J11.6 THE POTENTIAL UTILITY OF TAMDAR DATA IN AIR QUALITY FORECASTING

Neil Jacobs[1], Meredith Croke[1], Peter Childs[1], Allan Huffman[1], and Yubao Liu[2]

[1]AirDat LLC, Morrisville, NC 27560
[2]National Center for Atmospheric Research, Boulder, CO 80307

1. INTRODUCTION

Observations collected by a multi-function in-situ atmospheric sensor on commercial aircraft, called the Tropospheric Airborne Meteorological Data Reporting (TAMDAR) sensor, contain measurements of humidity, pressure, temperature, winds aloft, icing, and turbulence, along with the corresponding location, time, and altitude from built-in GPS are relayed via satellite in real-time to a ground-based network operations center.

The TAMDAR sensor was originally deployed by AIrDat in December 2004 on a fleet of 63 Saab 340s operated by Mesaba Airlines in the Great Lakes region as a part of the NASA-sponsored Great Lakes Fleet Experiment (GLFE). Over the last five years, the equipage of the sensors has expanded beyond CONUS to include Alaska and Mexico on Horizon, Republic, Chautauqua, Shuttle America, PenAir, Piedmont, Frontier Alaska, AeroMexico Connect and Mesaba Airlines, as well as a few research aircraft. Upon completion of the 2010 installations, more than 6000 daily sounding will be produced in North America at more than 360 locations. Additional expansions will be underway for regions around Hawaii, Caribbean, Antilles, Central America, and the Central/Western US. Emphasis has been placed on equipping regional carriers, as these flights tend to (i) fly into more remote and diverse locations, and (ii) make shorter flights that produce more daily vertical profiles and remain in the boundary layer for longer durations.

The data is presently being assimilated into an operational high-resolution (4km grid) CONUS-scale Advanced Research WRF (ARW), known as the NCAR-AirDat RTFDDA-WRF, using the NCAR/ATEC Real-Time Four-Dimensional Data Assimilation (RTFDDA) technologies. The system is built upon the WRF model framework, but uses a Newtonian relaxation observational nudging data assimilation engine, which allows the model to more effectively assimilate asynoptic measurements.

This new TAMDAR data set is discussed below in terms of the potential utility in air quality research and applications, including determining mixing-layer heights and evolutions, observation-based forecast adjustments, as well as forecast verification. In addition to the direct use of the TAMDAR soundings, the output from the NCAR-AirDat RTFDDA-WRF, which effectively assimilates TAMDAR data and other diverse observations, provides a unique and useful initialization for air quality models.

* *Corresponding author address*: Neil A. Jacobs, AirDat, LLC, 2400 Perimeter Park Dr. Suite 100, Morrisville, NC 27560. Email: njacobs@airdat.com

2. BACKGROUND

In response to a government aviation safety initiative, National Aeronautics and Space Administration (NASA), in partnership with the Federal Aviation Administration (FAA) and National Oceanic and Atmospheric Administration (NOAA), sponsored the early development and evaluation of a proprietary multi-function in-situ atmospheric sensor for aircraft.

AirDat LLC, located in Morrisville, North Carolina, was formed to develop and deploy the TAMDAR system based on requirements provided by the Global Systems Division (GSD) of NOAA, the FAA, and the World Meteorological Organization (WMO).

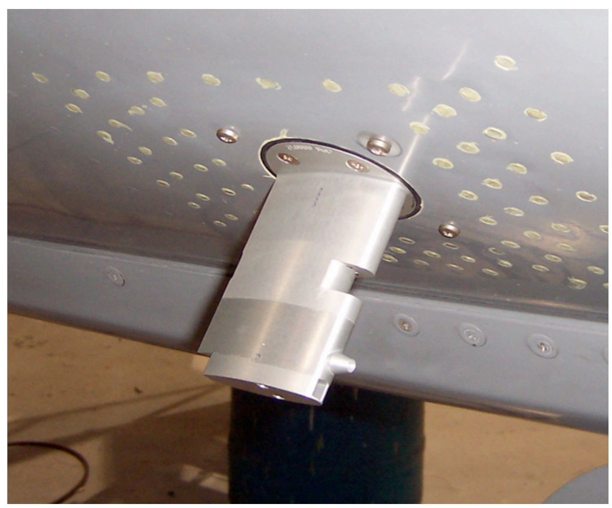

Fig. 1. The TAMDAR probe mounted on a Saab 340 aircraft.

