9.4 A NOWCASTING SYSTEM USING FULL PHYSICS NUMERICAL WEATHER PREDICTION INITIALIZED WITH CASA AND NEXRAD RADAR DATA

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1. INTRODUCTION

Increasingly accurate cloud-resolving models can now be run in real-time thanks to improvements in computer speed, increases in number of processors per machine, multi-processor algorithms and advanced data assimilation techniques. While traditionally the most accurate forecasts of thunderstorms in the first 0-3 hours have come from extrapolation of echoes, the tipping point when full physics models have the advantage is moving closer to t=0 (e.g. Kong et al., 2010). Using a full-physics model allows for the prospect of better forecasting changes in mode, direction and speed of motion and overall evolution compared to extrapolative methods.

The Center for Analysis and Prediction of Storms has been on the forefront of developing high resolution models, such as the Advanced Regional Prediction System (Xue et al., 2000, Xue et al., 2001), complex data flows for real-time processing of radar and other high resolution data (e.g, Brewster et al., 2005, Brewster et al., 2008), and running real-time experiments using ARPS, WRF-ARW and WRF-NMM (e.g., Xue et al., 2010, Kong et al, 2010).

In late 2006 the NSF Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA, McLaughlin et al. 2010, Mc Laughlin et al., 2010) 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). Figure 1 shows the location of the CASA radar network with inset photographs of the radar towers.

Data from the CASA radars have been as part of a series of experiments to test the effectiveness of the CASA radars and their unique adaptive sampling methods to improve weather warnings, emergency preparedness and emergency response in and around the CASA IP-1 radar network. During the past two springs the emphasis of the numerical weather prediction (NWP) aspects of the CASA experiments has increasingly been driven toward improving very short-term forecasts of severe thunderstorms while decreasing the turnaround time, to effectively drive the system toward a 0-2 hour nowcasting system. This paper reports on some results from the NWP experiments performed in the spring of 2009 and 2010.

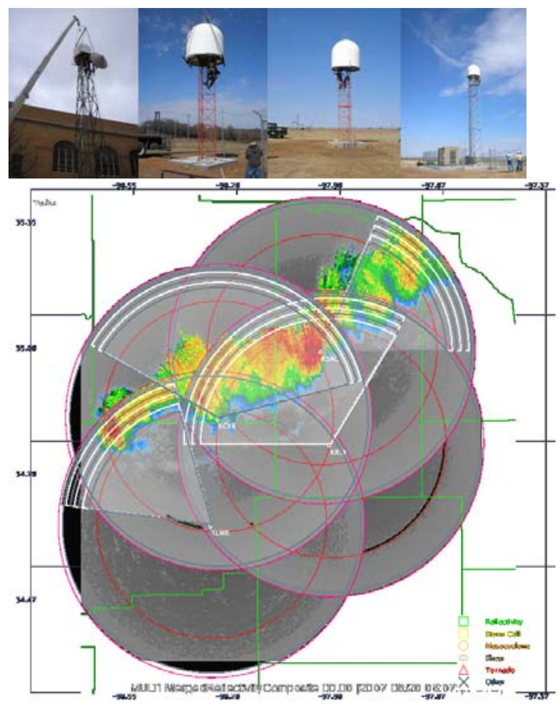

Fig 1. a) *Photographs of four IP1 CASA X-band radars being installed. b) Reflectivity from IP1 CASA IP1 radars on a map of southwestern Oklahoma, with an overlay display indicating the adaptive scanning plan for a single scan plan. Multiple arc lines in each sector show how many elevation angles are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

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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. 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). The radars operate 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 systems.

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 (NWC) in Norman. Raw data from the CASA radars along with the results from the real-time analysis and NWP experiments are examined in the Hazardous Weather Testbed (HWT) in the NWC. Teams of Emergency Managers and evaluate the data and give feedback regarding the usefulness of the data and products in meeting the needs of their communities.

3. SPRING 2009 DATA ASSIMILATION

For the CASA data assimilation effort the CAPS 3DVAR system 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). In this application of the IAU, the vertical velocity and pressure increments are not applied because we don't have high resolution measurements of those variables aside from Mesonet data at the surface. This allows the under-observed variables to freely adjust to increments in horizontal winds, latent heating and hydrometeors through the model dynamics.

