12th Conference IOAS-AOLS
New Orleans, Louisiana, January 20-24, 2008

15B.7 HIGH RESOLUTION ASSIMILATION OF CASA AND NEXRAD RADAR DATA IN NEAR REAL-TIME: RESULTS FROM SPRING 2007 AND PLANS FOR SPRING 2008

Keith A. Brewster[1]*, Jerry Brotzge[1], Kevin W. Thomas[1],
Yunheng Wang[1], Ming Xue[1,2], Jidong Gao[1], Dan Weber[1], and Kyle Howe[3]
[1]Center for Analysis and Prediction of Storms, Univ. of Oklahoma, Norman, Oklahoma
[2]School of Meteorology, University of Oklahoma, Norman, Oklahoma
[3]Dept. of Atmospheric and Oceanic Sciences, McGill University, Montreal, Quebec

1. INTRODUCTION

Increased computer speed and advanced techniques to assimilate Doppler weather radar are making high resolution numerical forecasts of thunderstorms and associated severe weather a reality. Along with basic research in data assimilation at storm-resolving scales, The Center for Analysis and Prediction of Storms continues to test efficient analysis and forecast systems utilizing massively parallel computer architecture and the latest radar technology.

In late 2006 the NSF Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA, McLaughlin et al. 2005) deployed a network of four X-band dual-polarization Doppler radars in southwestern Oklahoma. This CASA NetRad network was deployed as CASA's first integrated project (IP1, Brotzge et al. 2007, Junyent et al. 2005).

During the spring of 2007 data from the CASA NetRad and NWS/FAA/DoD WSR-88D NEXRAD radar were combined with other data, including surface observations and satellite imagery, in a high resolution data assimilation experiment as part of the CASA IP1 Spring Experiment-2007 (CSET-2007).

A series of 6-hour assimilated forecasts at 1-km resolution were produced in near-real time using different combinations of radar data to evaluate this first-generation application of the CASA radar data in NWP and to establish a baseline for enhancements of the analysis and assimilation techniques to be made in the near future.

*Corresponding author address: Keith Brewster, CAPS/Univ. of Oklahoma, Natl Weather Center, Norman, OK 73072, kbrewster@ou.edu

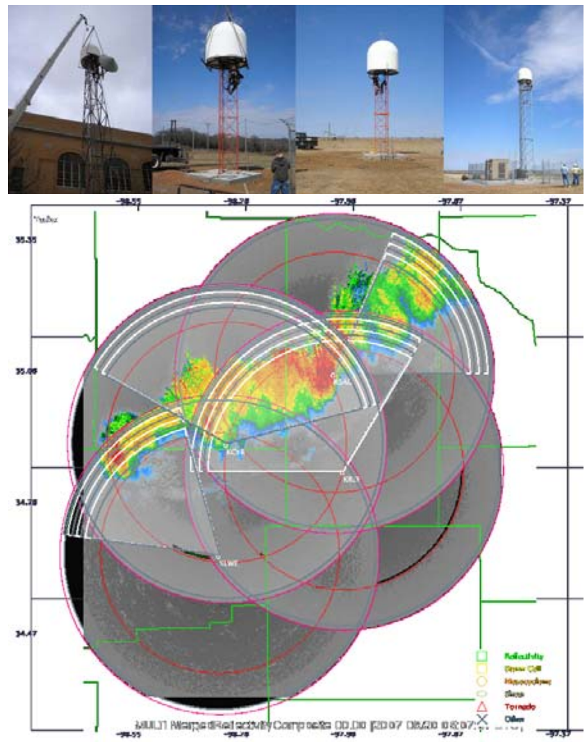

Fig 1. a) *Photographs of four IP1 CASA X-band radars being installed. b) Reflectivity from IP1 CASA IP1 radars on a map of southwestern Oklahoma, with an overlay display indicating the adaptive scanning plan for a single scan plan. Mutiple arc lines in each sector show how many elevation angles are scanned for that sector.*

This paper describes the CASA IP1 radar network, the methods used to insert radar data in the model in CSET-2007, describe a sample case illustrating the impact of the CASA radar, demonstrate the method of verifying tracks of vorticity centers, and report on plans for improved analysis and assimilation techniques for CSET-2008.

2. CASA NETRAD IP1 RADAR NETWORK

The CASA IP1 radar network consists of four dual-polarization X-band Doppler radars separated by about 25 km and is situated in southwest Oklahoma, midway between the Oklahoma City (KTLX) and Frederick (KFDR), Oklahoma WSR-88D radars of the NEXRAD operational radar network (Fig. 1). Specifically, the four CASA radars are located in Chickasha (KSAO), Rush Springs (KRSP), Cyril (KCYR) and east of Lawton (KLWE).

The radars were sited to maximize the dual-Doppler coverage areas within the network while utilizing existing high speed communications nodes of the Oklahoma OneNet (Brewster et al. 2005b). Originally the CASA radars were designed to have a nominal maximum range of 30 km, but recent radar enhancements allow operation with a maximum range of 40 km.

The radars are novel in that they scan in a coordinated fashion, using Distributed Collaborative Adaptive Sensing (DCAS) to maximize end-user utility depending on observed weather features (Zink et al. 2005). This is accomplished, for example, by adapting the sector scanning to scan identified thunderstorm cells with more vertical scans than nearby echo-free regions, as depicted in Fig 1b. The end-users who specified their data requirements include the National Weather Service, the emergency managers in the area, weather researchers, and the designers of the numerical weather prediction model systems.

The radars operate at X-band (3 cm) and thus are subject to attenuation by precipitation, which is corrected in real-time by a dual-polarization method (Park et al. 2005a, 2005b, Liu et al. 2006). The radars are generally operated at low elevation angles to scan below the radar horizon of the adjacent NEXRAD radars. Ground clutter is mitigated using a Gaussian model adaptive processing technique (GMAP, Siggia and Passarelli 2004), and velocity dealiasing is achieved using a dual-PRF waveform. Additional details about the radar system are reported by Junyent et al. (2005).