TAMDAR sensors can be installed on most fixed-wing aircraft from large commercial airliners to small unmanned aerial vehicles, where they continuously transmit atmospheric observations via a global satellite network in real time as the aircraft climbs, cruises, and descends. The TAMDAR sensor (pictured on a Saab 340, Fig. 1) offers a broad range of airborne meteorological data collection capabilities, as well as icing and turbulence data that is critical to both aviation safety and operational efficiency.

In addition to atmospheric data collection, the customizable turn-key system can also provide continuous GPS aircraft tracking, global satellite link for data, text and voice communication, automated transmission of OOOI times, real-time forecast products and mapping of icing, turbulence and winds aloft, a multi-function antenna for WSI or XM cockpit weather, and the ability to integrate satcom with EFBs.

TAMDAR observations not only include temperature, pressure, winds aloft, and relative humidity (RH), but also icing and turbulence. Additionally, each observation includes GPS-derived horizontal and vertical (altitude) coordinates, as well as a time stamp to the nearest second. With a continuous stream of observations, TAMDAR provides much higher spatial and temporal resolution compared to the Radiosonde (RAOB) network, as well as better geographic coverage, and a more complete data set than Aircraft Communication Addressing and Reporting System (ACARS), which lacks relative humidity, icing, and turbulence.

Current upper-air observing systems are also subject to large latency based on obsolete communication networks and quality assurance protocol. TAMDAR observations are typically received, processed, quality controlled, and available for distribution or model assimilation in less than a minute from the sampling time. The sensor requires no flight crew involvement; it operates automatically, and sampling rates and calibration constants can be adjusted by remote command from the AirDat operations center in Morrisville, NC.

AirDat icing data provides the first high volume, objective icing data available to the airline industry. Ice reporting is currently supported by PIREPs; while helpful, these subjective reports do not provide the accuracy and density required to effectively manage increasing demands on the finite airspace. High density real-time TAMDAR icing reports fill this information void, creating a significantly more accurate spatial and temporal distribution of icing hazards, as well as real-time observations where icing is not occurring. The icing data can be viewed in the raw observation form, or it can be used to improve icing potential model forecasts.

The real-time AirMap display can be accessed by TAMDAR users from any common internet-capable computer. The display offers user-selectable functions for icing, turbulence, and aircraft tracking, and it can be zoomed in to any location on the globe. Additionally, the user can select how the data is displayed. In the case of turbulence, the sliders on the right of the screen can be adjusted to isolate data points for a particular altitude range, or to display a specified turbulence magnitude range.

The TAMDAR sensor provides objective high-resolution eddy dissipation rate (EDR) turbulence observations. This data is collected for both median and peak turbulence measurements, and is capable of being sorted on a much finer (7-point) scale than current subjective pilot reports (PIREPs), which are reported as light, moderate, or severe. The EDR turbulence algorithm is aircraft-configuration and flight-condition independent. Thus, it does not depend on the type of plane, nor does it depend on load and flight capacity.

This high density real-time in-situ turbulence data can be used to alter flight arrival and departure routes. It also can be assimilated into models to improve predictions of threatening turbulence conditions, as well as a verification tool for longer range NWP-based turbulence forecasts. The AirDat turbulence display shows actual turbulence observations from TAMDAR-equipped fleets by location, altitude, and severity of turbulence. As with the icing observations, potential utility of this data in air traffic control decision making for avoidance and mitigation of severe turbulence encounters is extremely significant.

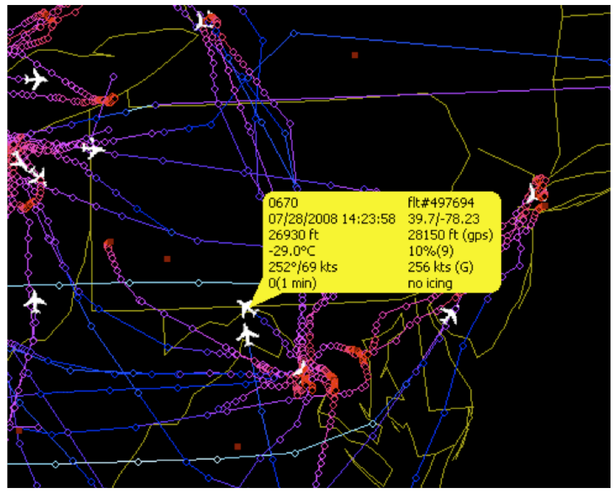

Fig. 2. Example of a TAMDAR point observation from flight out of DC.

