TAMDAR and MDCRS Impact on RUC forecasts

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1. Introduction

At the request of the FAA, we have performed, and are now reporting on, the impact of MDCRS, TAMDAR, and AMDAR (TAMDAR and MDCRS combined) on RUC forecasts of temperature, relative humidity, and wind. This is an extension of two earlier studies in which the impact of TAMDAR and AMDAR were assessed (Benjamin et al., 2010, and Moninger et al., 2010). To put the results of this experiment in perspective, we will repeat here some of the results reported in our earlier studies.

Our studies involved running the RUC multiple times, with different data suites withheld, over two 10-day experiment periods: a winter period and summer period. The winter period (26 November – 5 December 2006) was synoptically active in the northern United States, especially in the upper Midwest and Great Lakes area. The summer period (15-25 August 2007) was chosen because it included considerable intense weather in the Great Lakes region.

Our specific verification region (the "Great Lakes region") is the red rectangle shown in Figs. 1 and 2. There are 13 verifying RAOBs in this region (14 are shown, but only 13 reported data).

Figs. 1 and 2 show typical late-day coverage of TAMDAR and MDCRS, respectively, in the summer experimental period, for the region below 400 hPa where most TAMDAR turboprops fly. The data are color-coded by altitude.

2. Experiment design for observation impact experiments (This section was adapted from Benjamin et al, 2010)

For each RUC experiment, residuals (forecast minus observed (f-o) differences) for temperature (T), relative humidity (RH), and wind (V) were computed at all 13 reporting RAOB locations within the verification domain. These f-o residuals were calculated for 3-, 6-, and 12-h forecasts. The rms (root mean square) difference between forecasts and observations was computed for each 12-h RAOB verification time (00 and 12 UTC). This difference is sometimes referred to below as 'forecast error', or 'RMSE', but in fact also contains a contribution from observation error (including representativeness "error" from the inability of a grid to resolve sub-grid variations sometimes evident in observations).

In the following results, increase in forecast error from denying a given observation type can be considered equivalent to the added forecast skill when that observation type is added to other existing observations. Benjamin et al. (2004) explain this procedure.

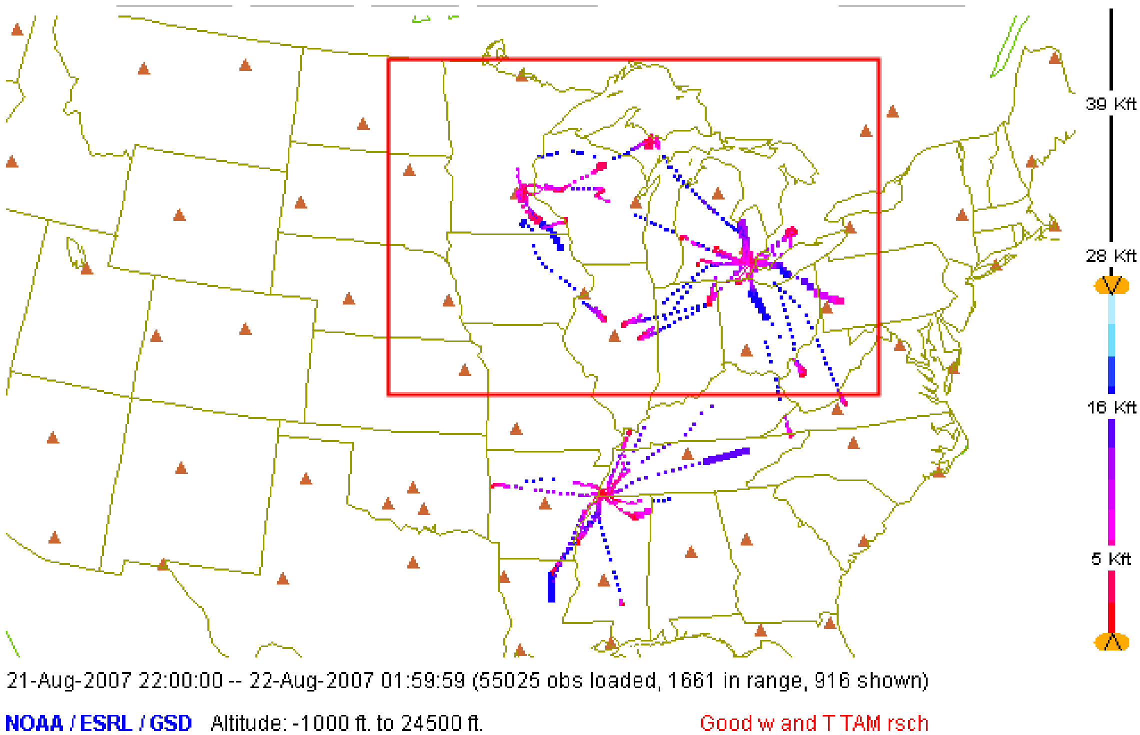


Fig. 1. TAMDAR data below 400 hPa for 00 UTC 22 Aug 2007 +/- 2 hours. The "Great Lakes Region" is indicated by the red rectangle; verifying RAOBs are shown as brown triangles.

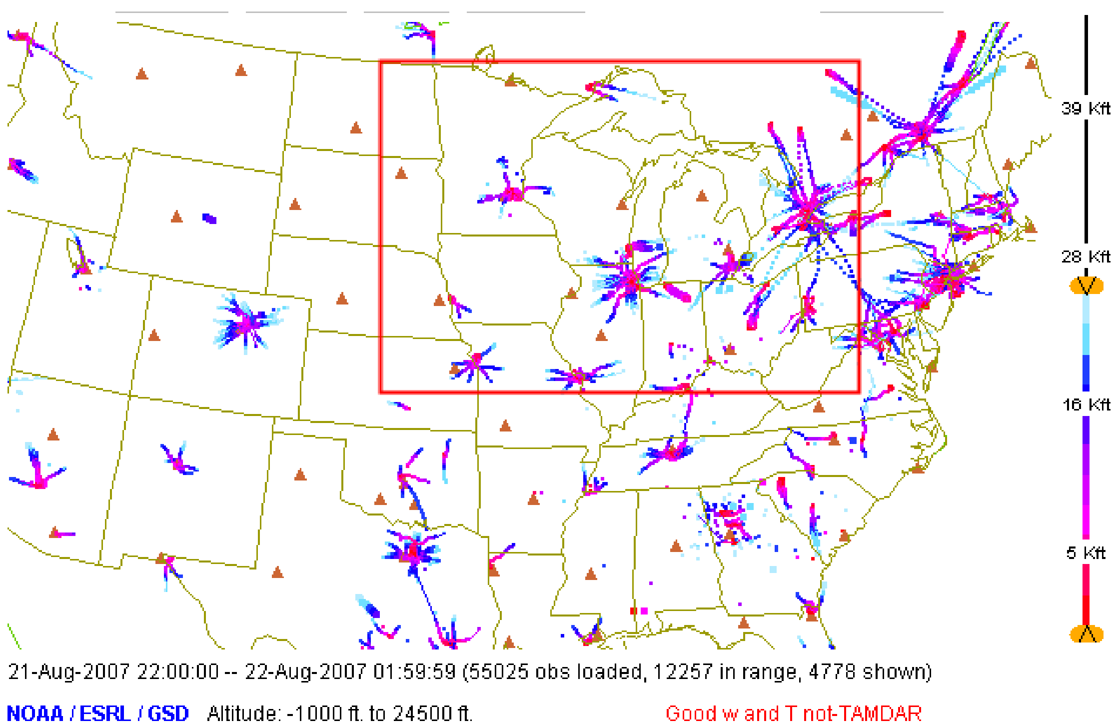


Fig. 2. As in Fig. 1, but for MDCRS data.

