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# **6.11a** AMDAR OPTIMIZATION STUDIES AT THE EARTH SYSTEM RESEARCH LABORATORY / GLOBAL SYSTEMS DIVISION

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## 1. INTRODUCTION

Commercial aircraft now provide more than 130,000 observations per day of temperature and winds aloft over the contiguous US. The general term for these data is AMDAR (Aircraft Meteorological Data Reports). See, e.g., Moninger et al., 2003 for more information about AMDAR. These data have been shown to improve both short- and long-term weather forecasts.

Recently, additional atmospheric variables—water vapor, turbulence, and icing—have become available as well. While not yet ingested into numerical weather prediction (NWP) models, these new data are proving useful to weather forecasters.

The costs of gathering these observations (primarily communications costs) are large and will increase as the number of observations increases. Before 2004 the US airlines providing the data bore nearly all of these costs. Since then the U.S. government has begun paying 50% of the costs and in the future will be asked to cover a larger share. Moreover, new companies with new business models are offering to sell to the government data from sensors and communication systems that the companies control. The new TAMDAR (Tropospheric AMDAR) sensor system (Daniels et al., 2006) is an example of this.

As a result of these developments, there is considerable interest in finding the optimum number and spatial/temporal distribution of observations that need to be taken and transmitted (that is, purchased by the government) under various weather regimes.

The Global Systems Division (GSD) of NOAA's Earth System Research Laboratory has, under FAA sponsorship, completed a study to begin to determine the optimal amount of data needed. We approached this problem in several ways. First, we studied how human forecasters currently use AMDAR data directly in their bench forecasting. Second, we studied how GSD's Rapid Update Cycle (RUC) forecast skill changed as we varied the amount of AMDAR data ingested. Third, we have begun to develop a method to measure the sensitivity of individual RUC analyses to various data inputs. Finally, we are developing a proposed grid (RUC) based, three dimensional, "aircraft data need field", which might be used to "target" AMDAR observations to locations where those observations are expected to have the most impact on forecasts.

## 2. OPTIMIZATION GOALS

The goals of any data optimization program must be to maximize forecast skill while minimizing the costs of acquiring the data. Of course, data needs are different for different forecast problems. We have therefore developed a "taxonomy" of forecast problems and made estimates of the relative amount and kind of AMDAR data needed for each kind of forecast problem.

Moreover, NWP models have different requirements for input data than do human forecasters, and models of different scales (global, national, regional, and local) all have different requirements. In this study we have looked at the impact of AMDAR on only a national-scale model (the RUC) for 0- to 12-h forecasts at 20-km horizontal grid resolution.

Thus, there can be no single optimal density of data for AMDAR or any other data source; the required data density depends on what is to be forecast.

Here we present a start at, and a roadmap for, developing an operational knowledge of the optimal amount of AMDAR data in a variety of circumstances.

## 3. WORKING ASSUMPTIONS

In the US, AMDAR data are currently gathered by dozens of aircraft fleets operated by seven major airlines (American, Delta, Federal Express, Northwest, United, United Parcel Service, and Southwest). In addition, data from the TAMDAR sensor have been provided as a demonstration for the past year by AirDat, LLC.

Each of these fleets has different avionics and different capabilities for enabling/disabling the acquisition and transmission of AMDAR data. With the oldest avionics, a given aircraft can be enabled/disabled only at maintenance time; human intervention is required. Airlines have occasionally made this effort for meteorological reasons. For instance, UAL has "enabled" specific aircraft that typically fly into Phoenix during the months when high-pollution events are more likely to occur in order to provide local air-quality forecasters with helpful AMDAR data.

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Fleets with newer avionics provide greater flexibility. The newest avionics packages allow AMDAR data to be enabled/disabled while the aircraft is in the air. Individual flight phases (ascent, descent, en-route) can be enabled/disabled, as can the rate at which data are taken.

The primary thinning strategies used in this study (described in Section 5.3) presuppose that enabling/disabling individual flight segments can create a relatively uniform distribution of AMDAR data. Moreover the "aircraft data need field" discussed in Section 7 presupposes that this process can be done quickly enough to "target" higher-density AMDAR observations based on meteorological conditions.

## 4. TAXONOMY OF FORECAST TASKS BENEFITTED BY AMDAR DATA

Any optimization that decreases the amount of AMDAR data in a particular region may have negative effects on the local forecasting in that region. We therefore have studied the ways in which forecasters have used AMDAR data—including TAMDAR data.

These uses were examined and reported by Mamrosh et al. (2001) and others; we have extended that work because the amount of AMDAR data has increased since 2001, and because TAMDAR data, which include relative humidity, have been available for the past year.

The methodology used was to examine Area Forecast Discussions (AFDs), which are written by National Weather Service (NWS) forecasters for the general purpose of describing the reasoning behind their forecasts, as well as areas of particular concern or forecaster uncertainty. AFD's written over a period of several months that mentioned "AMDAR", "Aircraft", "AMDAR", "ACARS" or "TAMDAR" were analyzed.

The main limitation of this method is that we cannot conclude that forecasters who did **not** mention of AMDAR or its variants in an AFD did not use them. AFDs are a freeform type of discussion and there is no requirement that forecasters have to mention every type of information used. Indeed, it became apparent during this study that certain Weather Forecast Offices (WFOs) are very thorough in discussing all the data used, while other WFOs use the AFDs in a different manner. Given this limitation, our findings represent a **lower bound** on the use of AMDAR data by operational forecasts.

For each use identified, the operational meteorologist on our team (E. Szoke), using input from a limited survey of additional operational forecasters, has made an estimate of the amount and kind of AMDAR data needed to make an adequate forecast.

We have broken these uses into categories, with a particular emphasis on those forecasts most relevant to aviation.

### 4.1 Winds

#### 4.1.1 Upper level winds

This was the **most common use** of AMDAR, with the data used to fill in the large gaps between radiosonde data, and particularly where such data are absent, such as off the West or East Coasts, to better determine the strength of upper level jets. Forecasters often used the AMDAR data to examine whether a forecast **model was initialized correctly** in terms of jet speed, as well as to monitor how well the model forecasts of jet speed compared with reality. Plan views of the data on the workstation (AWIPS) used in National Weather Service forecast offices, typically overlaid with satellite imagery, are frequently used to assess the data.

- Needed data: AMDAR winds
- Needed data density: at least every 3 hours, with a vertical resolution of 50 mb (~5000 ft).

#### 4.1.2 Surface and low-level winds

A major forecast responsibility is maintaining accurate Terminal Aviation Forecasts (TAFs), and ascent/descent AMDAR soundings are often important and relevant for this purpose since they sample winds at the very site where the forecast is verifying. Forecasters used sounding displays to help them forecast surface winds. Since this type of display has not been available on AWIPS until recently, the GSD web display (Moninger et al., 2003) was used to display AMDAR soundings. Of particular interest was the **occurrence of strong surface winds**. The forecaster would look for such winds just above the surface, as well as use the temperature data to monitor the growth of the boundary layer to determine when the stronger above-surface winds might mix downward.

The increased horizontal coverage provided by TAMDAR fills gaps between the traditional AMDAR, profiler and VAD coverage in the lower troposphere. (VAD, or Velocity Azimuth Display, is a wind profile produced from radial velocity data acquired by WSR-88D radars.) This can be quite useful for making improved TAF wind forecasts, and in some situations gives enough information to include a warning of LLWS (low-level wind shear) in the TAF, especially for periods when the stronger winds get close to (but do not yet reach) the surface.