The radar moment data are generated at the radar and are transmitted within seconds to the CASA Systems Operations Control Center (SOCC) at CAPS, in the National Weather Center in Norman.

3. SPRING 2007 DATA ASSIMILATION

For the CSET-2007 data assimilation effort the CAPS ADAS analysis program (Brewster 1996), including a complex cloud analysis with latent heating adjustment was used to generate analysis increments on a 1-km resolution grid (Fig. 2) to be assimilated in the CAPS Advanced Regional Prediction System (ARPS) non-hydrostatic model (Xue et al. 2000, 2001) using incremental analysis updating (IAU, Bloom et al. 1996). IAU was applied with a triangular time-weighting function in four consecutive 10-minute cycles (Fig. 3). Previous research (Hu et al. 2006a,b) suggested that 10 min cycling of reflectivity using the ADAS cloud analysis was effective at initializing and sustaining ongoing convection. In this application of the IAU, the vertical velocity and pressure increments are not applied, so those variables may freely adjust to increments in horizontal winds, latent heating and hydrometeors.

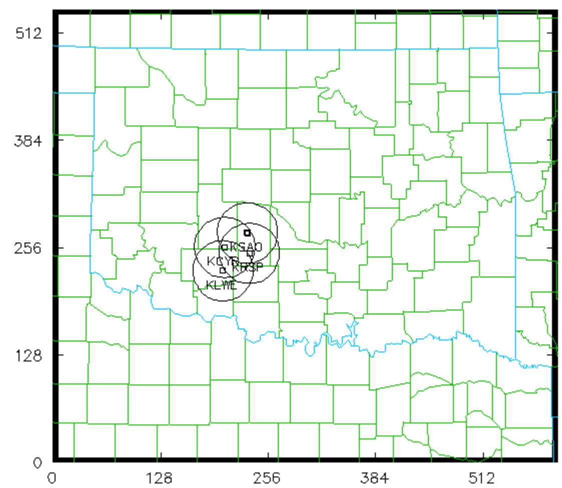

Fig. 2. 1-km assimilation and forecast domain covering most of Oklahoma and neighboring parts of North Texas and southern Kansas. CASA radars with 30 km range rings in black Distance scale in km.

This experiment represents the first real-time, automated use of the CASA data in NWP, the first real-time use of the IAU assimilation in cycling at CAPS.

The initial time of the assimilation for each day was adapted to the weather, beginning at the hour of first echo development in the CASA

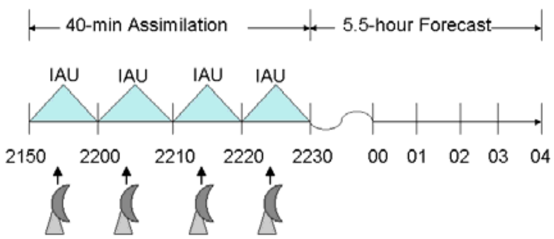

Fig 3 Schematic of data assimilation and forecast for a sample nominal start time of 22 UTC.

network, or at the time of arrival in the network for ongoing convection moving into the network. Thus the forecasts were also adaptive, being started in response to the weather in the domain. A 5.5-hour forward forecast was made following the 40-minute data assimilation period. This forecast will be compared to actual radar echoes from the CASA and NEXRAD networks.

On days without precipitation in the CASA network, the model was not run as the CASA radars were not designed for clear-air detection, and for the real-time runs in CSET-2007 only the reflectivity data were assimilated.

The radar remapping, analyses and model forecasts were done on 150 processors of a Pentium4 Xeon EM64T Linux Cluster at the OU Supercomputing Center for Education and Research (OSCER). When run in pairs (75 processors per forecast), each pair of 6h assimilation and forecast took about 8 hours wall clock time in this configuration.

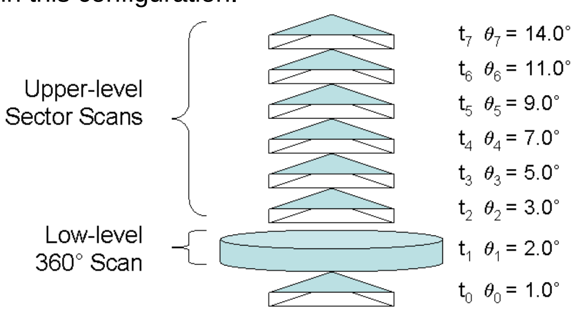

Fig 4. *Construction of pseudo-volume from multiple scans of a CASA NetRad radar*.

4. PROCESSING OF THE RADAR DATA

For these experiments the radar data from all sources are processed through the ADAS Cloud Analysis, that combines the radar data satellite and surface data.. The cloud analysis was initially adapted from the cloud analysis of LAPS (Albers et al. 1996) with several upgrades for ARPS (Zhang et al. 1998, Brewster 2002, Hu et al. 2006a).

Some cloud information comes from the hourly surface aviation observations taken between 50 and 55 minutes after the hour. Starting the assimilation cycling with the 50-00 minute time window thus allows these data to anchor the first analysis. Cloud information from any specials that may be taken other times are also used in the appropriate data assimilation window.

The radar processing is done in terms of radar volumes. The CASA radar data are collected in terms of sectors, typically covering the most intense convection, with a 360 surveillance scan at the 2° tilt, as illustrated in Figure 4. In the sequence of processing employed during CSET-2007 each sector scan decision is made in 1-minute intervals, the interval known as the Meteorological Command and Control (MC&C) heartbeat. From the collection of scans taken in the 10-minute window, the search for an appropriate radar scan sequence begins with the heartbeat that ends at the 6 minute point of the window, and continues backward in time to find a set of tilts that meets the minimum conditions of one complete 360 scan and having at least a total of 950 azimuthal degrees coverage as summed over all tilts in the vertical sequence. The pseudo-volume selection decision is made independently for each radar, but, in general, the radar scans among CASA radars are coincident in time because the CASA NetRad scanning is synchronized by the MC&C.