Verification in this paper uses 10-hPa vertical resolution, including significant-level RAOB observations and native model levels interpolated to that resolution, for calculating f-o differences using a verification capability explained in Moninger et al. (2010). This high vertical resolution of forecast errors allows clearer attribution of differences to physical mechanisms than does verifying against RAOB data only at mandatory levels (e.g., 850, 700, 500, 400, 300, 250, 200, and 150 hPa), and also increases the number of verifying observations by using RAOB significant levels.

For quality control of RAOB data used in verification, f-o values from the control experiment were subjectively screened for egregiously large values and removed when found. While some erroneous values may have escaped detection, the accepted values were used uniformly in verifying all experiments and therefore do not affect the relative impacts shown below.

2.1 Control experiments, and consistency between previous and current experiments

Each observing system experiment (OSE) compares a data denial run in which all data from a given data suite are withheld over the entire RUC domain, with a control run in which all data are included. The MDCRS data denial run occurred after the computer ("ijet") on which the other OSEs had been performed was decommissioned. Therefore, we performed the no-MDCRS run on a new supercomputer, "wjet". To be sure results were consistent between the two computers, we ran additional runs duplicating runs previously done on ijet (control, no-AMDAR, no-TAMDAR). Differences between corresponding control or data denial runs were larger than could be expected from round-off error alone. However, careful analysis of output from the runs revealed that round-off error (an expected difference between the old and new computers) caused slightly different observations to fail quality control, and the difference in the assimilated observations caused the unexpectedly large differences in the forecast results. However, the differences between corresponding runs on the old and new computers were in every case substantially less than the differences between data-denial runs and their corresponding (summer or winter) controls. Therefore, we believe the comparisons between our previous OSEs and the new ones are valid.

3. Relative Humidity forecasts

We present results here in a similar fashion to that used in Benjamin et al., 2010. **Bar graphs show the difference between the RMSE for each forecast when an indicated observation suite is removed, minus the RMSE of a control run that assimilated all observations. The height of each bar may be taken as a measure of the impact of that observation suite on the indicated forecast.**

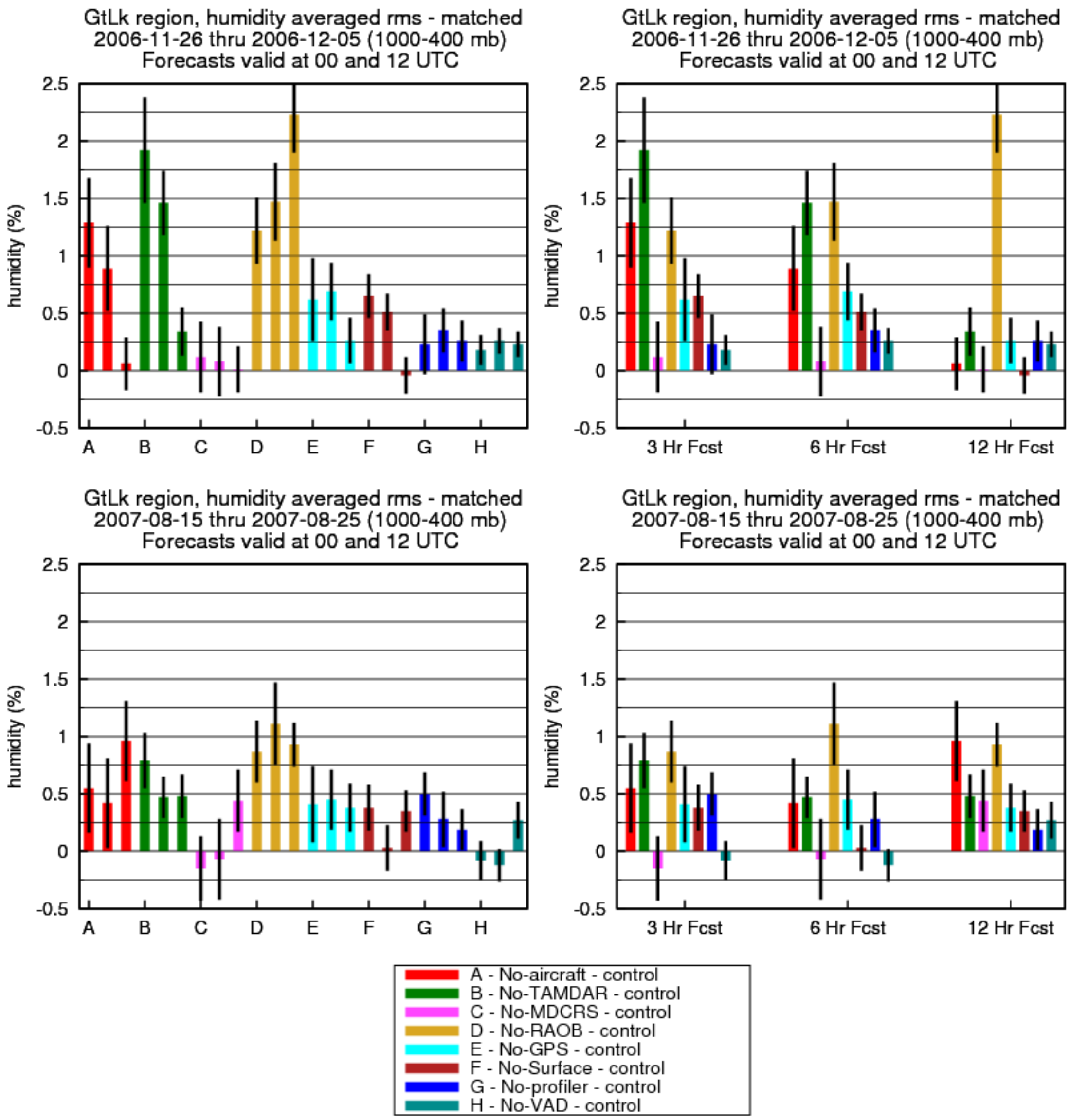


Fig. 3 Differences in rms error (vs. RAOB) between observation denial experiments and control runs for 1000-400 hPa for relative humidity for the Great Lakes region. Results for each of the observational denial experiments are coded with a different color (aircraft – red, TAMDAR – green, MDCRS – pink, RAOB – tan, GPS – cyan, Surface – firebrick, profiler – blue, VAD dark cyan . For graphics at left, the three adjacent columns for each OSE are for 3-h, 6-h, and 12-h forecasts valid at 00 and 12 UTC. For graphs at right, the same results are organized by observation type for each forecast projection (3h, 6h, and 12h). Statistical uncertainties are indicated for each observation denial experiment by narrow black lines showing +/- 1 standard error from the mean impact. (See Benjamin et al, 2010, for more details.)

