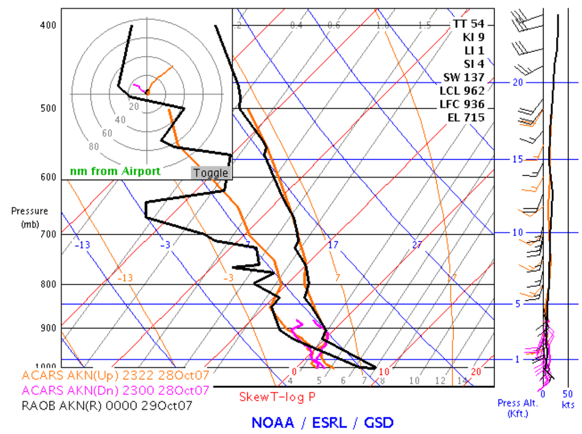

Fig. 13. TAMDAR ascent and descent soundings at King Salmon (AKN), and the AKN 00 UTC RAOB; 29 Oct 2007.

4.2 *TAMDAR-PenAir comparisons with GFS forecasts*

Moninger (2007a) reported in detail on differences between TAMDAR-Mesaba data and RUC 1-h forecasts. Unfortunately, TAMDAR-PenAir data are outside the RUC domain. So to perform a similar evaluation in Alaska, we have recently begun to accumulate statistics of differences between TAMDAR-PenAir data and GFS 3-h forecasts. Forecast values are interpolated in space to the observation location. Only data that are taken within +/- 60 minutes of the valid time of the GFS forecast are used in the comparison. Since the GFS runs 4 times per day, and one of these runs is at night when PenAir seldom flies, we make TAMDAR-PenAir comparisons at 03, 15, and 21 UTC +/- 1 hour.

The GFS is a global model, designed to produce forecasts out to 16 days. It is a spectral model, with an effective grid size of approximately 35 km. This can be contrasted with the RUC dev/dev2 models (see section 2) that update every hour, and have a 20-km grid size.

Because of the different model characteristics, different time-match criteria (+/- 60 min for the GFS vs. +/- 30 min for the RUC), and different forecast projections (3-h for the GFS vs. 1-h for the RUC) (Moninger, 2007a), we don't expect agreement to be as close between aircraft observations and GFS forecasts as with the RUC. Moreover, all models forecasts have errors and we consider neither the RUC nor the GFS to be the "truth". Nonetheless, the GFS can provide a common background with which we can compare different kinds of measurements over Alaska.

a. Temperature

Before comparing the GFS with aircraft data, it is worth seeing how well the GFS matches RAOBs. Because GFS 3-h forecasts are never valid at RAOB times, we compare analyses and 6-h forecasts with RAOBs in Fig. 14.

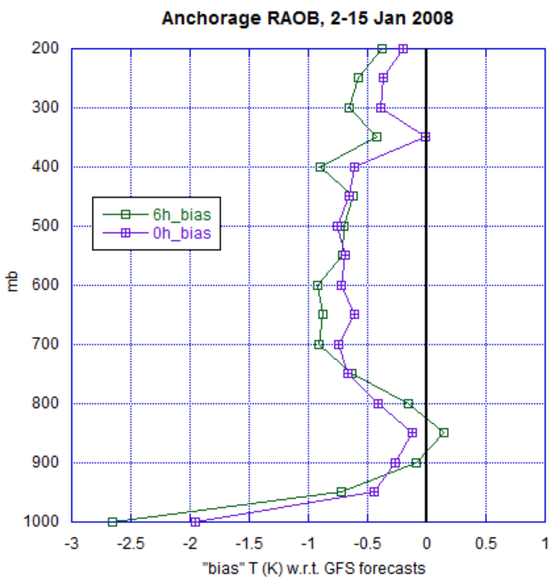

Fig. 14. Temperature "bias" (RAOB minus model) for analyses (purple) and 6-h forecasts (green) for the GFS compared with the Anchorage RAOB 2-15 Jan 2008.

The RAOB shows a substantial cool "bias" with respect to the GFS near the surface for both analyses and 6-h forecasts, and at and above 700 hPa has a cool bias of 0.5 – 1 ºC. Of course this is traditionally viewed as a (warm) model bias, since the RAOB is traditionally taken as "truth".