For NEXRAD data, the first complete volume that begins after the beginning of the data assimilation window is selected, except in those cases where 10-minute clear-air mode scanning is done. In that case, a scan covering the data assimilation window beginning at most two minutes before the data window is selected. Level-2 data from 14 NEXRAD radars in and around the forecast domain are used. NIDS (Level-3) data are used if the Level-2 NEXRAD data are not available.

The data from each radar are remapped to the model grid points, after screening for clutter and anomalous propagation. The remapping is accomplished using a local least squares fit to a function that is quadratic in the horizontal and linear in the vertical (Brewster et al. 2005b).

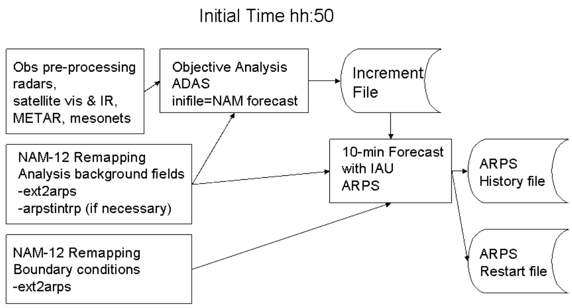

Fig 5. *Assimilation flowchart at initial time*.

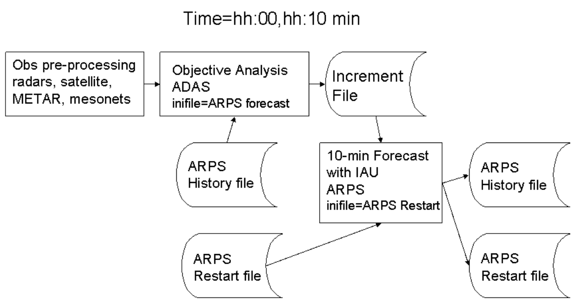

Fig 6. *Assimilation flowchart during the cycling period.*

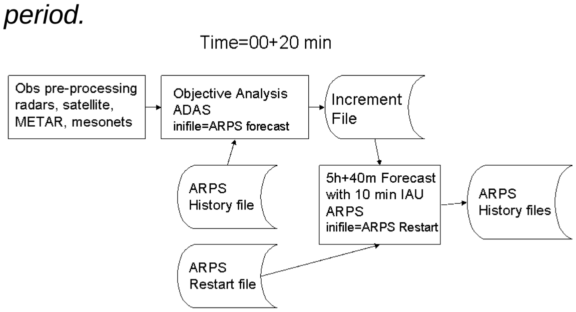

Fig 7. *Flowchart for the final cycle and forward model forecast.*

The remapped reflectivities from all radars are combined in a 3D radar mosaic using the maximum reflectivity from all sources at each point.

Latent heat adjustment is made for columns where clouds are added in the analysis at each cycle. A moist adiabatic ascent with entrainment is calculated and any excess in this temperature over the analyzed temperature is then added to the analyzed value. The same ascent profile is used to derive the mixing ratios of cloud water and cloud ice, which form increments to the background variables. Because of scavenging by precipitating hydrometeors, the cloud water and ice are reduced to 10 percent of the analyzed mixing ratio where precipitating hydrometeors are also diagnosed. This is a heuristic adjustment based on testing for a few cases, and more work is needed to find the most accurate accounting for the scavenging.

As indicated by the flowcharts in Figs 5-7, the first background field comes from the 12-km NAM forecast (interpolated in time from 3-hourly output grids). Thereafter the background is the ARPS model forecast valid at the beginning of the cycle.

5. RADIAL VELOCITY ASSIMILATION

We would like to use the radial velocity data from all radars and measure their impact on the analyses and forecasts. Due to the computational demands of analyzing the very large volume of radial velocity data from the radars it was necessary to develop specialized MPI code to handle the radial velocity data efficiently on the massively parallel processing system. Similar to techniques employed with the ARPS model the Doppler velocity (and other data) are handled by dividing the domain horizontally into patches that are distributed to the processors for analysis computations. The radar data are similarly distributed and the ADAS remapping of the radial data into Cartesian columns with the same horizontal spacing as the analysis grid facilitates this distribution. The radial velocities are locally co-converted to Cartesian wind component differences and analyzed using the Bratseth scheme as describe by Brewster (1996). The analyzed winds were then used in the IAU assimilation which is cycled in the same way as described in Section 4.

The software upgrade to efficiently process the 1-km resolution radial velocity data was accomplished after the real-time runs, and some preliminary results are included in the following comparisons to the real-time forecasts using reflectivity.

6. PRELIMINARY RESULTS

Quantitative verification of forecasts from CSET-2007 is still ongoing, but some sample results are shown here to provide a sense of the overall performance of the assimilation and modeling system.

Figure 8, a vertical cross-section of reflectivity from the first analysis time for 01 UTC, 9 May 2007, demonstrates how the CASA NetRad data fill-in the reflectivity below the NEXRAD data coverage, below about 1.2 km in this cross-section. Figure 9 shows the fifth model level (about 250 m AGL) where the NEXRAD covers only the area close to the KTLX and KFDR radars, while the addition of the CASA NetRad radar data fills the domain within the range of the NetRad radars.