The screenshot in Figure 2 shows planes in the vicinity of Washington Dulles International and their respective TAMDAR observations. Holding the mouse over a flight produces a “call out” of the most recent observations. This particular flight is currently reporting no icing or turbulence at a pressure altitude of 26,930 feet. The relative humidity is 10%, and the temperature is -29°C with a wind speed of 69 knots at 252°.

The TAMDAR sensor, combined with the AirDat satellite communications network, data center, and atmospheric modeling, provides unique operational benefits for participating airlines. Some of these benefits include real-time global tracking and reporting of aircraft position, real-time delivery of aircraft systems monitoring data, and airline operational support (e.g., automated OOOI times).

The TAMDAR installation includes a multi-function antenna, which can be used for receiving cockpit weather displays, text messaging, email, and satellite voice communication to and from the cockpit and cabin, as well as air-ground-air data transmission via the data center (i.e., air-to-air) when appropriately equipped. Since the communication link is satellite based, the coverage is global, and seamlessly functional for any location and altitude with a sub-60 second latency. Since TAMDAR is independent of the existing aircraft communication systems, it offers additional layers of redundancy, as well as carrier-defined data stream flexibility.

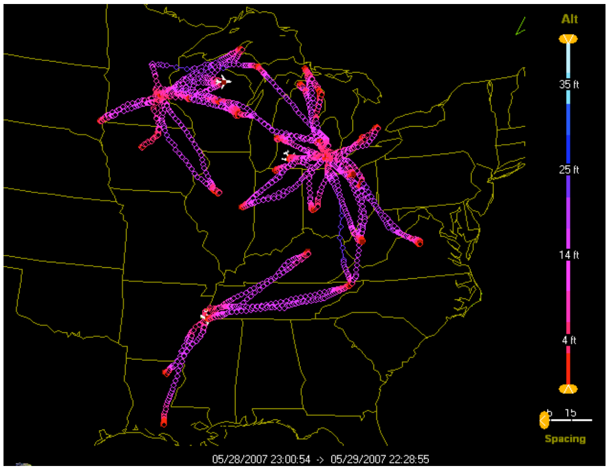

Fig. 3. Flight routes and observations for 28-29 May 2007.

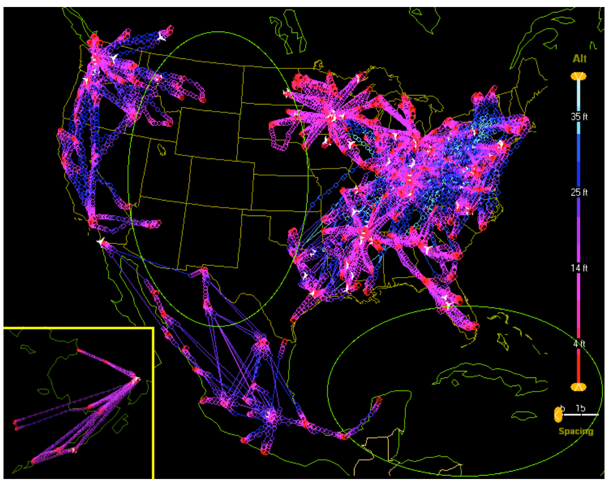

Fig. 4. Flight routes and observations for 4-5 Sept 2009.

An example of the flight data density for a typical day in May 2007 is shown in Fig. 3, which is essentially the same density as 2006 (with Mesaba). Equipage of sensors on additional aircraft across the continental US and Alaska began in late 2008. Jacobs et al. (2009) provides an example of the increase in observations and flights from 2007 to 2008 (cf. Jacobs et al. 2009, Fig. 1 and Fig. 2). Since 2009, AirDat has expanded the sensor network to include Alaska (Fig. 4 inset), Mexico, PacNW, and Florida (Fig. 4). Additionally for 2010, the network will be expanding into regions in the vicinity of Hawaii, Caribbean, Antilles, Central America, and the Central/Western US. This will essentially fill most of the remaining voids (green circles) seen in Figure 4.