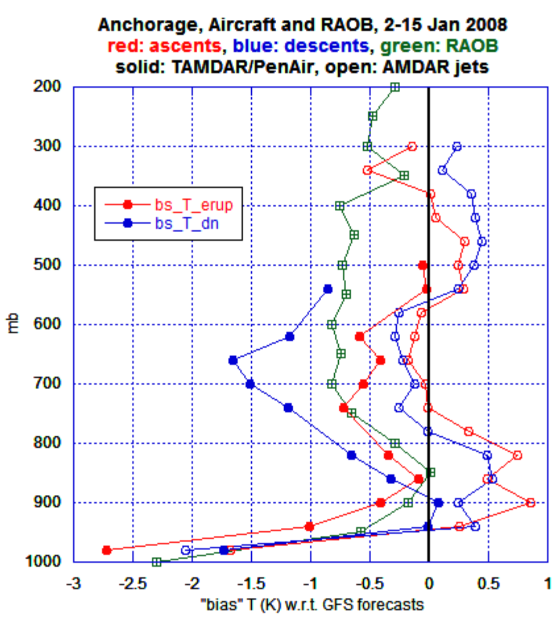

Fig. 15. Average temperature differences (observation minus GFS forecasts for AMDAR jets (open circles), TAMDAR-PenAir (solid circles), and RAOBs (squares), 2-15 Jan 2008.

Figure 15 shows observation minus model temperature differences between aircraft/RAOB and GFS near Anchorage for a 13-day period in January 2008. Open circles show statistics for AMDAR jet aircraft; closed circles are for TAMDAR-PenAir aircraft. Red curves show data taken during ascents; blue curves show descents. These curves show statistics with respect to GFS 3-h forecasts. The green curve in this and subsequent figures shows the average of the RAOB data with respect to 1) the GFS analysis and 2) the GFS 6-h forecast (shown individually in Fig. 14).

At low levels, the substantial bias shown by both AMDAR jets and PenAir is consistent with substantial near-surface bias in the RAOB, suggesting that the GFS is forecasting too warm near the surface, and that the aircraft are measuring consistently with the RAOB. Above 950 hPa, TAMDAR actually tracks the RAOB bias better than traditional AMDAR jets do, but descents are cooler than ascents. AMDAR jets have a bias closer to zero, but further from the RAOB bias. For both AMDAR and TAMDAR, temperature measurements taken during descent are generally lower than those taken during ascent.

Regarding the substantial cool bias shown by TAMDAR descents between 750 and 600 hPa, it is worth noting that this is a relatively small data set for TAMDAR, with as few as 33 data points in some of these altitude ranges for descents. So, these early results should be taken with some caution.

These results suggest that TAMDAR/PenAir temperature data are at least as accurate as those from AMDAR jets in an average sense.

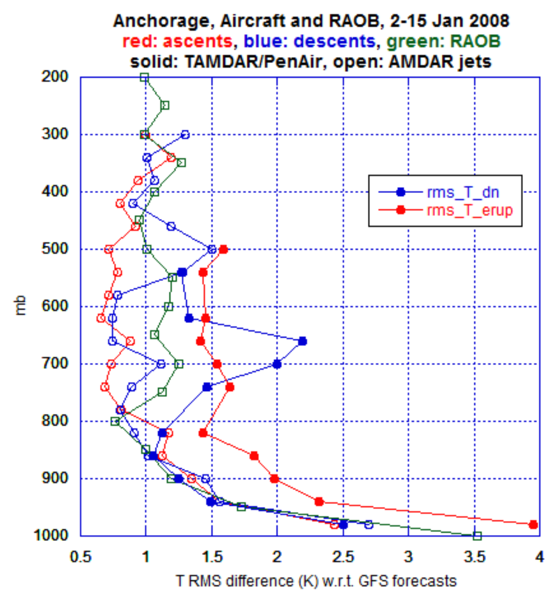

Fig 16. As for Figure 15, but for temperature RMS difference.

Figure 16 shows RMS differences for temperature (TAMDAR-PenAir and RAOB vs. GFS). The large RMS near the surface is attributable to the apparent GFS bias mentioned earlier. The large RMS difference for TAMDAR descents at 660 hPa *may* be a statistical fluctuation due to the small amount of data (33 observations), but the additional 34 observations at 700 hPa also show high RMS difference and provide some corroboration. In general, TAMDAR shows somewhat higher RMS temperature differences with the GFS than either the RAOB or AMDAR jets, for this limited data set.

b. Wind

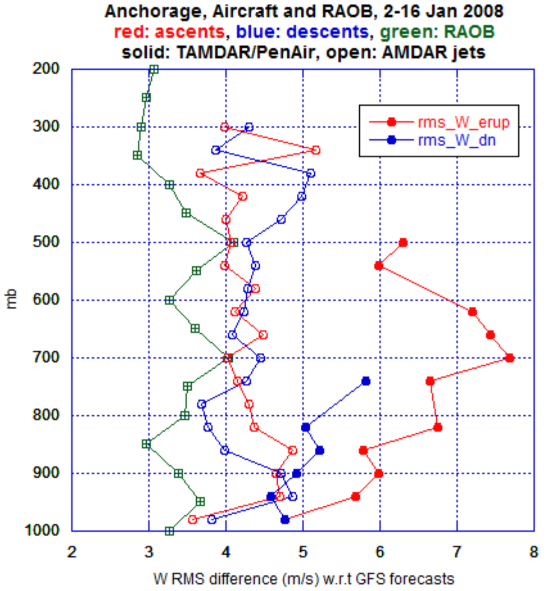

Fig 17. As for Fig. 16, but for wind RMS difference.