We include results from the no-AMDAR, no-TAMDAR, and no-MDCRS experiments to look in detail at the impact of different kinds of aircraft data; we include the other observations—covered in detail in Benjamin et al., 2010—to put the aircraft results in perspective.

In Fig. 3 and similar figures to follow, we present our results. We use different colors to depict results for each observation type.

The top plots in each figure show the winter retro period; the bottom plots show the summer period. In the left-hand graphs of each plot, the three adjacent columns for each experiment are for 3-h, 6-h, and 12-h forecasts, respectively. The right-hand graphs show the same information as that on the left, but organized by forecast projection to allow easier interpretation from that perspective.

The black bars indicate +/- one standard error from the forecast impact of each observation type. Differences of one standard error are significant at the 67% confidence level; differences of two standard errors are significant at 95%. That is, other experiments over different periods having similar climatology would have the indicated odds of yielding the same impacts. These errors do not include the impact of sampling a limited climatology of weather events (see section 5). (See Benjamin et al., 2010 for more details.)

Fig. 3 shows the impact of these data sources for RH forecasts of the indicated durations in the Great Lakes region. For instance, the left-most bar in upper-left plot of Fig. 3 shows that when AMDAR data (all aircraft data) are removed from the RUC, the 3-h RH forecast error between the surface and 400 hPa increases by approximately 1.3 +/- 0.4 %RH. Therefore, when AMDAR data are included, they *reduce* 3-h RH forecast errors in that region by ~1.3 % RH. This is more than a 3 standard error effect, and is therefore highly statistically significant.

The green bars show the impact of TAMDAR, and it may be seen that TAMDAR is responsible for most of the AMDAR impact on these 3h RH forecasts. In fact, MDCRS (pink bars) adds no value to RH forecasts in the retrospective periods, except for 12-h forecasts in summer. That TAMDAR makes a substantially greater impact than MDCRS on these particular forecasts is unsurprising, because MDCRS does not measure RH. (The few WVSS-II water vapor sensors—an alternative vapor sensor developed by a separate group—then flying were not ingested by the RUC.)

For 12-h forecasts, AMDAR makes no impact in the winter, but shows significant impact in the summer. This may be because fast-moving winter storms carried most of the impact of AMDAR observations out of the Great Lakes region within 12 hours. For the National region (shown in Benjamin et al., 2010), AMDAR's impact on 12-h forecasts is significant for both winter and summer.

For 3-h and 6-h forecasts, the impact of RAOBs (the only sensor besides TAMDAR measuring upper-air in-situ moisture) is similar to that from AMDAR and TAMDAR. However, comparison between RAOB and TAMDAR/AMDAR impact must be done carefully because most RAOBs are only available at 00 UTC and 12 UTC. Thus among the forecasts shown in Fig. 3, RAOBs were only included in the RUC analysis for 12-h forecasts. In this case, RAOBs have substantially more impact than AMDAR, TAMDAR, and MDCRS during the winter, and more impact than TAMDAR and MDCRS separately during the summer. The impact of RAOBs on the other forecasts shown is indirect—only through the hourly cycling of the RUC. Nevertheless, RAOBs generally have at least as much impact as AMDAR on 3-h and 6-h RH forecasts in the Great Lakes region.

The other vapor-sensing observations, GPS-Met (integrated precipitable water), and surface data (dewpoint reports from METARs and mesonets) also provide significant positive impact for most RH forecasts, although far smaller than the impact from TAMDAR (and AMDAR). In addition, non-vapor-sensing observations (profiler and Nexrad VAD winds) make a positive impact for most RH forecasts, evidently because the improved wind information they provide improves relevant horizontal transport and vertical motion fields in the model.