- Needed data: AMDAR winds and temperature. Humidity is helpful to monitor mixing-out of the inversion.
- Needed data density: at least every hour, with a vertical resolution of 15 mb (~500 ft).

#### 4.1.3 Validating Profiler winds

Migrating birds occasionally contaminate wind profiler measurements. An algorithm removes questionable profiler data (such winds may still be displayed on AWIPS using an alternative display), but forecasters questioning either the validity of the removed data or data that might have been missed by the algorithm can use the AMDAR data to compare to the profiler data wherever AMDAR ascent/descent soundings are reasonably close to profiler sites.

- Needed data: AMDAR winds
- Needed data density: dependent on the level. See the needed data densities for upper and lower level winds.

### 4.2 Low Clouds and Fog

4.2.1 Monitoring the Marine Inversion

Some of the more frequent users of AMDAR data are the WFOs at Los Angeles and San Diego, where the **marine inversion is often the main factor in determining the weather**. A strong marine inversion can lead to widespread low cloudiness and potential fog, affecting not only airport operations and TAF forecasts, but highly influencing the maximum temperature forecast and therefore general public forecasts. Forecasters at these Southern California WFOs have found the AMDAR data to be quite valuable for diagnosing the strength of the marine inversion and watching for changes over time. Again, the **high temporal resolution** (compared to the 12-h resolution for the nearest radiosondes) is a unique aspect of the AMDAR data at major airline hubs.

- Needed data: AMDAR winds, temperature and humidity.
- Needed data density: at least once per hour, with a vertical resolution of 5 mb (~150 ft) up to 6000 ft.

4.2.2 Fog

AMDAR was mentioned as a determining factor in forecasting whether fog will form in a number of instances. The presence or absence of lower level moisture in the TAMDAR data was helpful in both public and aviation forecasts, in deciding the chance of fog. Traditional AMDAR sounding data without humidity were also used to forecast fog, but assumptions were made about the moisture since only the temperature was available, so confidence in using the TAMDAR data is likely higher for fog forecasting.

- Needed data: AMDAR winds, temperature and, **critically, humidity**
- Needed data density: at least once per hour, with a vertical resolution of 5 mb (~150 ft) up to 3000 ft.

4.2.3 Low Ceilings

Critical to TAFs, better knowledge of the lower level moisture and temperature help with forecasting the formation and dissipation of low clouds, as well as better determination of the very important (for aviation) level where the clouds might form. One office in the TAMDAR region specifically mentioned that a decision to keep cloud bases above 5000 ft AGL in the TAF was based on the drier air in the TAMDAR soundings. **Depth** of low-level cloud layers, also important for forecasting possible burnoff of low ceiling, can be estimated from humidity profiles (but not from ceilometer data).

Offices have also used the AMDAR sounding data to monitor the low-level inversion to help determine when low clouds might clear.

- Needed data: AMDAR winds, temperature and, **critically, humidity**
- Needed data density: at least once per hour, with a vertical resolution of 10 mb (~300 ft) up to 5000 ft.

### 4.3 Precipitation

4.3.1 Precipitation Potential

Wind and temperature data, examined in the sounding mode, were used at times to look for **patterns of warm advection** that would indicate conditions more favorable for precipitation. TAMDAR data were sometimes used to forecast the start time of precipitation, which could be delayed if the boundary layer was dry.

- Needed data: AMDAR winds, temperature and humidity.
- Needed data density: at least once per hour, with a vertical resolution of 25 mb (~800 ft) up to 20,000 ft.

4.3.2 Orographic Precipitation

The Seattle WFO used low-level AMDAR winds to monitor the flow into the nearby mountains and the potential for orographic precipitation.

- Needed data: AMDAR winds, temperature and humidity.
- Needed data density: at least every 3 hours, with a vertical resolution of 15 mb (~500 ft) up to 10,000 ft.

4.3.3 Precipitation Type

The temperature soundings in the lower levels of the atmosphere are a unique measurement for locations without a nearby radiosonde, and even where radiosondes are available, the AMDAR data give **far better temporal resolution** than the 12-hourly soundings. This can be critical in certain situations such as determining the odds of snow vs. rain. In the case of possible freezing rain, **high vertical resolution temperature** data are essential for diagnosing layers of above-freezing temperatures.

Sometimes precipitation will begin as rain, with surface temperatures well above freezing, but change to snow as evaporation cools the column of air. This “wet-bulb cooling” effect can yield a snowstorm when rain might have seemed to be the more likely forecast. The cooling is greatest when the atmosphere is dry in lower levels, so that rain falling into this dry air can result in several degrees of cooling as the lower levels become saturated. Thus, measurements of both moisture and temperature in the lowest few km are critical to determine how much cooling will occur, if it is in fact occurring, and whether rain will change over to snow.

- Needed data: AMDAR winds and temperature. But in a "wet bulb cooling" situation, **humidity data are critica**l.

- Needed data density: at least every hour, with a vertical resolution of 10 mb (~300 ft) up to 7,000 ft.

### 4.3.4 Convective Potential

During the convective season temperature soundings are used to monitor the strength of a capping inversion. This can allow for much better short-range forecasts of the **timing of thunderstorm initiation** (important for TAFs) in locations where AMDAR soundings occur with sufficient frequency, or help a forecaster decide that thunderstorms will not form when the cap remains too strong or strengthens during the day. Knowledge of the depth of the surface-based moisture from AMDAR soundings that include humidity is critical to determine the true convective potential, and is not available except from radiosondes. This can work not only to increase the chance of precipitation when drier than expected air appears in the soundings, but also can delay the precipitation or lower the probabilities of convection.

Typically the forecaster uses the cap as determined by the closest morning radiosonde, perhaps updated by NWP soundings. AMDAR soundings provide real-time updates that can be compared to NWP soundings, and are especially important in **rapidly evolving environments**, as well as situations where important mesoscale changes are occurring on scales that the radiosonde network cannot resolve.

- Needed data: AMDAR winds, temperature and **critically, humidity**.
- Needed data density: at least every hour, with a vertical resolution of 10 mb (~300 ft) up to 5,000 ft.

### 4.3.5 Severe Weather Potential

When severe weather is possible, monitoring the capping inversion as noted above remains important. While some strengthening of the cap can result in a delay in convective initiation, it can also lead to stronger storms by increasing the amount of potential energy (CAPE) available. Low-level moisture is critical to accurate CAPE calculations. Typically forecasters calculate surface-based CAPE using updated surface conditions with an earlier applicable radiosonde, but this assumes that the surface dewpoint is representative of moisture in the lowest ~100 mb. Often it is not, and in such cases the real CAPE (true energy available for a storm) will be much lower than indicated by a surface-based calculation. AMDAR data with humidity information provide the missing lower level detailed moisture necessary for accurate calculations of CAPE, while the temperature data show how much low-level warming is occurring and hence how close conditions are to convective initiation.

CIN, or Convective INhibition, is the amount of energy needed to produce convective initiation. Moisture measurements are critical for accurately calculating CIN as with CAPE.