3. FORECAST MODELING

Numerous third-party studies have been conducted by NOAA-GSD, the National Center for Atmospheric Research (NCAR), and various universities to verify the accuracy of TAMDAR against weather balloons and aircraft test instrumentation, as well as quantifying the TAMDAR-related impacts on numerical weather prediction (NWP; e.g., Moninger et al. *in pres*., 2009, Benjamin et al. 2009, and Jacobs et al. 2009).

Ongoing data denial experiments show that the inclusion of TAMDAR data can significantly improve forecast model accuracy with the greatest gains realized during more dynamic and severe weather events (e.g., Croke et al. 2010 and Jacobs et al. 2009).

Upper-air observations are the single most important data set driving a forecast model. Fine-scale regional forecast accuracy is completely dependent on a skillful representation of the mid and upper-level atmospheric flow, moisture, and wave patterns. If these features are properly analyzed during the model initialization period, then an accurate forecast will ensue.

Forecast models that employ a 3-D variational assimilation technique (3DVAR), which weights observations based on their observed time are limited in their ability to extract the maximum value from a high resolution asynoptic data set. This method greatly reduces the effectiveness of observations not taken at the precise synoptic hour (e.g., 00, 06, 12, and 18 UTC).

Recent advancements in computational power have enabled 4-D variational assimilations techniques to become an operationally feasible solution. This method is far superior when initializing a forecast model with a data set such as TAMDAR because the observations are assimilated into the numerical grid at their proper space-time location.

TAMDAR data has been shown to increase forecast accuracy over the US on the order of 30-50% for a monthly average, even for 3DVAR models (Moninger et al. 2009, Benjamin et al. 2009). For specific dynamic weather events, it is not uncommon to see the improvement in skill more than double this value. Another factor to consider is that the verification in skill assessment to date has been conducted over the US, which already hosts the most observation-rich region on the globe (Bengtsson and Hodges 2005). Thus, it is likely that forecast accuracy will be improved far more than these reported values if TAMDAR is deployed in non-US regions, which currently have sparse or no upper-air observations.

a) RT-FDDA-WRF

Over the last year, AirDat and NCAR have worked together to implement a version of RTFDDA-WRF, which is an “observation-nudging” FDDA–based method built around the WRF-ARW core. This system is able to assimilate synoptic and asynoptic observational data sets, including various surface data (e.g., METAR, SYNOP, SPECI, ship, buoy, QuikScat seawinds, mesonets, etc.), and various upper-air observations (e.g., TEMP, PILOT, wind profilers, aircrafts (TAMDAR), satellite winds, dropsondes, radiometer profilers, RAOBS, Doppler radar VAD winds, etc.).

Several recent improvements have been made to the observation nudging scheme, including the ability to assimilate multi-level upper-air observations using vertical coherency principles. Additional improvements have been made to the terrain-dependent nudging weight corrections, including a ray-searching scheme, which eliminates the influence of an observation to a model grid-point if the two sites are physically separated by a significant mountain ridge or a deep valley. This is outlined in greater detail in Yubao et al. (2002) and Childs et al (2010). An example of wind fields and vertical transport can been seen in Figure 5; a 1 km grid centered over the DC area.

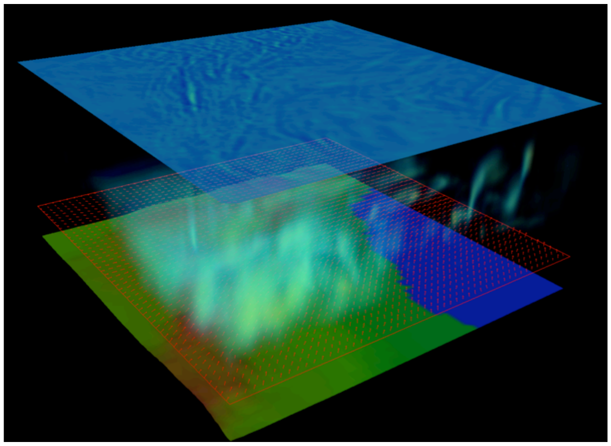

Fig. 5. Forecast output from 1 k inner nest showing wind field, TKE and omega.