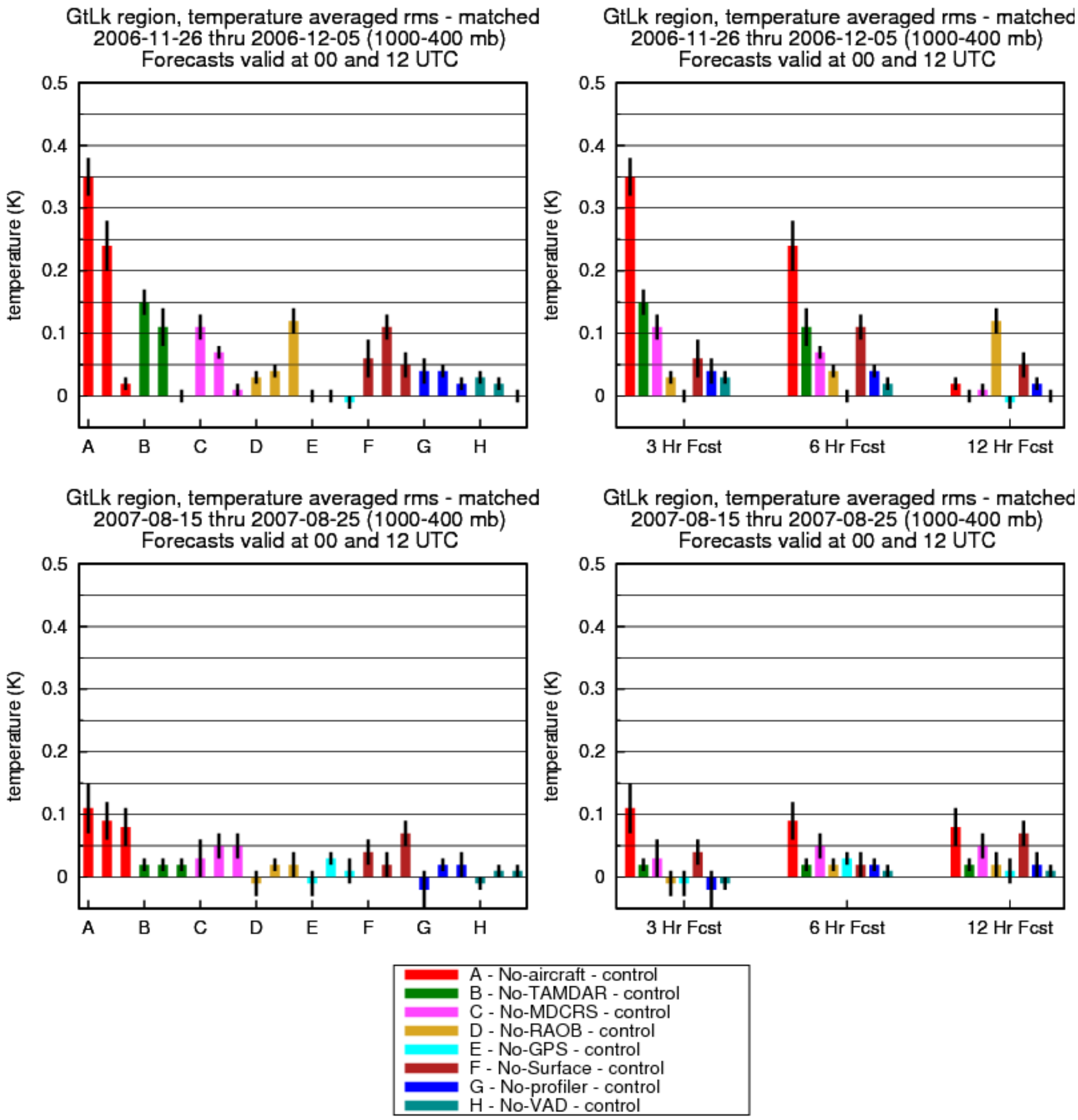


Fig 4. As in Fig. 3, but for temperature.

4. Temperature forecasts

For 3-h and 6-h temperature forecasts in winter (Fig. 4), both TAMDAR and MDCRS contribute to the substantial overall AMDAR impact. Removing *either* TAMDAR or MDCRS degrades the forecast. Evidently the regional coverage provided by TAMDAR complements the MDCRS data concentrated at hub airports, and the MDCRS data also complements the TAMDAR data.

In summer, impacts of AMDAR, TAMDAR and MDCRS are generally less, though still positive and generally statistically significant for temperature forecasts.

Surface observations also make a positive contribution to temperature forecasts in this low region of the atmosphere. And, as with aircraft, their impact is generally greater in winter than in summer.

Observations from profiler and VAD also make a significant impact on most temperature forecasts from 1000-400 hPa, though generally less than other data suites, and again less in summer than in winter.

5. Wind forecasts

For winds, most of the improvement in 3-h and 6-h forecasts is due to MDCRS. The TAMDAR impact is not statistically significant in summer, and in winter it is strongly negative for 12-h forecasts. MDCRS impact is not statistically significant at 12h in either season. Overall AMDAR impact is significant for 3-h and 6-h forecasts, but not at 12h.

Although TAMDAR provides no significant value added for short-term (3-h and 6-h) wind forecasts in summer, it does provide significant wind impact in the winter for these forecasts. TAMDAR wind impact is limited during this test period due to the relatively large TAMDAR wind errors (compared with MDCRS aircraft). These large errors are not caused by the TAMDAR sensor itself, but by the heading information provided by the SAAB turboprops in the Mesaba fleet upon which TAMDAR sensors flew in 2006-2007. These aircraft have less accurate heading information than do the jets that provide MDCRS data. (More recent TAMDAR wind data from sensors installed on regional jets with better heading information have been of much higher quality. Also, in October 2009 AirDat implemented a data correction that substantially improves the quality of wind information from the Mesaba aircraft. Although we have verified this improved wind information, we have not investigated the impact this may have on RUC forecast accuracy.)

It is important to note that over a longer (2.5 year) period, we have previously shown (Moninger et al., 2010) that TAMDAR's impact on 3-h wind forecasts, although small, is consistent and statistically significant. Specifically, TAMDAR reduces 3-h wind forecast errors by 0.09 ±0.01 m/s for forecasts valid at 00 UTC. (Fig. 6.) The TAMDAR impact on 12-h forecasts over the last 7 months of 2008 (the time period for which we evaluated real-time 12h forecasts, not shown) was slightly positive overall, reducing wind errors by 0.02 +/- 0.007 m/s. This suggests that the strongly negative TAMDAR winter impact shown in Fig. 5 is a climatological anomaly.