In addition to monitoring the capping inversion, forecasters are interested in monitoring the vertical wind shear, typically measured by calculating Storm Relative Helicity (SRH) over the lowest 3 km AGL. This is the calculation used with CAPE and CIN to determine storm type, because a balance of sufficient SRH and CAPE yields conditions that support organized supercell storms, while lower values would point toward less-organized, and possibly non-severe, storms. The **greater spatial resolution of AMDAR low-level winds** over radiosondes and profilers is quite useful for calculating SRH. (Interesting products could be made for display in AWIPS, including time-height wind displays, as is done with the current wind profiler network data, hodographs, and looping of standard SkewT displays.)

- Needed data: AMDAR winds, temperature and **critically, humidity**.
- Needed data density: at least every hour, with a vertical resolution of 5 mb (~150 ft) up to 6,000 ft.

## 4.4 Temperature

### 4.4.1 Maximum Temperature

By monitoring the low level temperature structure of the atmosphere with AMDAR sounding data, forecasters may adjust the expected high temperatures for a given day. For example, if the morning AMDAR data show a warming trend in the boundary layer, the forecaster might raise the expected high for the afternoon. Humidity data help determine whether clouds might form and lower the expected maximum temperature.

- Needed data: AMDAR temperature and humidity
- Needed data density: at least every two hours, with a vertical resolution of 10 mb (~800 ft) up to 10,000 ft.

### 4.4.2 Minimum Temperature

With the moisture data available from TAMDAR, there was some use to adjust the minimum temperature forecast, using the dryness of the lower levels to adjust the forecast for a colder night. Conversely, the presence of more moisture would mean that lower clouds might be slow to clear and hence keep overnight temperatures higher.

- Needed data: AMDAR temperature and humidity
- Needed data density: at least every three hours, with a vertical resolution of 10 mb (~300 ft) up to 10,000 ft.

## 4.5 Other Uses

### 4.5.1 Timing of Cold Front Passages

Some offices reported using AMDAR data in the timing of cold front passages, generally by using low-level data in plan view form.

- Needed data: AMDAR winds
- Needed data density: at least every three hours, with a vertical resolution of 10 mb (~300 ft) up to 10,000 ft.

4.5.1 Cold Air Damming

The low-level wind and temperature structure are critical to determining the extent of cold air damming (blocking by higher terrain), which can significantly alter precipitation and cloud forecasts. In addition, knowing the humidity structure and hence the stability of the air moving into a larger scale barrier, such as the Appalachians or Front Range of the Rockies, can help forecasters determine the potential for a cold-air damming situation to develop, or, when present, help determine its demise.

- Needed data: AMDAR wind and temperature
- Needed data density: at least every three hours, with a vertical resolution of 25 mb up to 10,000 ft.

4.5.2 Air Pollution Forecasting

Although not mentioned in the AFD's, several state air quality offices use AMDAR data in their work. They use the soundings to determine mixing depths, inversion height and magnitude, changes in temperature aloft, and ventilation index. They report that the information they derive from AMDAR is used as the basis for most of their forecasting products, including health watches and high pollution advisories. They report that they frequently mention the AMDAR data in their forecast discussions provided to the public (Reith, C. 2005, personal communication).

- Needed data: AMDAR temperature and winds
- Needed data density: as often as possible from 10-18 UTC and hourly thereafter, with a vertical resolution of 10 mb (~300 ft) up to 10,000 ft in the summer and 5,000 ft in the winter; and with coarser vertical resolution up to 18,000 ft.

## 5. SENSITIVITY OF THE RUC MODEL TO AMDAR

### 5.1 Past AMDAR Sensitivity Studies

Most of the major meteorological centers around the world that run either regional and or global data assimilation and forecast systems have performed Observation Sensitivity Experiments (OSEs) involving AMDAR data. Almost all of these aircraft denial experiments were performed by denying all of the observations in a particular region or altitude range, and comparing the analyses and forecasts to a run that contained all observations. **We were unable to locate any studies that performed the denial experiments based on *data density* or a systematic addition or reduction in the number of reports.**

Below are brief descriptions of the AMDAR studies most relevant to our study.

- Cardinali et al. (2003) at the European Centre for Medium Range Weather Forecasting performed a study in which all ascent and descent AMDAR data were removed over North America and Europe. They concluded that ascent/descent AMDAR data improve short range forecasts over North America, the North Atlantic region, and Europe, and improve medium-range forecasts over the North Atlantic, Europe, and the Arctic. Notably, they also concluded that the inclusion of AMDAR ascent/descent reports makes a *significant improvement in skill at day 8.*
- Benjamin et al. (2004a) of NOAA's Earth Systems Research Laboratory contrast and compare the impact of denying aircraft data and profiler data over a limited area domain (using RUC) and discuss the data density issue. They indicate that for most forecast projections out to 12-h, AMDAR data are the most important data source above 300 mb, with profilers generally being most important (at non-synoptic times) below that level.
- Petersen et al. (2004) at NOAA's Environmental Modeling Center studied the affects of removing AMDAR ascent/descent data in the RUC model. They concluded, among other things, that including the ascent/descent data improved 12-h forecasts of wind, temperature, and RH (even though the AMDAR data they studied did not include RH data) at all levels.
- Verner et al. (2004) of the Canadian Modeling Center performed aircraft data denial experiments two ways: first, by removing all AMDAR data, and then removing only temperature data, then only wind data. They concluded that AMDAR data are most important over North America and the Northern Hemisphere, but there is a significant impact in short-range forecasts in the tropics. Their results also indicate that there is usually more impact from the wind observations than from the temperature observations. However, temperature data have more impact on temperature forecasts than do wind data.
- Benjamin et al. (2006a,b) describe the impact of including TAMDAR data with all other AMDAR data over the US. They indicate that TAMDAR improves temperature and wind forecasts somewhat in the lower troposphere.

### 5.2 Time Period and Regions Chosen

We chose 22-28 April 2005 as our period of interest. This was a period with considerable unsettled weather, particularly over the U. S. Midwest. We chose an active week of weather across the nation so that the full potential impact of AMDAR data could best be assessed.

The dominant feature for much of the period was a deep closed upper-level low centered near the Great Lakes, downstream of a high-amplitude ridge extending across far western Canada southward into the Rockies. Upstream of the upper-level ridge a deep trough was positioned through much of the period off the West Coast, and the overall pattern allowed for systems emanating from the trough off the coast to move into the Rockies beneath the high-amplitude ridge and then amplify downstream on the south side of the deep Great Lakes closed low, often merging with a shortwave trough rotating around the Great Lakes system. Cold air was present with this pattern east of the Rockies, and especially over the Midwest and Great Lakes region, due to high pressure pushing south out of Canada.

The period begins with a deep cyclone moving into the Ohio Valley with the air cold enough for record-breaking snows in portions of Ohio. Widespread convective rain and snow showers follow this across the Ohio Valley through 24 April before the system pulls eastward. At the same time the first shortwave trough breaks off from the system off the West Coast and plows underneath the ridge, bringing widespread precipitation to the western states before moving across the rest of the nation as an extensive cold front. By the end of the study period the deep upper-level Great Lakes low lifts northward into southern Canada allowing the flow across the nation to become more zonal, setting up more of an east-west frontal system across the eastern two thirds of the nation, while the active weather resumes in the West as the trough that had hung off the coast finally moves into California.

Figure 1 shows the verification regions used. An additional region is the entire RUC domain, which extends off the East and West Coasts and into Canada and Mexico.