Radar reflectivity from all radars (NEXRAD and CASA) are quality controlled, then remapped using a 3D least squares method, and are combined in a 3D radar mosaic using the maximum reflectivity from all sources at each point (Brewster et al., 2005).

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, with corrections for entrainment and scavenging when there are raindrops present (i.e., indicated by radar precipitation echoes).

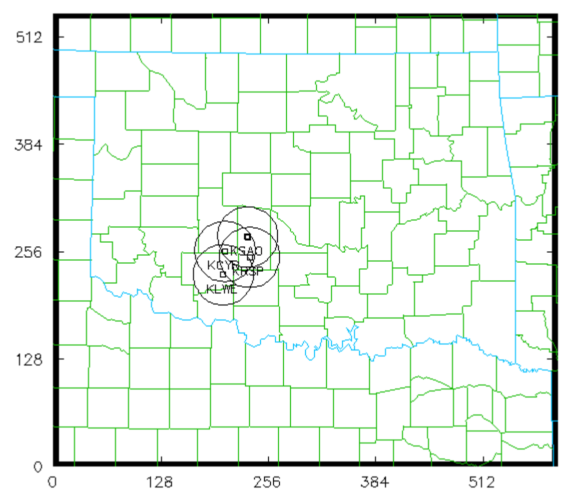

Fig. 2. 1-km assimilation and forecast domain used in 2009 covering most of Oklahoma and neighboring parts of North Texas and southern Kansas. CASA radars with 40 km range rings in black Distance scale in km.

Radial velocities are analysed using the 3DVAR scheme described in Gao et al. (2004, 2008) and Ge et al., 2007. The radial velocities are quality controlled and de-aliased, then remapped to the Cartesian grid using a 3-dimensional least squares fitting of surrounding data. This serves the purpose of interpolating where the data are more sparse than the grid while thinning and smoothing the data where more dense than the grid spacing.

For 2009, the initial time of the assimilation for each day was adapted to the weather, beginning near the time of the first echo development in the CASA 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. We had sufficient computing resources to have up to two forecasts running at the same time.

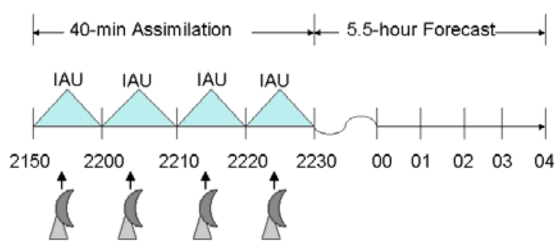

Fig 3 Schematic of data assimilation and forecast for a sample nominal start time of 2200 UTC, indicating the sequence of cycling with IAU.

The initial 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.

The 2009 forecast domain was 600 × 540 km. Improvements in multi-processor algorithm efficiency and the use of 800 cores of the OU OSCER supercomputer resulted in a 1.5 h turnaround time for the 5.5 h forecasts in 2009, an improvement over prior years. Forecast products in graphical form were immediately posted to the web and thus available to the people in the HWT, and elsewhere as the forecasts were generated.

4. 14 MAY 2009 CASE

Forecasts were made for 15 cases in the spring 2009 with a wide variety of weather. A notable case in 2009 was the successful assimilation and forecasting of the evolution of the May 13, 2009 tornado near Anadarko, Oklahoma. This tornado and accompanying supercell thunderstorm produced millions of dollars of damage, including significant damage to the Western Farmers Cooperative power generating plant in Anadarko, Oklahoma.