The initial RTFDDA-WRF system began cycling on 6-h intervals to 72 hours in late July 2009. The initial configuration used the Lin microphysics scheme (now the Morrison 2-moment), the Kain-Fritch cumulus scheme (no CP for the 4 km), the YSU boundary layer, and the NOAH LSM. The radiation was handled by the RRTM (longwave) and Dudhia (shortwave), and high resolution SST data (RTG SST HR).

b) 4DVAR-WRF

The 4DVAR-WRF prototype was built in 2005, and has been under continuous refinement since then, including the development of a TAMDAR observation operator and additional optimizations to the variational code to maximize the impact of TAMDAR data. It runs as a combination of WRF, WRF+ (the WRF tangent linear model and adjoint model) and WRF-Var (with 4D-Var extensions) executables. The cost function also includes a penalty term, *Jc*, to control noise during the minimization.

4D-Var can assimilate the same observation types as 3D-Var does, and it can assimilate more observations from non-moving platforms, such as SYNOP, than 3D-Var. There are many adjustable parameters in WRF-Var, such as the variances and scale lengths of the background errors. Most of these parameters have been adjusted for optimizing the 3D-Var performance.

The 4DVAR-WRF is significantly more computationally expensive to run than the RTFDDA-WRF. Due to the expensive computational cost, the present configuration can only run a single 12 km North American domain, which is the same as configured for the RTFDDA-WRF. A tropical grid similar to the RTFDDA-WRF will also be configured.

The 4DVAR-WRF also has the ability to use all the synoptic and asynoptic (e.g., TAMDAR) observations. The multivariate background covariances used in 3DVAR and 4DVAR formally impose constraints that ensure slow manifold adjustment by the observations. This also helps prevent “spin-up” problems that exists in all cold-start operational models, as well as reduces the likelihood that gravity wave noise will be produced.

4. RAW SOUNDING DATA

The TAMDAR units are currently set to sample at 300 ft intervals on ascent and descent. This resolution can be adjusted in real time to whatever interval is desired. The satellite connection to the sensor is a 2-way connection, so sampling rates, calibration constants, firmware upgrades, etc. can all be done remotely from a ground-based location. The sampling rate in cruise is time based. The soundings, or vertical profiles, are built as each observation is received. All of the profile-based variable calculations (e.g., CAPE, CIN, etc.) are calculated when the plane enters cruise or touches down. When an airport is selected, successive soundings can be displayed within a certain time window. This enables the user to view the evolution of the profile. Two brief examples that pertain to air quality are discussed below.

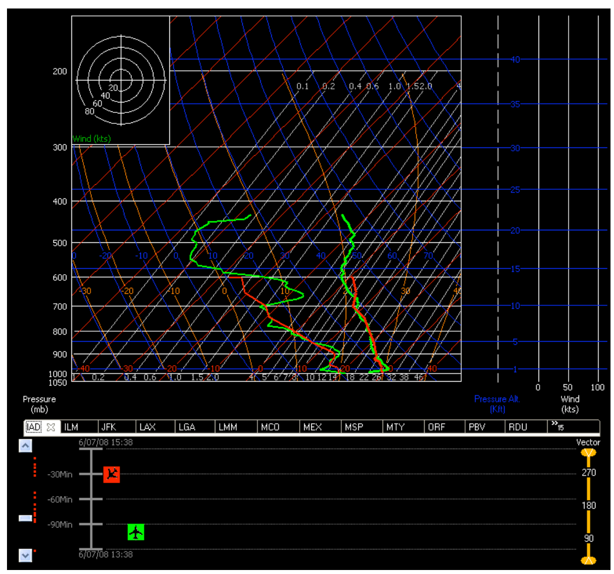

Fig. 6. TAMDAR soundings at IAD valid 7 June 2008 at 1405Z (green) and 1508Z (red)

The early part of June 2008 was particularly problematic in the way of air quality for NC and VA, as there was a substantial heat wave that coincided with stagnant air and several forest fires blazing in the coastal plain of NC. Most airports in the vicinity (e.g., RDU, GSO, ILM, RIC, ORF) saw several daily flights from TAMDAR-equipped planes. An example of a rapid diurnal shift can be seen in Figure 6, valid 7 June 2008, where a shallow, but strong inversion was observed at

IAD at 1405Z (green sounding), but by 1508Z (red sounding), it was mostly gone, as the surface began to warm. A very think low-level haze was reported in the DC area until about 1030 LT, at which point, it began to mix out. IAD had 14 soundings this day.