Forecasts valid at 00 and 12 UTC were validated against radiosondes at mandatory pressure levels. The entire RUC domain contains 99 radiosondes; the large domain 44; the small domain 14.

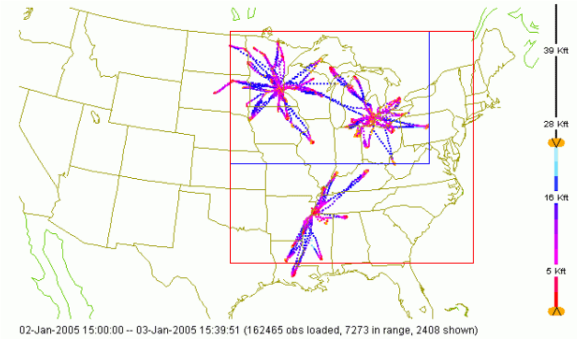

*Fig. 1. Large (red) and small (blue/red) verification regions, shown with a sample of TAMDAR data.*

### 5.3 Description of the Observation Sensitivity Experiments (OSEs)

We chose to vary the AMDAR dataset ingested in several ways:

- All AMDAR data. This dataset comprised 880210 observations during the weeklong study period.
- No AMDAR data
- No TAMDAR data. AMDAR data thinned to no more than one data point every 320 km x 320 km x 2000 ft every 12 hours. This data set comprised 28660 observations, or 3.2% of the total. We call this the **thin4** case.
- AMDAR data thinned to no more than one data point every 320 km x 320 km x 2000 ft every 6 hours above 20,000 ft, and every 3 hours below 20,000 ft. This dataset comprised 55582 observations, or about 6.3% of the total. We call this the **thin5** case.

Figures 2-4 show data for a typical 12-h period for the various thinnings described above.

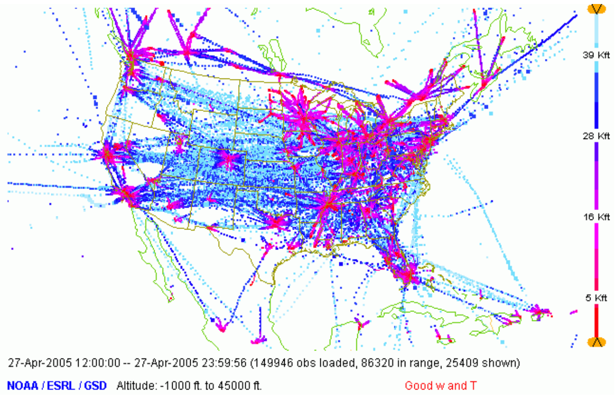

*Fig. 2. All AMDAR data, 1200 - 2359 UTC 27 April 2005. 86320 observations in range.*

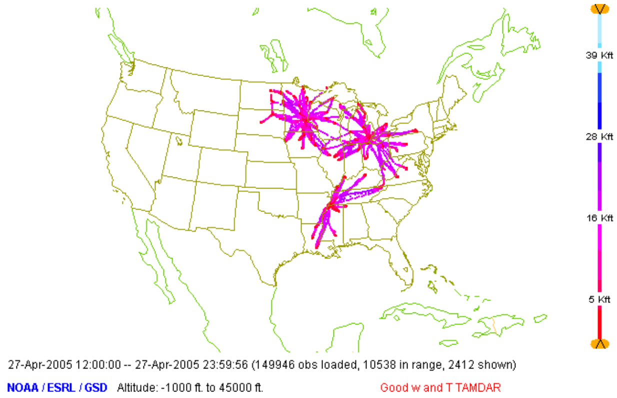

*Fig. 3. TAMDAR data, 1200 - 2359 UTC 27 April 2005. 10538 observations in range.*

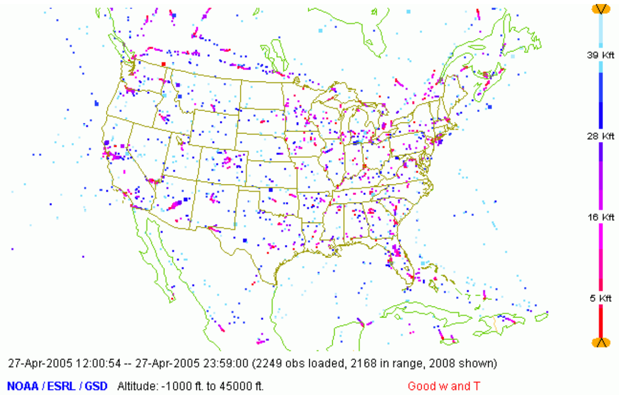

*Fig. 4. "thin4" case, 1200 - 2359 UTC 27 April 2005. 2168 observations in range.*

Figure 5 shows the vertical distribution of observations for the thin4 and thin5 case. The thin5 case has about three times as many observations as thin4 below 20,000 ft. We ran this case to explore a thinning which might begin to provide local forecasters with some of the temporal resolution they require for the forecast tasks discussed in Sec. 4, though we understand that the thin5 case provides **far fewer observations** than required for most of the forecast problems discussed.

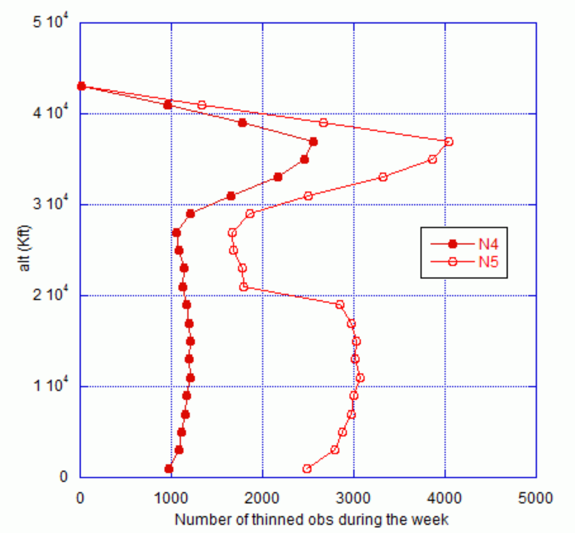

*Fig 5. Number of thin4 (N4) and thin5 (N5) observations during the study period.*

Figure 6 shows the vertical distribution of observations in the full dataset. Note the difference in the abscissa scale from Fig. 5. The full dataset has a much larger fraction of observations below 10,000 ft than do the thinned datasets because of the many high-resolution ascent soundings in the full dataset that provide data every 300 ft in the vertical.

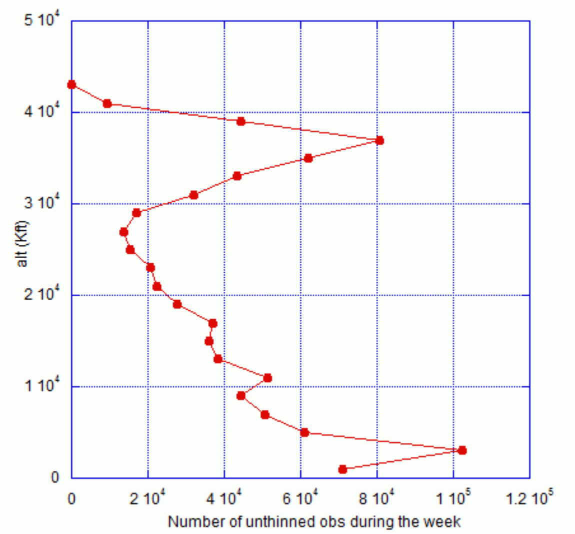

*Fig. 6. Number of all-AMDAR observations during the study period. Abscissa runs from 0 to 120,000.*

We recognize that the thinning strategies used in the "thin4" and "thin5" cases would be unfeasible to implement in practice, because they would require each aircraft's avionics to be aware of what data other aircraft had gathered and transmitted in the recent past. Nevertheless, we chose these strategies because they have the potential to give us meaningful information about the impact of well-defined data densities on the RUC.