Figure 17 shows RMS vector wind difference. A particularly poor (over Alaska) GFS forecast (3-h, valid at 21 UTC 15 January 2008) has been removed, along with two TAMDAR-PenAir aircraft that occasionally reported spurious wind values. TAMDAR ascents show considerably higher RMS difference with GFS forecasts than is shown by AMDAR jets, likely due to the larger heading errors from the Saabs than from AMDAR jets. There are too few TAMDAR descent reports above 740 hPa to produce reliable statistics. At and below 740 hPa, TAMDAR-PenAir descents show lower RMS differences than ascents do, in contrast to what we have seen with the Mesaba fleet (see below)—but these statistics are based on few data, so we take these results with caution.

To put these results in perspective, we performed a similar comparison in the Great Lakes region. (We have reported on similar comparisons before (Moninger et al. 2007a), but these used the RUC rather than the GFS.) Figure 18 shows this. As in Alaska, TAMDAR turboprops show higher RMS wind differences than do jets. But in the Great Lakes region we have sufficient descent data to see that TAMDAR wind errors on descent are greater than on ascent. We await further data to see whether this remains true in Alaska with the PenAir fleet.

AMDAR jets have wind error characteristics similar to RAOBs above 750 hPa. Below that level, both TAMDAR and jets show higher RMS difference than RAOBs. But this might be true variability not captured by the twice-a-day RAOBs.

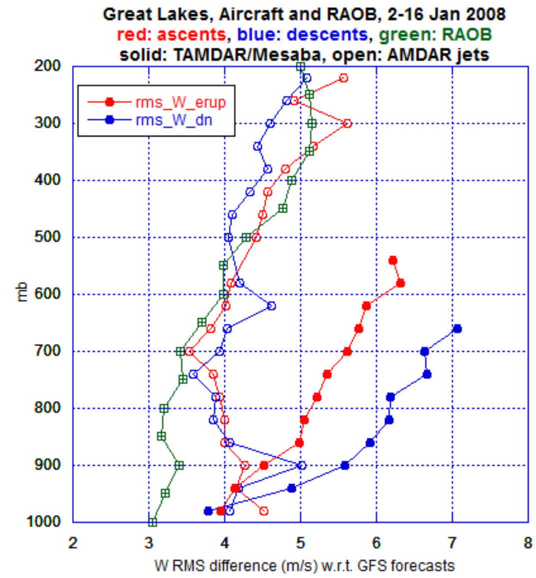

Fig 18. As for Fig. 17, but for the TAMDAR-Mesaba fleet and the Great Lakes region.

c. Relative Humidity

Since AMDAR jets generally do not measure relative humidity—and none do in Alaska—we cannot perform similar comparisons between jets and TAMDAR-PenAir for RH. However, we can compare TAMDAR RH with RAOB RH. Figure 19 shows RH "bias" (observation minus GFS) for TAMDAR and the Anchorage RAOB.

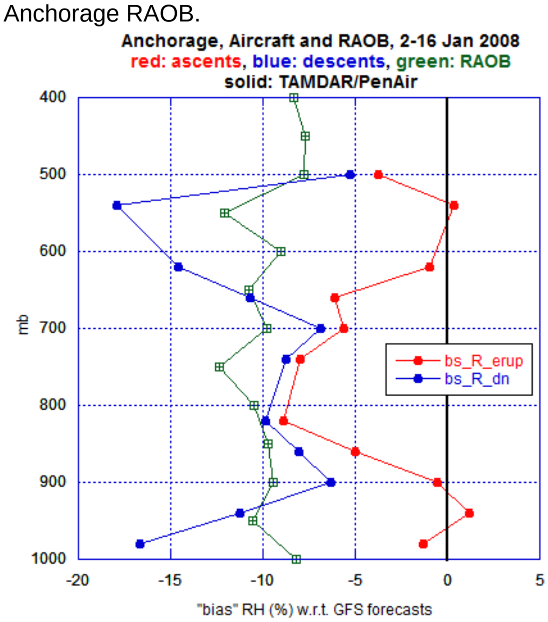

Fig. 19. RH "bias" (observation minus model) for TAMDAR ascents (red) and descents (blue) for 2-16 Jan 2008 near Anchorage, and for the Anchorage RAOB.

The RAOB "bias" varies between -8 and -12 %RH in the altitude range in which TAMDAR flies. This is generally consistent with the TAMDAR descent bias. However, the TAMDAR bias differs between ascents and descents, with the descents generally showing a drier bias than the ascents. We encountered this same bias difference between ascents and descents earlier (January 2006) in the Mesaba fleet. In that case, AirDat was able to identify and fix the problem within two months.