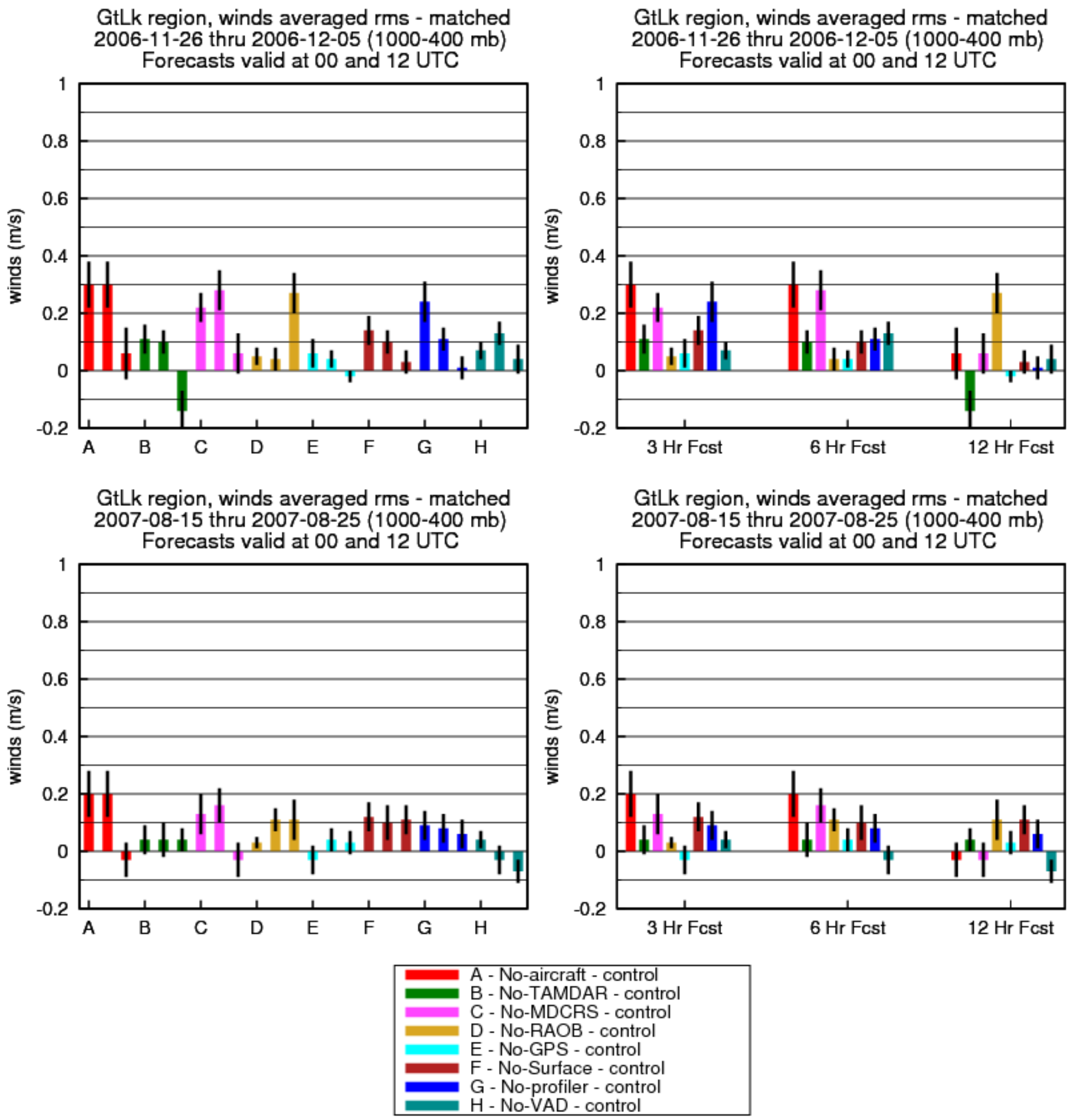
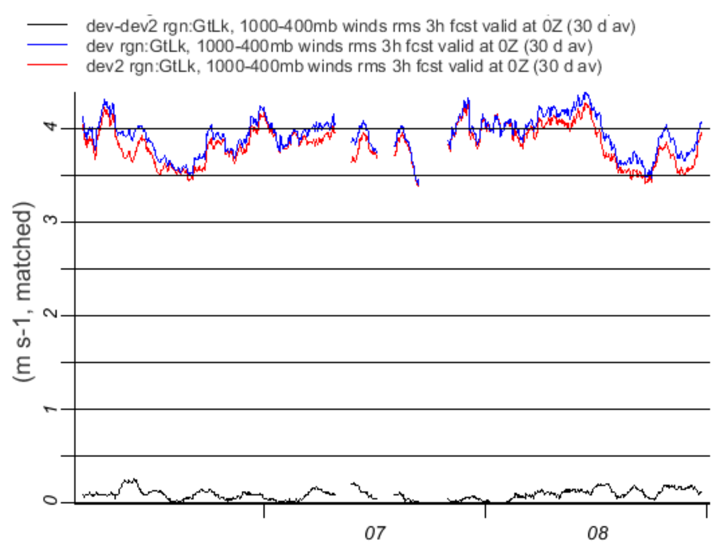


Fig 5. As in Fig. 3, but for winds.

Fig 6. Time series of 3-h wind forecast RMS error with respect to 00 UTC RAOBs in the Great Lakes region. “dev2” RUC cycle (TAMDAR – red), “dev” RUC cycle (no TAMDAR – blue), difference – black.



Surface data also generally make a positive impact in wind forecasts in the 1000-400 hPa layer, as do profiler data. The impact of GPS on wind forecasts is negligible, as one would expect for a sensor that does not measure winds.

Regarding the MDCRS impact on upper-level (400-100 hPa) wind forecasts, it is worth noting that at flight levels above 400 hPa, MDCRS has more impact than any other data suite for short-term (3-h and 6-h) forecasts in summer, and impact about equal to that of profilers in winter, as shown in Fig. 7.

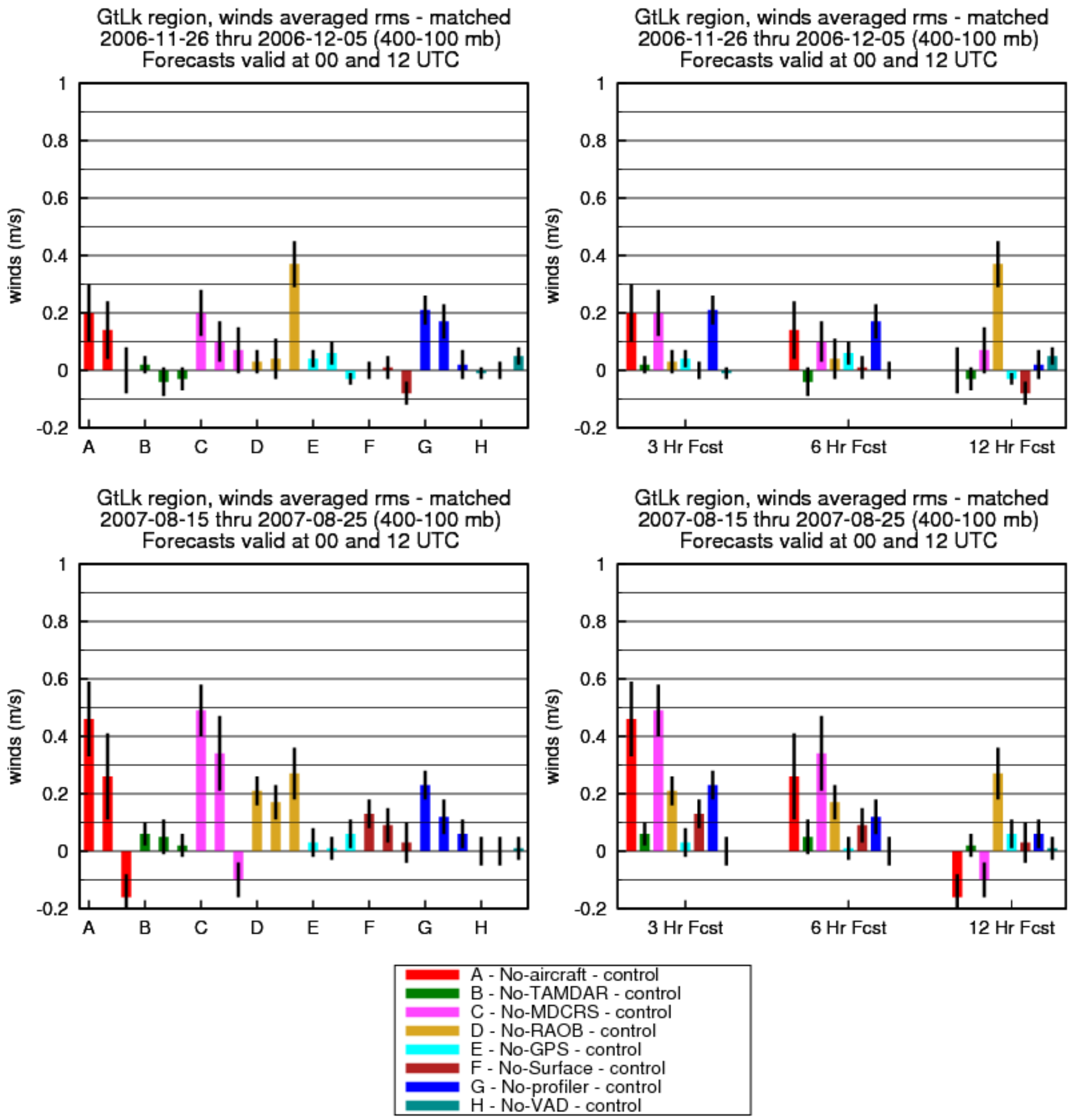


Fig. 7. As in Fig. 5, but for 400 – 100 hPa.