We believe that, once a desired data density is determined for a particular forecast task and meteorological condition, and given knowledge of proposed flight schedules, individual flight segments could be enabled/disabled in ways that could approach the desired data density.

### 5.4 Results

The RUC ingests a wide variety of surface and upper-air data (Benjamin et al., 2004b); AMDAR is only one of many sources. Thus, the sensitivity of the RUC to AMDAR data may be relatively less than in other models that do not ingest so many disparate kinds of data. In our studies, AMDAR data were the **only** data varied; all other data sources were held constant.

We first look at RUC error characteristics when all AMDAR are ingested. Figure 7 shows RMS Vector Wind errors for RUC forecasts validated against RAOB data for the large region. These errors are consistent with what has been seen previously, as reported, for instance, in Benjamin, et al. (2004b). Errors are largest at jet stream levels where winds are largest and increase with longer forecast projections.

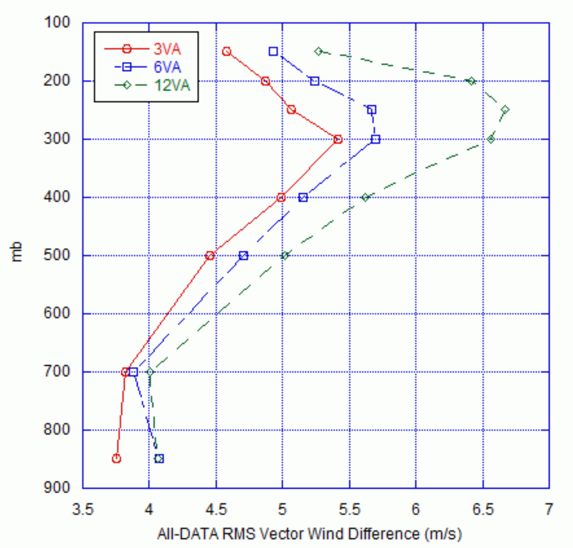

*Fig. 7. RUC wind forecast errors for 3-h (3VA), 6-h (6VA) and 12-h (12VA) forecasts, large region, all AMDAR data.*

Figure 8 shows RUC temperature errors for the large region. This double-peaked structure, peaking at low levels and again around 200 mb, is typical of what has been seen and reported before for other time periods and regions.

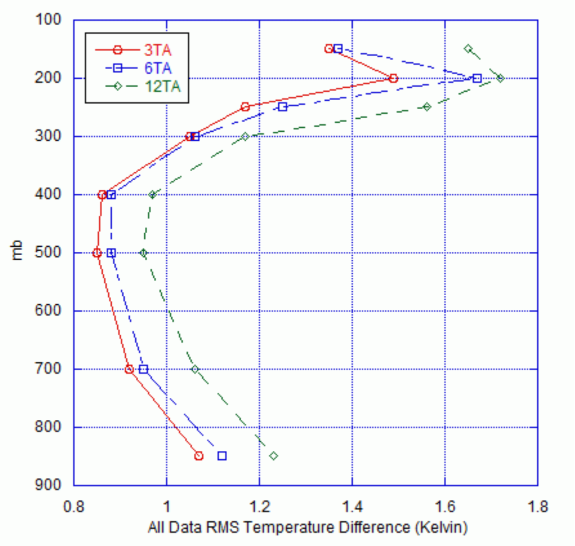

*Fig. 8. RUC temperature forecast errors for 3-h (3TA), 6-h (6TA) and 12-h (12TA) forecasts, large region, all AMDAR data.*

### 5.4.1 All AMDAR vs. No AMDAR

Figure 9 shows the **increase** in the wind errors shown in Fig. 7 when all AMDAR data are **removed**. The higher the abscissa value, the more the RUC forecasts degrade in the absence of AMDAR data, or conversely, the more AMDAR data help the RUC forecasts when they are included. Note that the AMDAR data are most beneficial at flight levels, where most AMDAR observations are taken. Fortunately, this is near the levels where RUC errors are greatest. The skill improvement due to AMDAR data decreases with forecast projection, from 3-h to 6-h to 12-h.

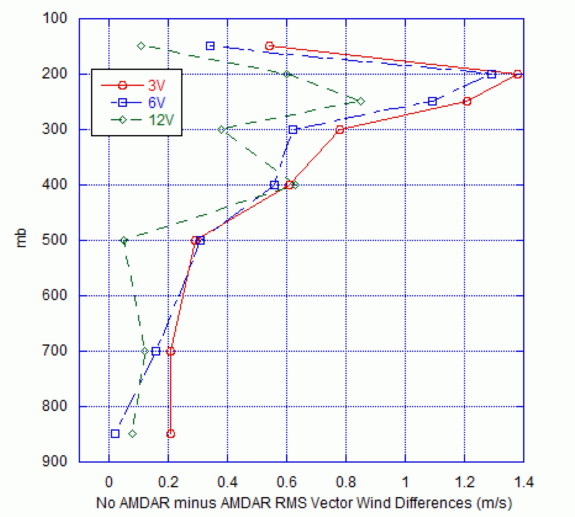

*Fig. 9. RUC wind forecast error differences between the no-AMDAR and all-AMDAR run for 3-h (3V), 6-h (6V) and 12-h (12V) forecasts, large region.*

Figure 10 is similar to the previous but for the small region. Note that at 850 mb, 6-h and 12-h wind errors actually decrease slightly when AMDAR are left out, indicating that AMDAR data are hurting more than helping. Because TAMDAR observations dominate at low levels in the small region, we believe this is caused by the relatively poor quality of TAMDAR winds in April. Fortunately, the quality of TAMDAR winds has increased since April.

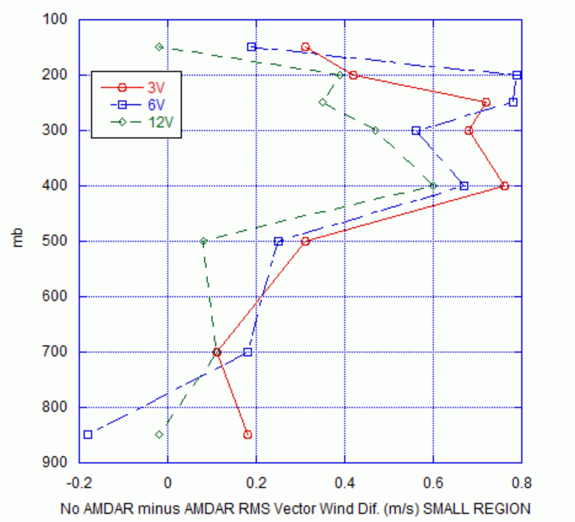

*Fig. 10. RUC wind forecast error differences between the no-AMDAR and all-AMDAR run for 3-h (3V), 6-h (6V) and 12-h (12V) forecasts, small region.*

Figure 11 shows the increase in RUC temperature errors for the large region when AMDAR data are removed. It indicates that AMDAR data are most beneficial at flight levels, and also near the surface. The peak for temperature forecast impact near the surface was not examined in previous RUC Observing System Experiments (OSEs) that have focused on a domain centered on the National Profiler Network. That domain includes few major airline hubs, whereas the large domain in this study includes many major Midwest and Eastern airline hubs. We are therefore seeing the effect of ascent and descent data at these hubs, and this is causing AMDAR to be important to RUC temperature forecasts below 800 mb. This points out the importance of AMDAR soundings for low-level stability, cloud, and convection forecasts.