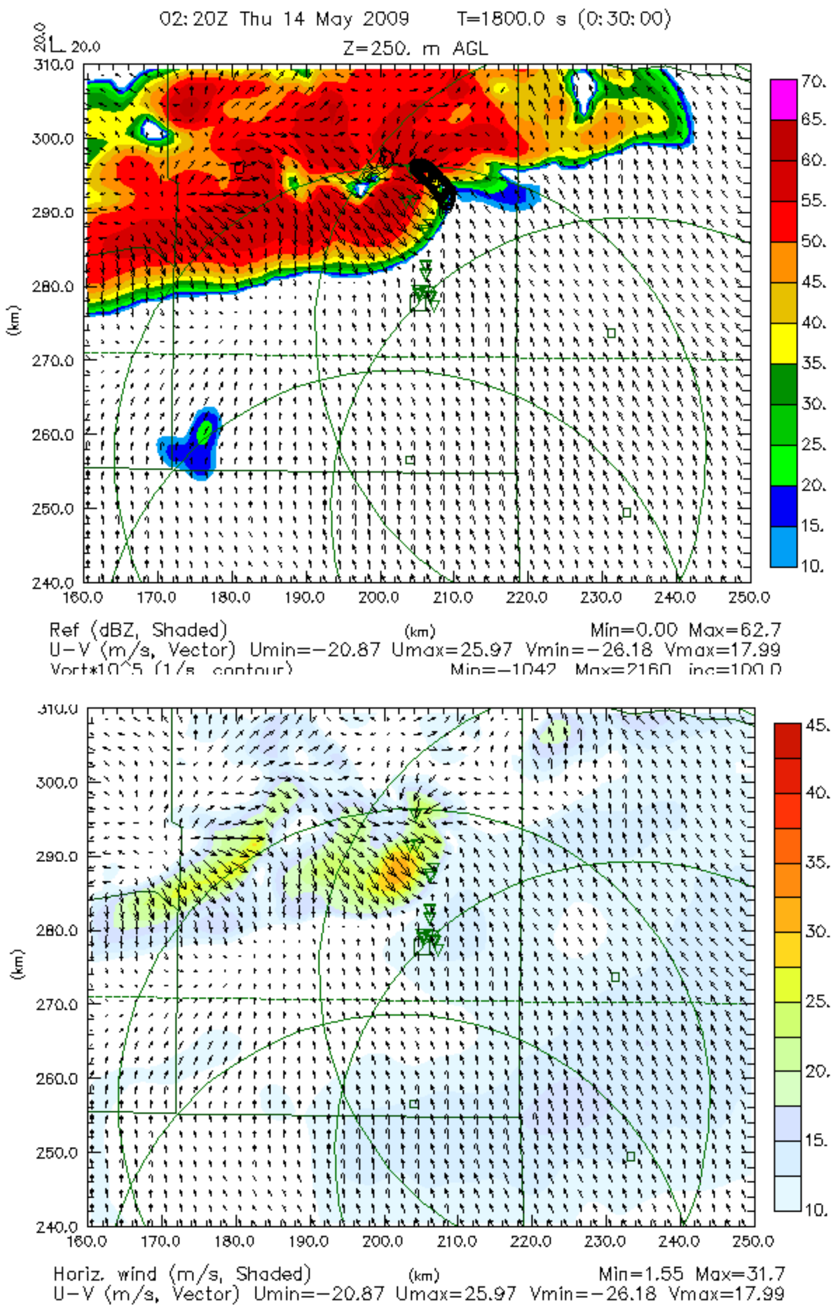

Figure 4. ARPS forecast wind and reflectivity fields at 0220 UTC at 250 m AGL for a subset of the ARPS forecast domain. Left: Simulated reflectivity (colors), wind vectors and positive vertical vorticity (contours), Right: Wind vectors and wind speed (colors). Triangles indicate the locations of observed damage. The large open square is the location of the town of Anadarko and small squares indicate the location of the CASA radars. The background map has county boundaries and CASA 40-km range rings.