The zero or negative wind impact for MDCRS for 12-h forecasts is likely a result of the small size of the Great Lakes region. If we consider MDCRS impact nationally (Fig. 8), we see their impact is significant at all forecast projections (although small at 12-h in winter). Unsurprisingly, TAMDAR impact is negligible in the National region, because TAMDAR, at the time of these experiments, provided data only in and near the Great Lakes region and almost exclusively below 400 hPa.

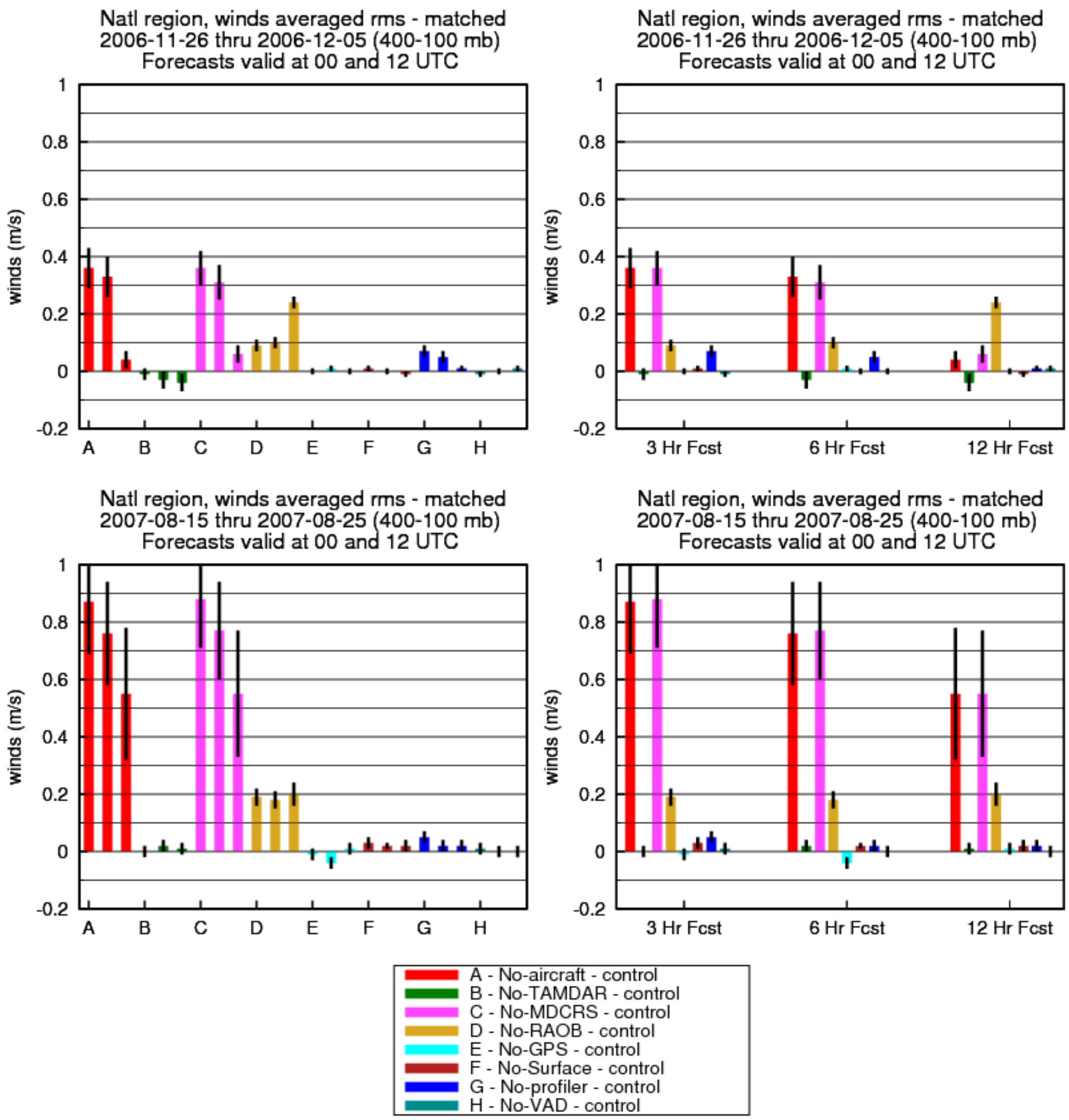


Fig. 8. As in Fig. 7, but for the National region.

6. TAMDAR wind-only impacts (adapted from Moninger et al., 2010)

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. 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 9. 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.

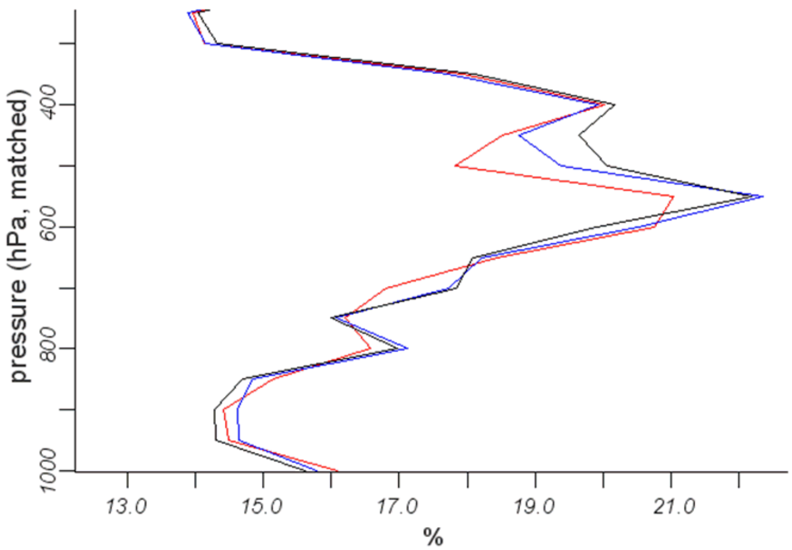


Fig. 9. 9-h RH forecast errors (RMS difference from 0000 UTC RAOBs) for the Great Lakes region, for the winter retrospective period, for three cases: Red: all-TAMDAR data, Black: no-TAMDAR data, Blue: TAMDAR wind and temperature data only.

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.