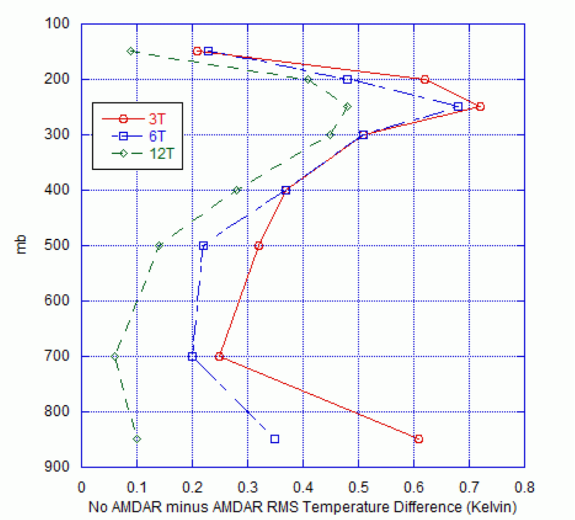

*Fig. 11. RUC temperature forecast error differences between the no-AMDAR and all-AMDAR run for 3-h (3T), 6-h (6T) and 12-h (12T) forecasts, large region.*

Figure 12 is similar to the previous except it is for the small region. Note that AMDAR data (dominated by TAMDAR at low levels in the small region) make a major contribution to increased RUC temperature forecast skill at low levels. This is not surprising; our ongoing studies of TAMDAR data suggest that temperature has consistently been the most reliable data at low levels.

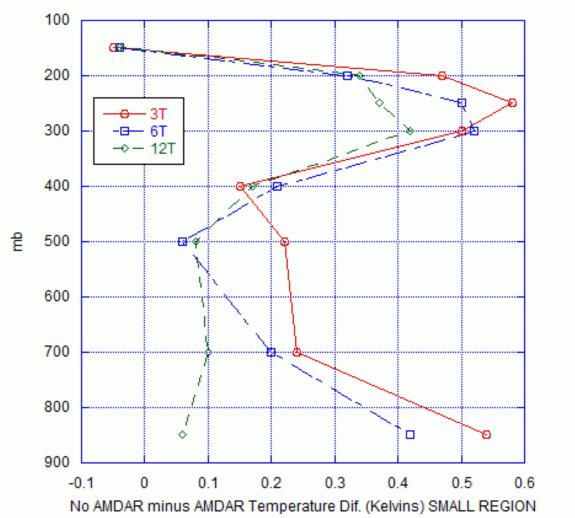

*Fig. 12. RUC temperature forecast error differences between the no-AMDAR and all-AMDAR run for 3-h (3T), 6-h (6T) and 12-h (12T) forecasts, small region.*

5.4.2 No TAMDAR vs. All AMDAR

Figure 13 shows the increased errors in temperature when TAMDAR data only are removed, in the small region. This may be compared with Figure 12 which showed that, at low levels in the small region, all of the AMDAR data served to decrease 3-h temperature errors by about .55 ºC at 850 mb. Figure 13 indicates that TAMDAR is responsible for about 0.1 ºC of this decrease.

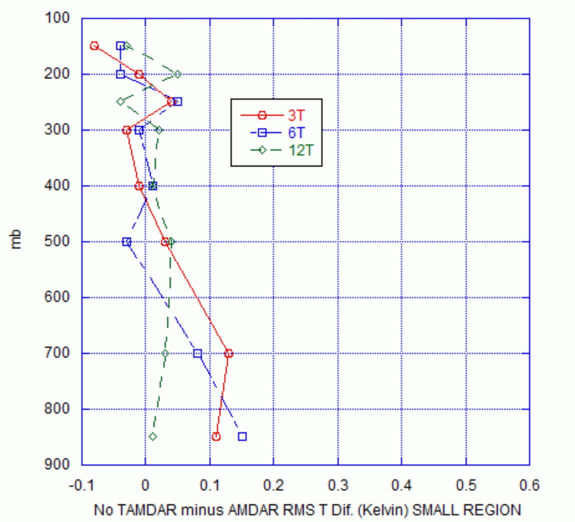

*Fig. 13. RUC temperature forecast error differences between the no-TAMDAR and all-AMDAR run for 3-h (3T), 6-h (6T) and 12-h (12T) forecasts, small region.*

Two factors may explain the rather small TAMDAR effect on temperature forecasts:

- The data shown in Figs. 12 and 13 include 12 UTC verification, for which there are fewer TAMDAR data than at 00 UTC.
- Although temperature was the most reliable TAMDAR variable in April, there were still problems with it (large biases on ascent and descent) that could have minimized the improvements in temperature skill due to TAMDAR.

Figure 14 below sheds light on the first of these points. It is the same as Fig. 13, except it is for the 00 UTC verification time. The impact of TAMDAR data at 700 mb is considerably larger at 00 UTC than at 12 UTC because larger numbers of TAMDAR observations influenced the initial conditions of forecasts that verified at 00 UTC.

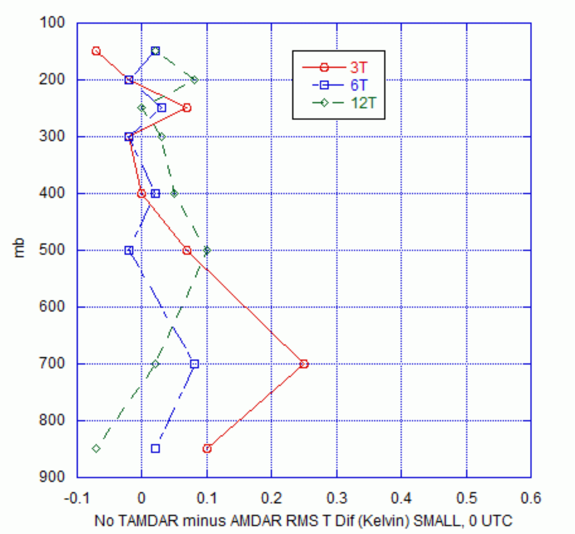

*Fig. 14. RUC temperature forecast error differences between the no-TAMDAR and all-AMDAR run for 3-h (3T), 6-h (6T) and 12-h (12T) forecasts, small region,* ***00 UTC only****.*

Figure 15 shows wind error increases in the small region when TAMDAR data are removed. This may be compared with Figure 10, which shows the error increases when all AMDAR data are removed. TAMDAR is seen to have no significant positive effect on wind forecasts in April. This is consistent with our expectations for the April period, based on the real-time RUC runs with and without TAMDAR. Since April, TAMDAR impact on wind forecasts has improved, as shown in Benjamin et al. (2006a,b).