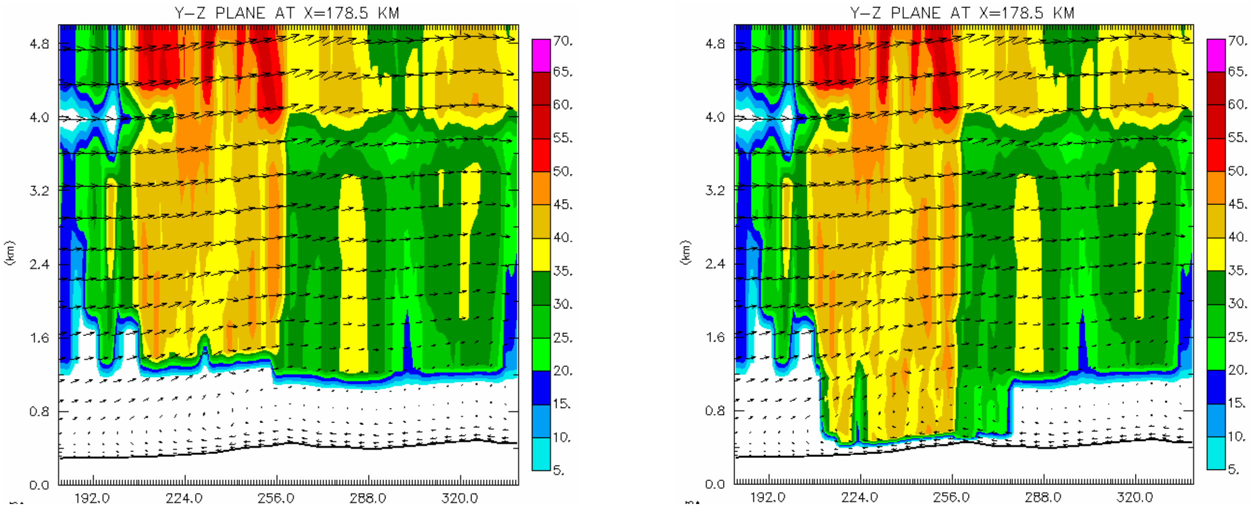

Fig. 8 Vertical cross-section of reflectivity from model hydrometeors for the 0050 UTC analysis for the 01 UTC 9 May 2007 assimilation. a) Using only NEXRAD reflectivity data, b) with the addition of CASA reflectivity data.

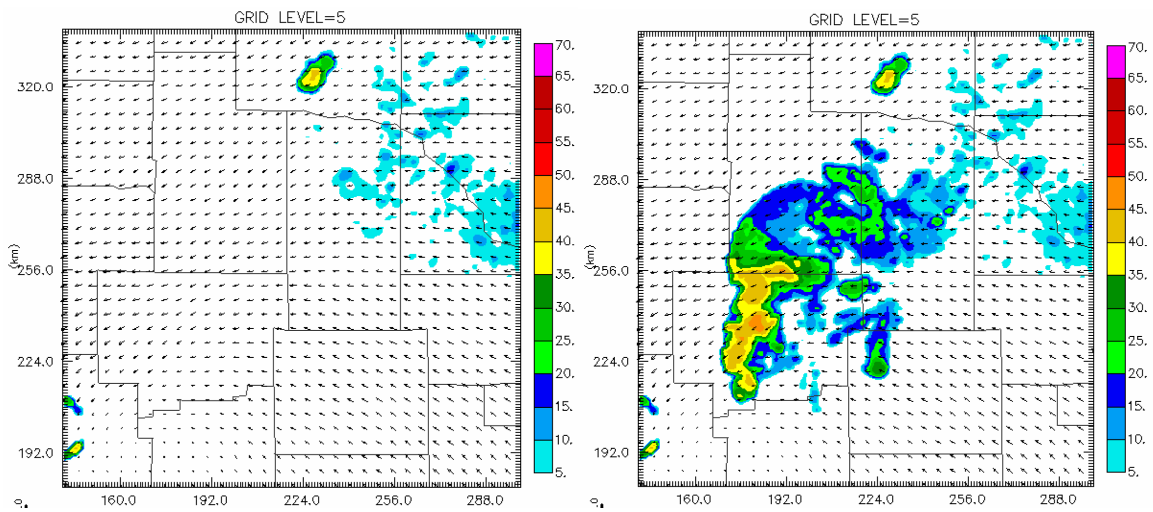

Fig 9. Horizontal cross-section at the k=5 model level (about 250 m AGL). a) NEXRAD only, b) NEXRAD combined with CASA NetRad.