For comparison, Figure 20 shows the same statistics, but for the TAMDAR-Mesaba fleet in the Great Lakes region. In this case, the ascent RH bias closely follows the RAOB bias—suggesting that TAMDAR-Mesaba ascents measure RH as faithfully as do RAOBs. But the TAMDAR-Mesaba descents are drier below 750 hPa and more moist above.

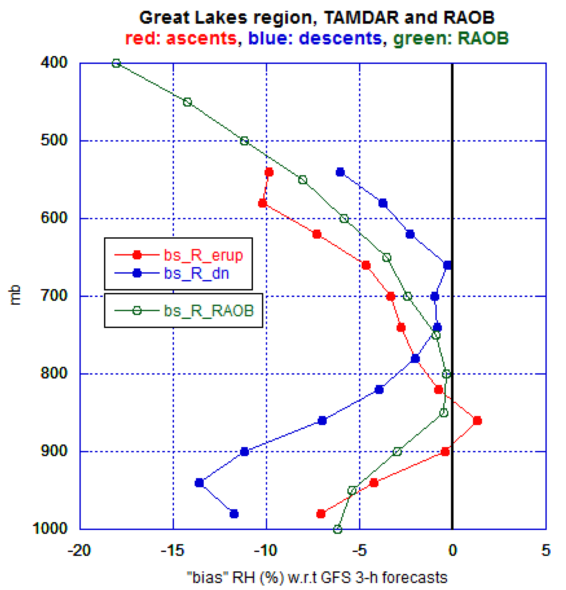

Fig. 20. RH "bias" (observation minus model) for TAMDAR ascents (red) and descents (blue) for 2-16 Jan 2008, and for RAOBs (green, w.r.t GFS analyses), in the Great Lakes region.

Finally, we look at RMS RH. Figure 21 shows this for Anchorage, with TAMDAR ascents and descents shown in red and blue respectively, and the Anchorage RAOB shown in green. The TAMDAR ascents generally have slightly lower RMS than the RAOB. The TAMDAR descents show somewhat higher RMS difference.

In general, TAMDAR-PenAir appears to measure relative humidity well.

5. SUMMARY AND A LOOK AHEAD

The TAMDAR sensor provides meteorological data on a regional scale over the US Midwest and Alaska. In the Midwest, we have evaluated the impact of TAMDAR-Mesaba's wind, temperature, and relative humidity data on the RUC model with real-time matched TAMDAR and no-TAMDAR runs for the past 3 years. In Alaska, we have compared new TAMDAR-PenAir with RAOBs and with the GFS model.

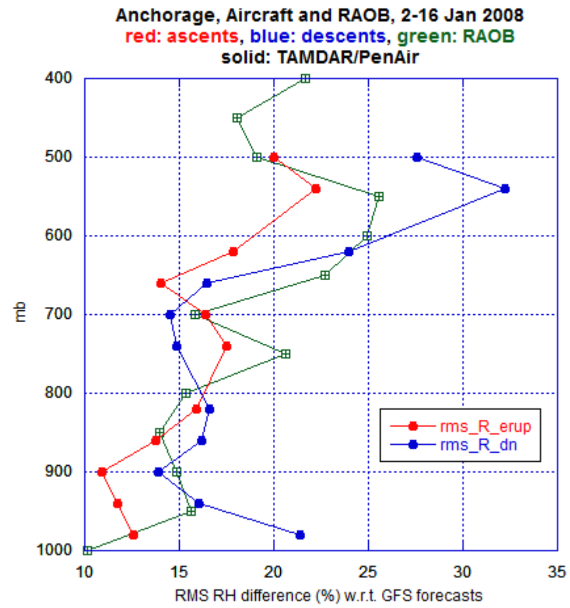

Fig. 21. As in Fig. 19, but for RMS RH difference.

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

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

As a result of these and internal NWS studies, NWS contracted with AirDat in the summer of 2007 to provide TAMDAR-Mesaba data to the federal government as an operational data stream for at least a year. These data will begin to be ingested into operational NWP models run at NCEP within a few months.

In Alaska, the TAMDAR-PenAir data are considered experimental, but AirDat has agreed to continue to provide these data to ESRL/GSD, and to the Alaska Region of the NWS for evaluation.

Over the next several months, TAMDAR will also be deployed on additional fleets, covering the western and southern US. These fleets will include jet aircraft, which will expose the TAMDAR sensors to higher altitudes and higher speeds than they have been exposed to thus far. Data from these new fleets will be made available by AirDat to ESRL/GSD so that we can evaluate the quality of the data and the impact of these new fleets and expanded coverage on weather forecasts.

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