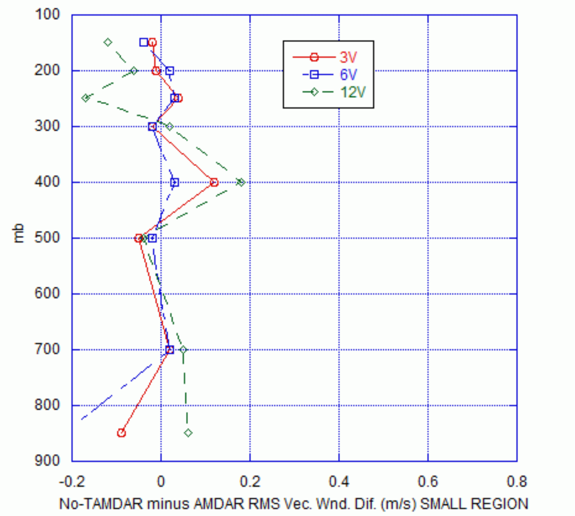

*Fig. 15. RUC wind forecast error differences between the no-TAMDAR and all-AMDAR run for 3-h (3V), 6-h (6V) and 12-h (12V) forecasts, small region.*

### 5.4.3 "thin4" and "thin5" vs. all AMDAR

Figure 16 shows 3-h wind forecast error differences between the no-AMDAR run and the thin4, thin5, and all-AMDAR runs. The solid circles show the same data as seen in Fig. 9 for 3-h forecasts. Below 500 mb the impact of the thin4 data on the 3-h wind forecast is consistent with almost no improvement over the no-AMDAR case. Above 500 mb however, the thin4 data does have some impact, reaching an impact of 0.8 m/s at 200 mb, an altitude where the full AMDAR data set provides an impact of 1.4 m/s. The thin5 case shows more than half the improvement of the all-AMDAR case at all levels.

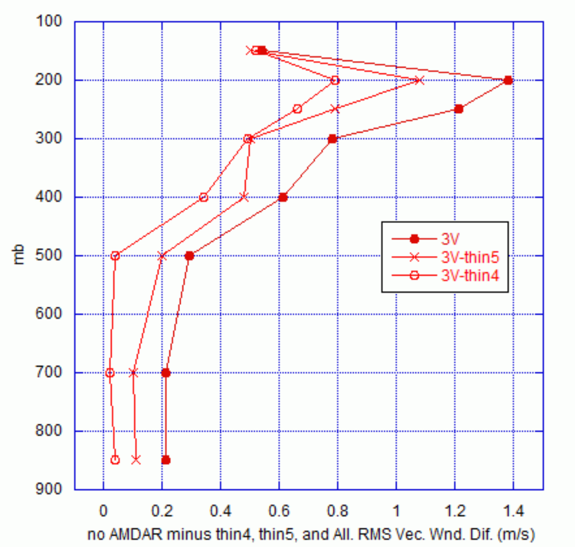

*Fig. 16. RUC 3-h wind forecast error differences between the no-AMDAR and the thin4, thin5, and all-AMDAR runs, large region.*

Although the overall RMS differences above 500 mb between the cases appear *relatively* small, it is important to realize that overall averages may miss important localized events where the extra data may be needed.

For instance, Fig. 17 shows the differences between the thin4 and all-AMDAR runs in 3-h wind forecasts at 250 mb. Substantial regions can be seen where the vector difference in the forecasted winds exceed 10 m/s (19.5 kts). These **large and significant errors—which can have substantial effect on aviation operations—remain** when the data are thinned so drastically.

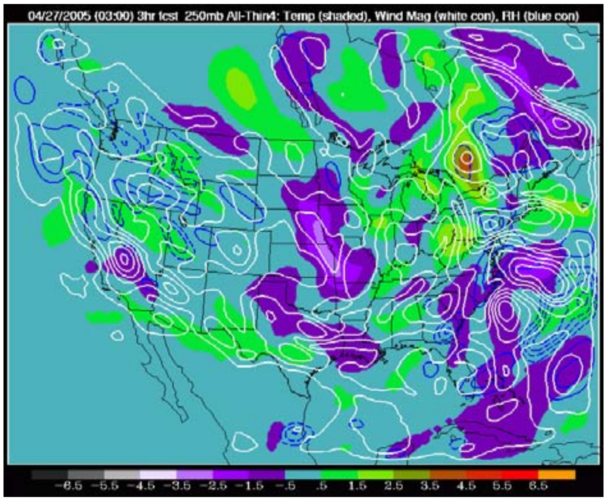

*Fig. 17. Magnitude of vector wind differences at 250 mb for 3-h forecasts between the "thin4" and the all-AMDAR runs. Valid at 06 UTC 27 April 2005. Wind contours, in white, are every 2 m/s; RH contours, in blue, are every 10%; temperature differences are shown in color from -6.5 to 6.5 ºC.*

Figure 18 is similar to Fig. 16, but for 3-h temperature forecasts. The thin5 case may be seen to have more than half of the impact of the all-AMDAR case at all levels.

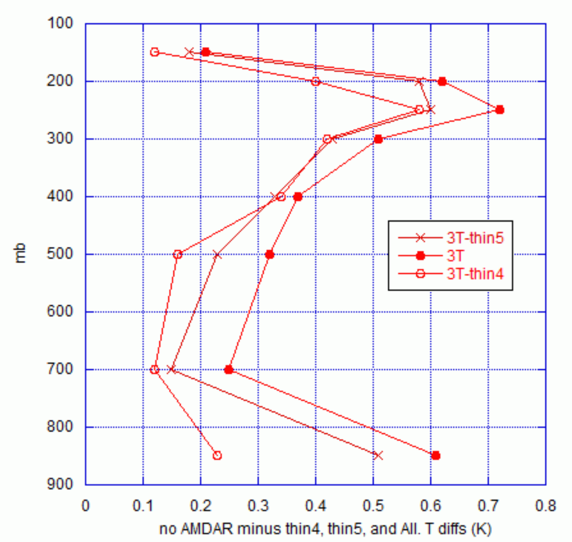

*Fig 18. RUC 3-h temperature forecast error differences between the no-AMDAR and the thin4, thin5, and all-AMDAR runs, large region.*

For temperature, Fig. 18 shows little difference between the thin4 and thin5 case above 500 mb. However for wind, (Fig. 16) there is considerable difference, with the thin5 case adding considerable value. We believe this is because the spatial correlation of temperature is greater than that for wind at these altitudes. Hence the additional thin5 measurements do not provide as much additional temperature information as they do wind information. This raises the consideration that one might optimize *differently* for wind than for temperature. We doubt, however, that this is likely to be cost-effective, and don't consider it further here.

### 5.5 Caveats

The overall RUC error statistics presented above give only part of the picture, and their importance should not be overestimated. In interpreting the OSE results the following caveats should be kept in mind.