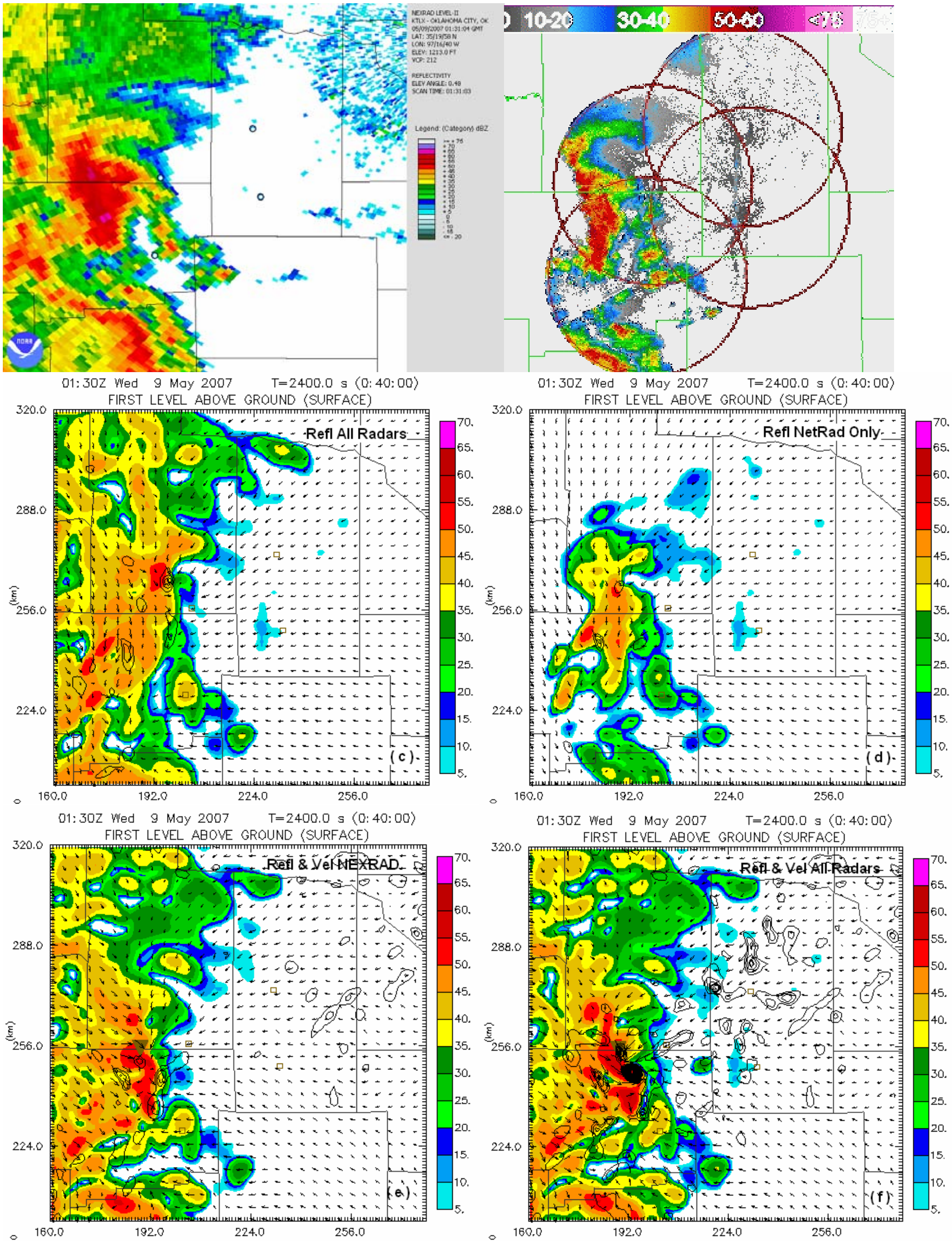

Fig 10. Forecast comparison at 0130 UTC, model reflectivity (dBZ) and vertical vorticity contours. a) KTLX 0.5 degree scan at 0129, b) CASA Composite at 0129, c) forecast including reflectivities from all radars, d) forecast with just CASA reflectivity data, e) forecast using reflectivity and velocity from just NEXRAD, and f) forecast using NEXRAD and CASA reflectivity and velocity.

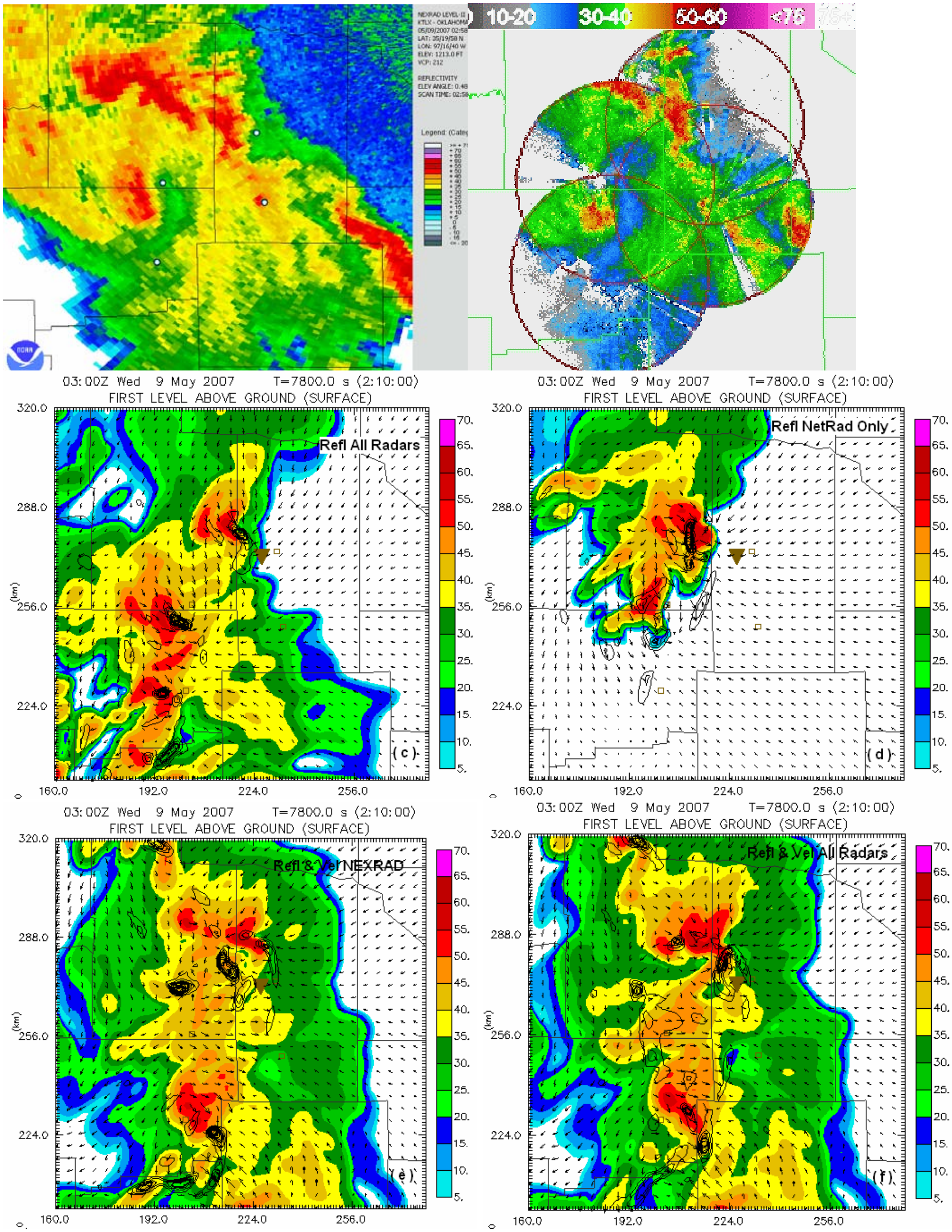

Fig 11. Forecast comparison at 0300 UTC, model reflectivity (dBZ) and vertical vorticity contours. a) KTLX 0.5 degree scan at 0129, b) CASA Composite at 0129, c) forecast including reflectivities from all radars, d) forecast with just CASA reflectivity data, e) forecast using reflectivity and velocity from just NEXRAD, and f) forecast using NEXRAD and CASA reflectivity and velocity

.