7. A Note of Caution

The Great Lakes region is small, and a 10-day experimental period is relatively short to capture a large range of weather systems. The climatology sampled is likely not representative of longer periods or larger areas. Thus, our results must be used with caution, and do not necessarily apply in larger domains and over longer periods.

To put this in perspective, we compare the wind forecast results over the entire depth of the atmosphere (1000 – 100 hPa) for the Great Lakes region (Fig. 10) and the entire RUC domain (Fig. 11). Note that the MDCRS impact on 12-h summer wind forecasts in the Great Lakes region is negative, but over the National region, it is strong and significant. It would be wrong to conclude from the small Great Lakes domain results alone that MDCRS data are not valuable for 12-h wind forecasts.

We cannot make similar comparisons for TAMDAR, because TAMDAR flew only in and near the Great Lakes domain in the time period we studied. TAMDAR-equipped aircraft now fly over much of the nation and parts of Mexico (Fig. 12). A similar relative impact study performed now would have much greater statistical significance.

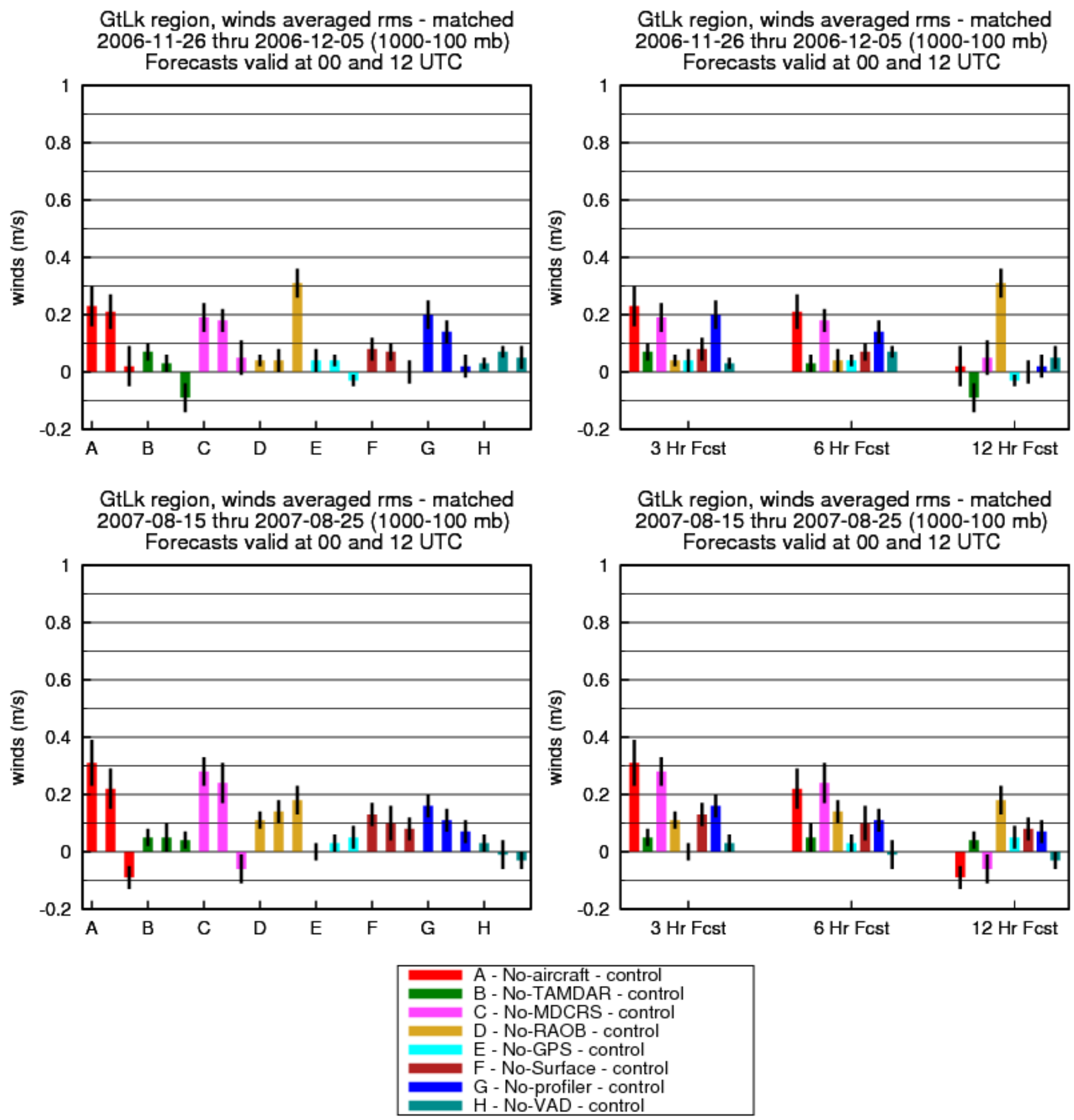


Fig. 10. As in Fig. 8, but for the Great Lakes region, and for 1000-100 hPa.