- The thin4 and thin5 datasets are considerably more uniform in time and space than the unthinned data. While this uniform dataset is optimal from a model ingest point of view, it is to be determined to what extent such a uniform dataset can be created *a-priori* by enabling and disabling AMDAR data from individual flight segments. It is also unknown what the impact on the RUC would be of a less uniform thinned dataset. It is likely that more data will be required for a realistic dataset that is less uniform than those we have created for these experiments.
- Small RMS error differences between cases may mask important large differences that can occur in critical situations on the local scale and/or at non-synoptic times, as Fig. 17 indicates. Many of the forecast tasks that depend on AMDAR discussed in Sec. 4 are local in nature. Specific evaluations may need to be carried out to find the appropriate amount of AMDAR data needed to facilitate such forecasts.
- Some redundancy of aircraft reports is required for quality control procedures of neighboring observations. Intermittent errors in aircraft reports may result in *forecast degradation* if not detected via QC with neighbors. Periodically enabling **all** AMDAR data (one possible strategy) would facilitate "buddy checking" between individual aircraft, and would reveal sensor malfunctions that might be too subtle to be detected in ordinary, optimized, operation.
- We have looked only at wind and temperature. Water vapor is an important atmospheric variable for many forecast tasks, as discussed in Section 4. With the advent of systems such as TAMDAR and WVSS-II (Petersen and Moninger, 2006), we have the potential to measure the distribution of vapor in unprecedented detail. The spatial and temporal variability of water vapor is not well known, because upper-air measurements of it are primarily from radiosondes, which have coarse spatial and temporal resolution. An optimization strategy that works well for wind and temperature may fail to provide optimal knowledge of water vapor.
- Turbulence is being measured now—by TAMDAR and by an algorithm installed on more than 100 UAL aircraft. Turbulence is highly variable in space and time. A strategy for optimally measuring turbulence is necessarily

quite different from that used for wind and temperature. In particular, significant turbulent events must be detected and reported whenever possible, even when an aircraft that is not otherwise reporting weather information.

## 6. ANALYSIS SENSITIVITY TESTING

The OSE results presented above are temporal and spatial averages. In order to begin to understand the impact of AMDAR thinning strategies in more detail, we have begun to implement in the RUC model a method of assessing the sensitivity of the analysis to individual data types and individual atmospheric variables, in individual regions. Our method is adapted from one described by Wahba (1995).

Measuring the sensitivity of RUC analyses to varying amounts of AMDAR data would allow us to investigate the optimal amount of AMDAR data for very specific time periods and regions without being restricted by the temporal and spatial scales of the radiosonde network.

We believe this technique could be a useful tool in assessing the impact of each observation type on the RUC analysis. It is important to realize, however, that impact on the analysis is not the same as forecast improvement. For instance, data could have substantial impact but could degrade forecast skill. Nonetheless, the information provided by the technique can be gathered quickly (in a few minutes for a single analysis) and can show whether various optimizations of AMDAR (or other) data are likely to have any impact on forecast skill.

## 7. AN "AIRCRAFT DATA NEED FIELD"

Modern avionics provides the potential to enable and disable the acquisition and transmission of AMDAR data on a time scale of less than a few hours. We therefore propose to validate a RUC-based three dimensional "aircraft data need field." This would allow a fraction of AMDAR observations to be "targeted" to those times and regions where detailed knowledge of atmospheric conditions is expected to have the greatest impact on forecasts. These would be gathered in addition to routine observations, possibly "thinned" over what is acquired today. We will present the specifications for our proposed aircraft data need field at the conference.

## 8. SUMMARY

AMDAR data have demonstrably improved forecasts made by both NWP models and human forecasters. Based on what we have shown here and what we will discuss at the conference, there appears to be some potential to decrease the amount of AMDAR data routinely taken while not substantially decreasing average model skill. However, the many caveats mentioned in Section 5.5 must be kept in mind. In particular, it is currently unknown to what extent the thinning strategies tested ("thin4" and "thin5) can be duplicated in practice, and what the impact of less-uniform, more realistic, thinning strategies might be.

If routine AMDAR data are decreased to contain costs, we believe it would be productive to re-target some of the removed AMDAR to regions that have a potential to experience unsettled and potentially dangerous weather. Section 4 enumerates many kinds of such weather events, for which AMDAR provides highly useful information.

We have made a start at developing a forecast field that can indicate where and when these target AMDAR observations would be most beneficial.

Follow-on work is necessary to develop an AMDAR optimization system that will contain costs while being responsive to the need to provide accurate forecasts of weather events.

## 9. ACKNOWLEDGEMENTS

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## 10. REFERENCES

Benjamin, S. G., B. E. Schwartz, E. J. Szoke, S. E. Koch, 2004a: The Value of Wind Profiler Data in U.S. Weather Forecasting. *Bulletin of the American Meteorological Society*: Vol. 85, No. 12, pp. 1871–1886

Benjamin, S. G., D. Dévényi, S. S. Weygandt, K. J. Brundage, J. M. Brown, G. A. Grell, D. Kim, B. E. Schwartz, T. G. Smirnova, T. L. Smith, G. S. Manikin. 2004b: An Hourly Assimilation–Forecast Cycle: The RUC. *Monthly Weather Review*: **132**, 495–518.

Benjamin, S. G., W. R. Moninger, T. L. Smith, B. D. Jamison, and B. E. Schwartz, 2006a: TAMDAR aircraft impact experiments with the Rapid Update Cycle. *10th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS)*, Atlanta, GA, Amer. Meteor. Soc.

Benjamin, S.G., W. R. Moninger, T. L. Smith, B. D. Jamison, and B. E. Schwartz, 2006b: Impact of TAMDAR humidity, temperature, and wind observations in RUC parallel experiments. *12th Conf. on Aviation, Range, and Aerospace Meteorology (ARAM)*, Atlanta, GA, Amer. Meteor. Soc.

Cardinali, C., L. Isaksen, E., Andersson, 2003: Use and impact of Automated Aircraft Data in a

Global 4DVAR Data Assimilation System. *Mon. Wea. Rev, 131, 1865-1877.*

Daniels, T. S., W. R. Moninger, R. D. Mamrosh, 2006: Tropospheric Airborne Meteorological Data Reporting (TAMDAR) Overview. *12th Conf. on Aviation, Range, and Aerospace Meteorology (ARAM)*, Atlanta, GA, Amer. Meteor. Soc.

Mamrosh, R., R. Decker, C. Weiss, 2001: Field forecaster evaluation of ACARS dataResults of the NAOS ACARS assessment. *Fifth Symposium on Integrated Observing Systems*, Albuquerque, NM. Amer. Meteor. Soc.

Moninger, W. R., R.D. Mamrosh, and P.M. Pauley, 2003: Automated meteorological reports from commercial aircraft. *Bull. Amer. Meteor. Soc.* **84**, 203-216.

Petersen, R., G. Manikin, and D. Keyser, 2004: Impact of MDCRS Ascent/Descent data in Rapid Update Cycle (RUC) forecasts. *Proceedings of the Third WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction* (Alpbach, Austria), pp 298 - 307. (Available at http://www.wmo.int/files/www/GOS/Alpbach2004/3B_3PetersenRalph.pdf)

Petersen, R., and W.R. Moninger, 2006: Assessing two different commercial aircraft-based sensing systems. *10th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS)*, Atlanta, GA, Amer. Meteor. Soc.

Verner, G. R. Sarrazin, Y. Zaitseva 2004. Deep impact studies in the CMC global NWP system. *Proceedings of the Third WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction* (Alpbach, Austria), pp 123-135..

Wahba, G. et al., 1995: Adaptive Tuning of Numerical Weather Prediction Models: Randomized GCV in Three- and Four-Dimensional Data Assimilation, *Mon. Wea. Rev.* pp 3358-3369