Figure 10 shows the reflectivity field at the lowest model level (10 m AGL) at the end of the assimilation period (0130 UTC) compared to the radar display from KTLX (a) and from the NetRad radar at this time. The characteristics of the ongoing convection, including details of the storm outlines are generally well replicated, though the observed reflectivites are a little stronger than the model's 1-km resolved values.

The CASA-NetRad-only run has a limited horizontal extent to the echoes compared to the observed, not surprisingly, but is otherwise well behaved. As in the combined run, the forecast tends to produce a maximum in low-level vorticity on the eastern edge of the cells.

The addition of velocity creates enhanced low-level vorticity on the edge of the strongest cell in the west-central portion of this figure, consistent with the observations (radar circulation indicated by the brown triangle at 192,256) with a small increase in vorticity from NEXRAD only velocity (Fig 10e) much stronger vorticity maximum once CASA data are added (Fig 10f). The change to the velocities also affects the reflectivity structure during the assimilation process.

Figure 11 shows the forecasted fields at 0300 UTC. At this time a circulation was noted in the KSAO CASA radar at the location shown by the brown triangle. Subsequent to this, a tornado developed that produced damage in the town of Minco, Oklahoma. The forecast model has produced a circulation indicated by the vertical vorticity contours. Another circulation indicated is associated with the evolving mesoscale convective vortex, some indication of which is seen in the spiral shape of the observed reflectivity. With reflectivity-only (Figs 11b,c) the eastward progress of the system is too slow, while the addition of NEXRAD velocity improves the depiction of the as well as

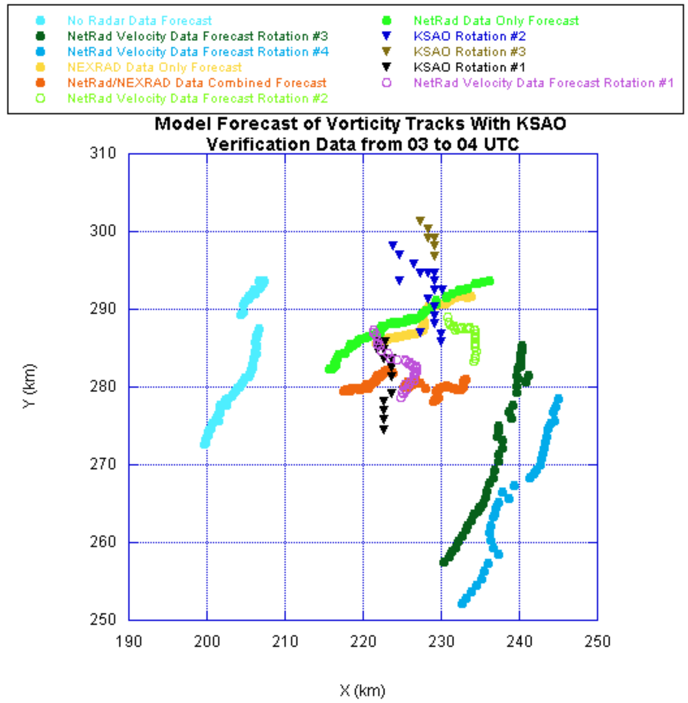

Fig 12 Vortex tracks comparing the radar (triangles) and the model paths (circles). 03-04 UTC 9 May 2007. See Color legend for track identification

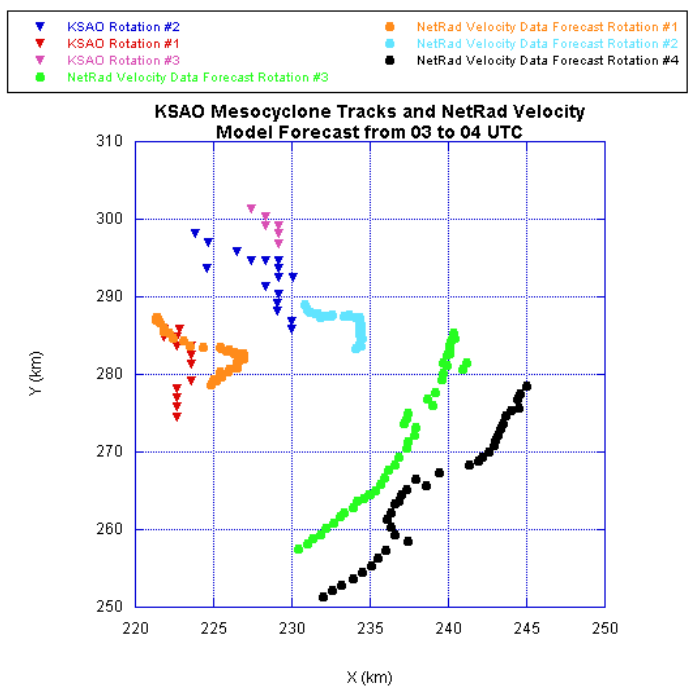

Fig 13 Vortex tracks comparing the radar (traingeles) and the model paths (circles). 03-04 UTC 9 May 2007. See Color legend for track identification

producing a maximum in low-level rotation near the observed feature. Addition of CASA data shows a vorticity maximum a little closer to the observation and better rotational structure to the reflectivity.

7. VORTICITY TRACK VERIFICATION

We found that the observation and data assimilation system were able to identify and forecast areas of strong vertical vorticity, which at times may be associated with thunderstorm mesocyclones. In order to verify a set of forecasts from 9 May 2007, the circulation centers from the low-level scans of the Doppler radars were recorded and translated into the model grid Cartesian coordinates. The location of the model centers of low-level rotation (k=7 surface, approximately 600 m AGL) were recorded from one-minute animations and the tracks of the circulation centers compared. This comparison was done while the MPI code was still under development, so it used a reduced set of velocity data that were at 2-km spacing (selecting every-other velocity datum from the 1-km remapped dataset). Complete analysis of the forecasts using full-resolution forecasts will be done soon.