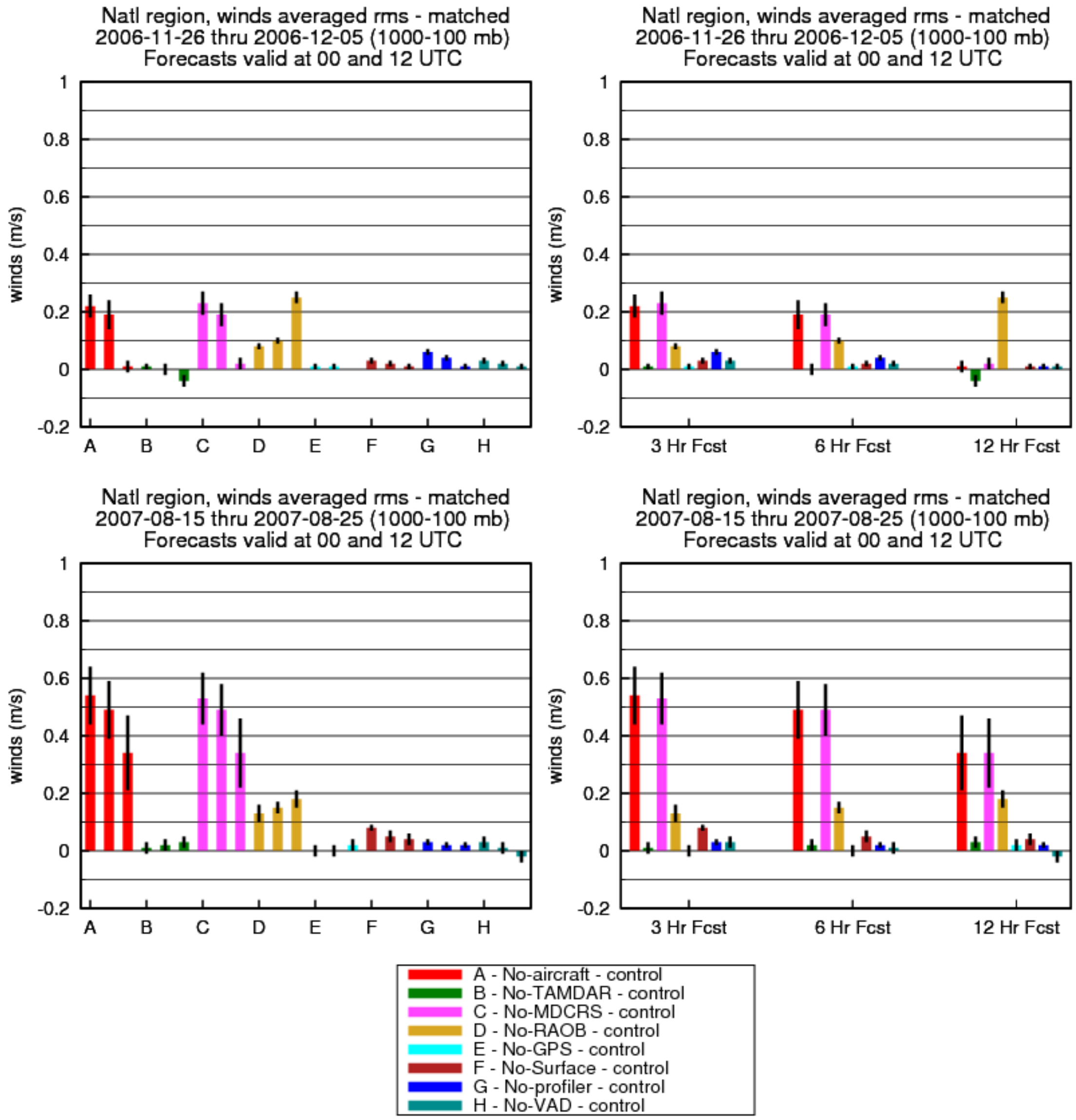


Fig. 11. As in Fig. 10, but for the National region.

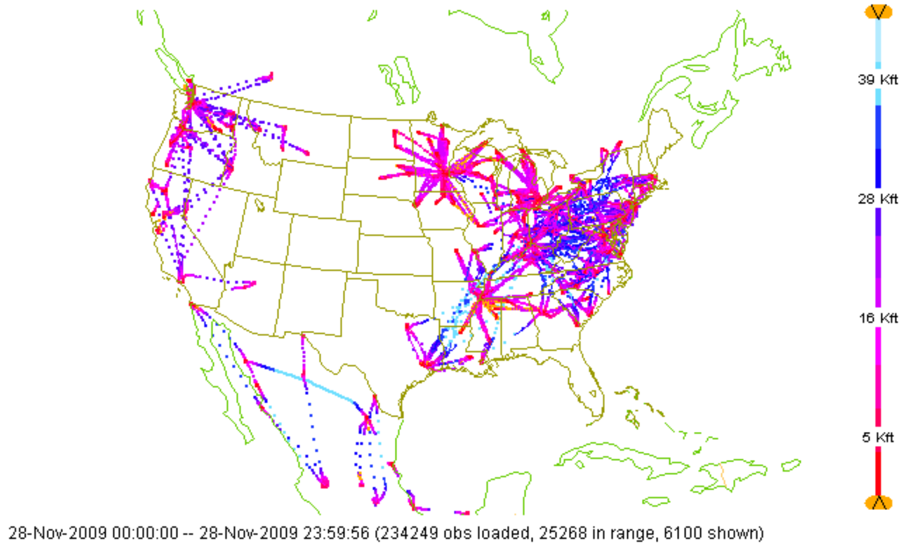


Fig. 12. Current TAMDAR coverage over the contiguous U.S. and Mexico.

8. Summary and conclusions

In summary, in the region, altitude range, and time period during which TAMDAR aircraft flew during the late fall and early winter of 2006 and summer of 2007, we get the following results.

- For 3-h and 6-h RH forecasts below 400 hPa, TAMDAR has a notable positive impact—much greater than the impact of MDCRS, and greater than all other data suites except RAOBs.
- For 12-h RH forecasts in summer below 400 hPa, both TAMDAR and MDCRS have significant impact; their joint impact is greater than the impact of either separately—equal to that from RAOBs, and greater than other data suites.
- For 3-h and 6-h temperature forecasts below 400 hPa in winter and summer, both TAMDAR and MDCRS provide significant impact. Their joint impact is greater than that from any other data suite.
- For 12-h temperature forecasts below 400 hPa, aircraft have little impact in the winter case, but do provide impact in summer.
- For 3-h and 6-h wind forecasts below 400 hPa, most of the impact of the aircraft fleet is due to MDCRS; TAMDAR has little impact in summer, but makes a significant impact in winter—about equal to that from surface data. Improved TAMDAR wind accuracy on new jet fleets, and 2009 improvements in TAMDAR turboprop winds argue that TAMDAR impact would be greater now.

In this study, which involves TAMDAR's Mesaba turboprop fleet in 2006-2007, TAMDAR's primary contribution is improving the accuracy of short-term forecasts of RH below 400 hPa, although it improves other forecasts as well—particularly winter temperature and wind forecasts. TAMDAR's impact on temperature and wind forecasts, over and above that of MDCRS, is likely due to the regional coverage it provides.

Short-term RH forecasts in the lower atmosphere are, of course, critical to public forecasts and to airport and aircraft operations. Therefore, we consider TAMDAR's contribution to improved model forecasts a valuable one. TAMDAR has additional substantial value by providing forecasters with *in-situ* soundings that provide vapor information.

Moreover, we have shown elsewhere (Moninger et al., 2010) that over a much longer time period (several years), TAMDAR has a notable—and statistically significant—impact on short-term RH, temperature, and wind forecasts.

9. Acknowledgements

We thank John Brown of GSD/AMB for his helpful meteorological insight and comments, Ed Szoke of GSD/FAB for choosing the retrospective periods used in this analysis, and Susan Sahm of GSD/AMD for her graphics and data processing programming.

References:

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

Benjamin, S. G., B.D. Jamison, W.R. Moninger, S.R. Sahm, B.E. Schwartz, and T.W. Schlatter, 2010: Relative short-range forecast impact from aircraft, profiler, rawinsonde, VAD, GPS-PW, METAR and mesonet observations via the RUC hourly assimilation cycle. *Mon. Wea. Rev*., **138**, Accepted for publication.

Moninger, W.R., S.G. Benjamin, B.D. Jamison, T.W. Schlatter, T.L. Smith, and E.J. Szoke, 2010: Evaluation of Regional Aircraft Observations using TAMDAR . *Weather and Forecasting*. Accepted for publication.