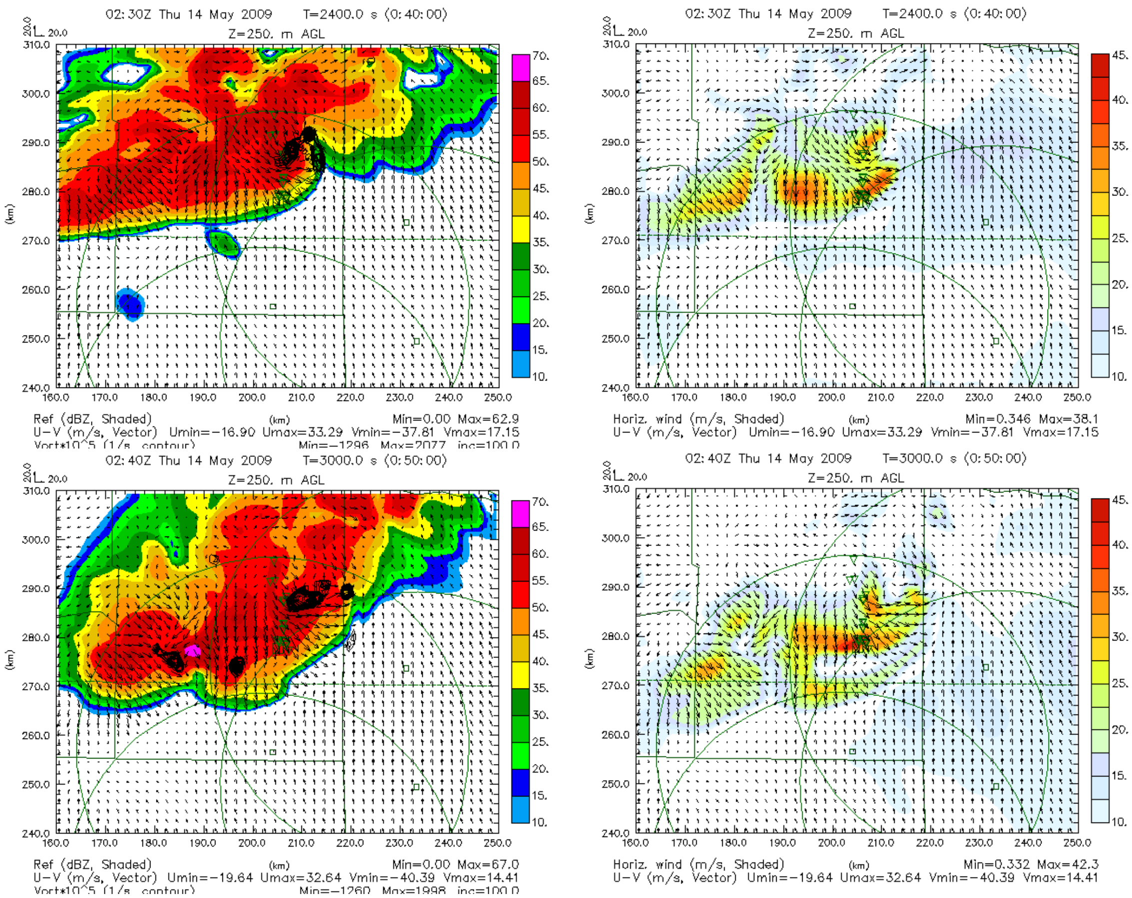

Figure 5. As in Fig. 4, except at 02:30 UTC (upper) and 2:40 UTC (lower), after 20 minutes and 30 minutes of IAU data assimilation using surface, CASA and NEXRAD data, respectively.

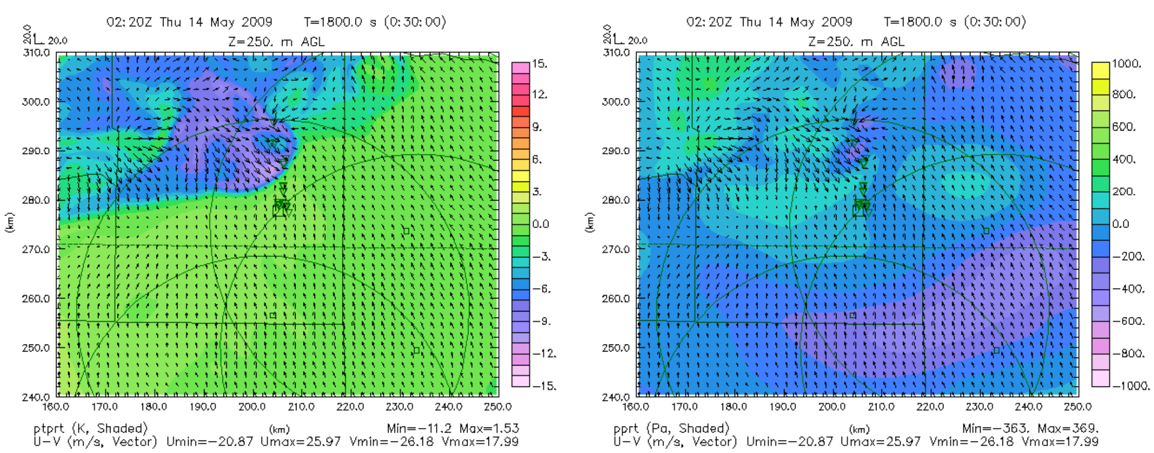

Figure 6. *As in Fig 4., except Left: Perturbation potential temperature (K), Right: Perturbation pressure (Pa)*