Fig. 12 shows vortex tracks from several forecasts (circles) compared with observed low-level circulations from the CASA radar data (triangles) in the period 03-04 UTC (1.5 to 2 h from the last data ingested). All of the forecasts produced vorticity maxima in the region, the forecasts without radar data having time for spin-up by this point in the forecast. However, without radar data (light blue circles) the location of the circulation tracks are about 25-30 km too far west. With reflectivity data assimilated the location of the circulations is excellent, though the tracks show primarily a west-to-east motion. Addition of radial velocity data from all radars produces vorticity tracks that are close to the observed location (Fig. 13) and two show the observed character of the actual paths, moving generally from south-to-north, then turning to the northwest.

8. CSET-2008: 3DVAR ANALYSES AND FORECASTS

In preparation for CSET-2008 the ARPS 3DVAR analysis program (Gao et al. 2004, Ge et al. 2007) will be similarly updated for MPI processing. Development of this code is aided by the fact that the 3DVAR code shares the same modular data I/O and pre-processing as ADAS. The MPI version of the code should allow the use of 3DVAR with the 1-km processed radar data during real-time in spring 2008. An assimilation cycle similar to the one used with ADAS in CSET-2007 will be used. The system will be set-up with the goal of completing all parallel forecast runs in time for subjective evaluation the following day in the Norman Hazardous Weather Testbed.

In addition to the forecast experiments we plan to run the 3DVAR program at high resolution (grid spacing of 200-500 m) over several levels from the surface to 3-km AGL over a domain surrounding the radar network (Fig. 14) as a real-time visualization tool.

A companion paper in this conference by Gao et al. (2008) describes the preliminary testing and tuning of the 3DVAR analysis.

9. DISCUSSION

Some verification results for one case have been shown here that demonstrate that the data assimilation system with cycled IAU performs well at ingesting reflectivity data from combined NEXRAD and CASA NetRad radars for springtime convection in the Southern Plains.

Once the analysis and assimilation is rerun for all of the CSET-2007 cases using the radial velocity data at full resolution (1-km horizontal spacing), complete quantitative verification will be performed to judge precipitation forecasting skill. 20 case days covering a wide variety of convective modes were tested and archived.

Additional periods with low-level circulations will be compared to observed circulations and scored for position error and skill in predicting trends. Forecasts with and without the CASA radar data will be compared for the two case days that had significant vortex features (10 April and 9 May 2007).

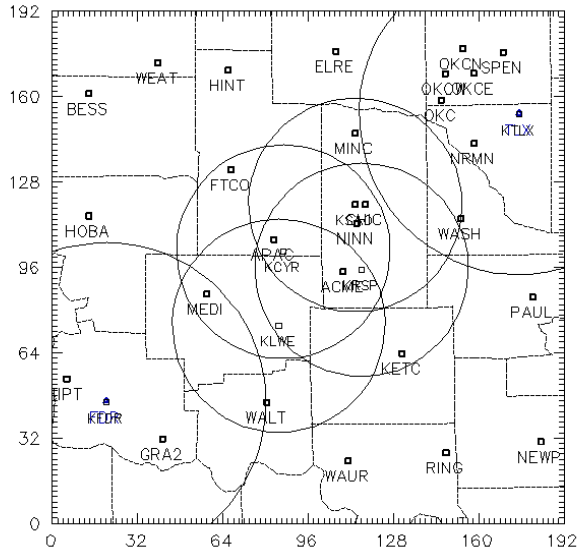

Fig. 14 One proposed real-time 3DVAR analysis domain for CSET-2008 showing 40-km range rings from the CASA radars, 60 km range rings from the NEXRAD radars and the locations of the Oklahoma Mesonet surface stations. Distance scale in km.

10. ACKNOWLEGMENTS

The authors would like to acknowledge the efforts of the CASA Sensing Team, especially Francesc Junyent, V. Chandra Chandrasekar and Nitin Bharadwaj, for building and deploying the CASA radar hardware and software. Thanks to all the CASA project teams for supporting the operation of the IP1 radars during CSET-2007. University of Oklahoma student weather forecasters from Oklahoma Weather Lab, especially Patrick Marsh, also supported the 2007 spring operations.

This project utilized high resolution surface observations from the Oklahoma Mesonet provided by the Oklahoma Climatological Survey.

The computations for the data assimilation and forecasts were done on the facilities generously provided by the OU Supercomputing Center for Education and Research (OSCER). Thanks to Henry Neeman, OSCER Director, and Brandon George, OSCER system administrator, for their help.

This work is supported primarily by the Engineering Research Centers Program of the National Science Foundation under NSF award number 0313747. Software development to bring CASA radar data into the CAPS analysis systems is supported in part through the NSF ITR Linked Environments for Atmospheric Discovery (NSF ATM-0331594). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation.

11. REFERENCES

Albers, S.C., J.A. McGinley, D.A. Birkenhuer, and J.R. Smart, 1996: The local analysis and Prediction System (LAPS): Analysis of clouds, precipitation and temperature. *Wea. and Forecasting*, 11, 273-287.

Bloom, S.C., L.L. Takacs, A.M. da Silva, and D. Ledvina, 1996: Data assimilation using incremental analysis updates. *Mon. Wea. Rev*., **124**, 1256-1271.

Brewster, K. A., 1996: Application of a Bratseth analysis system including Doppler radar. *Preprints, 15th Conference on Wea. Analysis and Forecasting*, Norfolk VA, Amer. Meteor. Soc., Boston, 92-95.

Brewster, K.A., 2002: Recent advances in the diabatic initialization of a non-hydrostatic numerical model. *Preprints, 21st Conf. on Severe Local Storms*, and *Preprints, 15th Conf. Num. Wea. Pred. and 19th Conf. Wea. Anal. Forecasting*, San Antonio, TX, Amer. Meteor. Soc., J51-54.