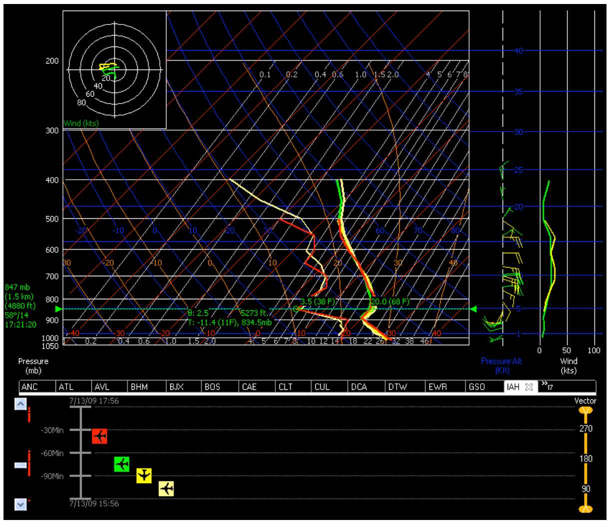

Fig. 7. TAMDAR soundings at IAH valid 13 July 2009 from 1620Z (light yellow) to 1730Z (red). The other two fall in between those times.

Another example is taken from a code-orange day in TX and LA. The series of soundings were observed in Houston, TX (IAH) during 13 July 2009. IAH had more that 20 soundings throughout the day. The series in Figure 7 begins with the yellow (oldest), which is valid 1620Z, and end with the red (newest), valid 1730Z. A substantial inversion was established due to warm advection by easterly winds between 800 and 550 hPa. Despite weakening by about 2 C during this time window, the inversion remained in place throughout the day. On the far left of Figure 7, the height (in pressure) of the inversion is 847 mb, which is 4880 ft. The "mouse over" text in the window on the profile itself shows a different height of 5273 ft, which is where the cursor is located on the profile.

5. SUMMARY

Lower and middle-tropospheric observations are disproportionately sparse, both temporally and geographically, when compared to surface observations. The limited density of observations is likely one of the largest constraints in weather research and forecasting. Since December 2004, the TAMDAR system has been certified, operational, and archiving observations. This real-time data is available for operational forecasting both in forecast models and in raw sounding format that included the additional metrics of icing and turbulence. The observations are archived back to December 2004 for case studies, verification and back testing.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Bengtsson, L. and K. I. Hodges, 2005: A Note on Atmospheric Predictability, Tellus, V58A, 154-157.

Benjamin, S. G., W. R. Moninger, B. D. Jamison, and S. R. Sahm, 2009: Relative short-range forecast impact in summer and winter from aircraft, profiler, rawinsonde, VAD, GPS-PW, METAR and mesonet observations for hourly assimilation into the RUC, (IOAS-AOLS), AMS, Phoenix, AZ.

Childs, P., N. Jacobs, M. Croke, A. Huffman, Y. Liu, W. Wu, G. Roux, and M. Ge, 2010: An introduction to the NCAR-AirDat operational TAMDAR-enhanced RTFDDA-WRF-ARW. 14th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS), AMS, Atlanta, GA.

Croke, M., N. Jacobs, P. Childs, A. Huffman, Y. Liu, Y. Liu, and R.-S. Sheu, 2010: Preliminary verification of the NCAR-AirDat operational RTFDDA-WRF system. 14th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS), AMS, Atlanta, GA.

Jacobs, N., P. Childs, M. Croke, Y. Liu, X.-Y. Huang, 2009: The optimization between TAMDAR data assimilation methods and model configuration in MM5 and WRF-ARW, 13th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS), AMS Phoenix, AZ, January 2009.

Liu, Y., S. Low-Nam, R. Sheu, L. Carson, C. Davis, T. Warner, S. Swerdlin, J. Bowers, M. Xu, H-M Hsu, and D. Rife, 2002: Performance and Enhancement of the NCAR/ATEC mesoscale FDDA and forecast system. 15th Conference on Numerical Weather Prediction, 12-16 August, 2002, San Antonio, Taxes, 399-402.

Moninger W.R., S.G. Benjamin, B.D. Jamison, T.W. Schlatter, T.L. Smith, and E.J. Szoke, 2009: Evaluation of Regional Aircraft Observations using TAMDAR. *Weather and Forecasting*, In Press

Moninger, W. R., S. G. Benjamin, B. D. Jamison, T. W. Schlatter, T. L. Smith, and E. J. Szoke, 2009: TAMDAR jet fleets and their impact on Rapid Update Cycle (RUC) forecasts, (IOAS-AOLS), AMS, Phoenix, AZ.