Brewster, K., M. Hu, M. Xue, and J. Gao, 2005a: Efficient assimilation of radar data at high resolution for short-range numerical weather prediction, World Weather Research Program Symposium on Nowcasting and Very Short-Range Forecasting, WSN05, Tolouse, France, WMO, Symposium CD, Paper 3.06.

Brewster, K., L. White, B. Johnson, and J. Brotzge, 2005b: Selecting the sites for CASA NetRad, a collaborative radar network. *Ninth Symposium on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans and Land Surface (IOAS-AOLS), 85th Amer. Meteor. Soc. Annual Meeting CD*, Paper: P3.4.

Brotzge, J., K. Brewster, V. Chandrasekar, B. Philips, S. Hill, K. Hondl, B. Johnson,

E. Lyons, D. McLaughlin, and D. Westbrook, 2007: CASA IP1: Network operations and initial data. Preprints, 23rd International Conf. on Interactive Information Processing Systems (IIPS) for Meteor., Ocean., and Hydrology, AMS Conf., San Antonio, TX.

Gao, J., M. Xue, K. Brewster, and K. K. Droegemeier 2004: A three-dimensional variational data assimilation method with recursive filter for single-Doppler radar, *J. Atmos. Oceanic. Technol.* **21**, 457-469.

Gao, J., K. Brewster, Y. Wang, K. W. Thomas, J. Brotzge, and M. Xue, 2008: High-Resolution Three-dimensional Wind Analysis of CASA IP-1 and WSR-88D Radar Data using the ARPS 3DVAR, *12th Conference on IOAS-AOLS,* New Orleans, LA, Amer. Meteor. Soc., 16.5.

Ge, G., and J. Gao, 2007: Latest development of 3DVAR system for ARPS and its application to a tornadic supercell storm, *22nd Conference on Weather Analysis and Forecasting/18th Conference on Numerical Weather Prediction*, Amer. Meteor. Soc., 2B.6.

Hu, M., M. Xue, and K. Brewster, 2006a: 3DVAR and Cloud Analysis with WSR-88D Level-II Data for the Prediction of Fort Worth Tornadic Thunderstorms Part I: Cloud analysis. *Mon. Wea. Rev.*, **134**, 675-698.

Hu, M., M. Xue, J.-D. Gao and K. Brewster: 2006b: 3DVAR and Cloud Analysis with WSR-88D Level-II Data for the Prediction of Fort Worth Tornadic Thunderstorms Part II: Impact of radial velocity analysis via 3DVAR, *Mon Wea Rev.*, **134**, 699-721.

Junyent, F., V. Chandrasekar , D.J. McLaughlin1, S. Frasier, E. Insanic, R. Ahmed, N. Bharadwaj , E. Knapp1, L. Krnan1 and R. Tessier, 2005: Salient Features of Radar Nodes of the First Generation NetRad System. Proceedings of Intl Symposium 2005, IEEE Geoscience and Remote Sensing, Seoul, Korea.

Liu, Y., V. Bringi, M. Maki, 2006: Improved rain attenuation correction algorithms for radar reflectivity and differential reflectivity with adaptation to drop shape model variation. *IEEE Geoscience and Remote Sensing Symposium, IGARSS-2006*, 1910-1913.

McLaughlin, D.J., V. Chandrasekar, K. Droegemeier, S. Frasier, J. Kurose, F. Junyent, B. Philips, S. Cruz-Pol, and J. Colom, 2005: Distributed Collaborative Adaptive Sensing (DCAS) for Improved Detection, Understanding, and Prediction of Atmospheric Hazards. 9th Symp. Integrated Obs. Assim. Systems - Atmos. Oceans, Land Surface (IOAS-AOLS), Amer. Meteor. Soc., San Diego, CA.

Park, S.-G., V. Bringi, V. Chandrasekar, M. Maki, and K. Iwanami, 2005a: Correction of radar reflectivity and differential reflectivity for rain attenuation at X Band. Part I: Theoretical and empirical basis. *J. Atmos. Oceanic Tech.*, **22**, 1621-1632.

Park, S.-G., M. Maki, K. Iwanami, V. Bringi, and V. Chandrasekar, 2005b: Correction of radar reflectivity and differential reflectivity for rain attenuation at X Band. Part II: Evaluation and application. *J. Atmos. Oceanic Tech.*, **22**, 1633-1655.

Schenkman A. D., A. M. Shapiro, K. Brewster, M. Xue, J. Gao, and N. Snook, 2008: High resolution assimilation of CASA radar data from a tornadic convective system, *Symposium on Recent Developments in Atmospheric Applications of Radar and Lidar*, Amer. Meteor. Soc. P1.6

Siggia, A.D. and R.E. Passarelli, Jr., 2004: Gaussian model adaptive processing (GMAP) for improved ground clutter cancellation and moment calculation. Proceedings of ERAD-2004, 67-73.

Xue, M., K. K. Droegemeier, and V. Wong, 2000: The Advanced Regional Prediction System (ARPS) - A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part I: Model dynamics and verification. *Meteor. Atmos. Physics*. **75**, 161-193.

Xue, M., K. K. Droegemeier, V. Wong, A. Shapiro, K. Brewster, F. Carr, D. Weber, Y. Liu, and D.-H. Wang, 2001: The Advanced Regional Prediction System (ARPS) - A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part II: Model physics and applications. *Meteor. Atmos. Physics*. **76**, 143-165.

Zhang, J., F. Carr and K. Brewster, 1998: ADAS cloud analysis. *Preprints, 12th Conf. on Num. Wea. Prediction*, Phoenix, AZ, Amer. Meteor. Soc., Boston, 185-188.

Zink, M., D. Westbrook, S. Abdallah, B. Horling, V. Lakamraju, E. Lyons, V. Manfredi, J. Kurose, and K. Hondl, 2005: Meteorological Command and Control: An end-to-end architecture for a hazardous weather detection sensor network, *Workshop on End-to-End, Sense-and-Respond Systems, Applications, and Services*, Seattle, WA, 37-42.