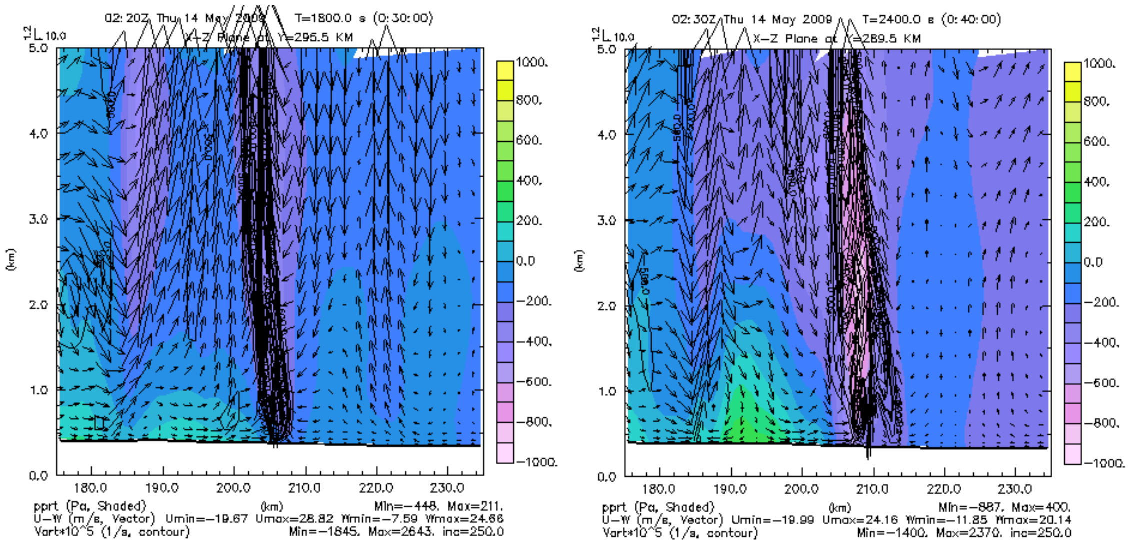

Figure 7. *Vertical X-Z cross-section through the center of the primary vorticity center. Perturbation pressure (Pa, colors), wind vectors and vertical vorticity (contours). Left: 0200 UTC, Right: 0230 UTC.*

Figure 4 shows a snapshot of the assimilation at 0220 UTC, which is near the time of the initial tornado damage, and 30 minutes into the assimilation cycle. Although the 1-km resolution is not high enough to resolve the tornado itself, a strong concentrated cyclonic circulation is indicated in the vertical vorticity contours very close to the observed damage path (inverted triangles), along the leading edge of the thunderstorm as it progresses toward the south-southeast. Wind speeds at this level exceeded 30 m s^{-1}

The progression of this feature in time was handled well by the ARPS system (Fig 5) as the feature continued to progress south-southeastward and the region of strong rotation evolved and eventually the cell became outflow dominant with strong north-northwesterly winds near the surface.

With a properly configured assimilation system it is also possible to diagnose the evolution of unobserved variables. In this case, the evolution of the pressure and temperature features can be followed over this same time period. Figure 6 shows a snapshot of the perturbation potential temperature and pressure fields at 0220 UTC. Similarly, vertical cross-sections through the main region of vorticity (example,Figure 7) show a structure consistent with accepted knowledge of rotation evolving with a strong mesocyclone, strong vertical velocity is correlated with strong vertical vorticity and a strong negative pressure perturbation develops in the base of the updraft, nearly -9 hPa at 0230 UTC.

An important goal of this project is to evaluate the effect of the CASA radar observations on such an assimilation and forecast system. Figure 8 compares the assimilated wind and vertical vorticity fields at 02:20 UTC and 02:30 UTC produced by the ARPS assimilations using IAU with the CASA data (left column) versus those produced excluding the CASA data. It is clear that although it is possible to create some low-level spin-up along the edge of this storm without the CASA data, the CASA data has aided in producing a stronger vertical vorticity maximum and is closer to the observed damage track.

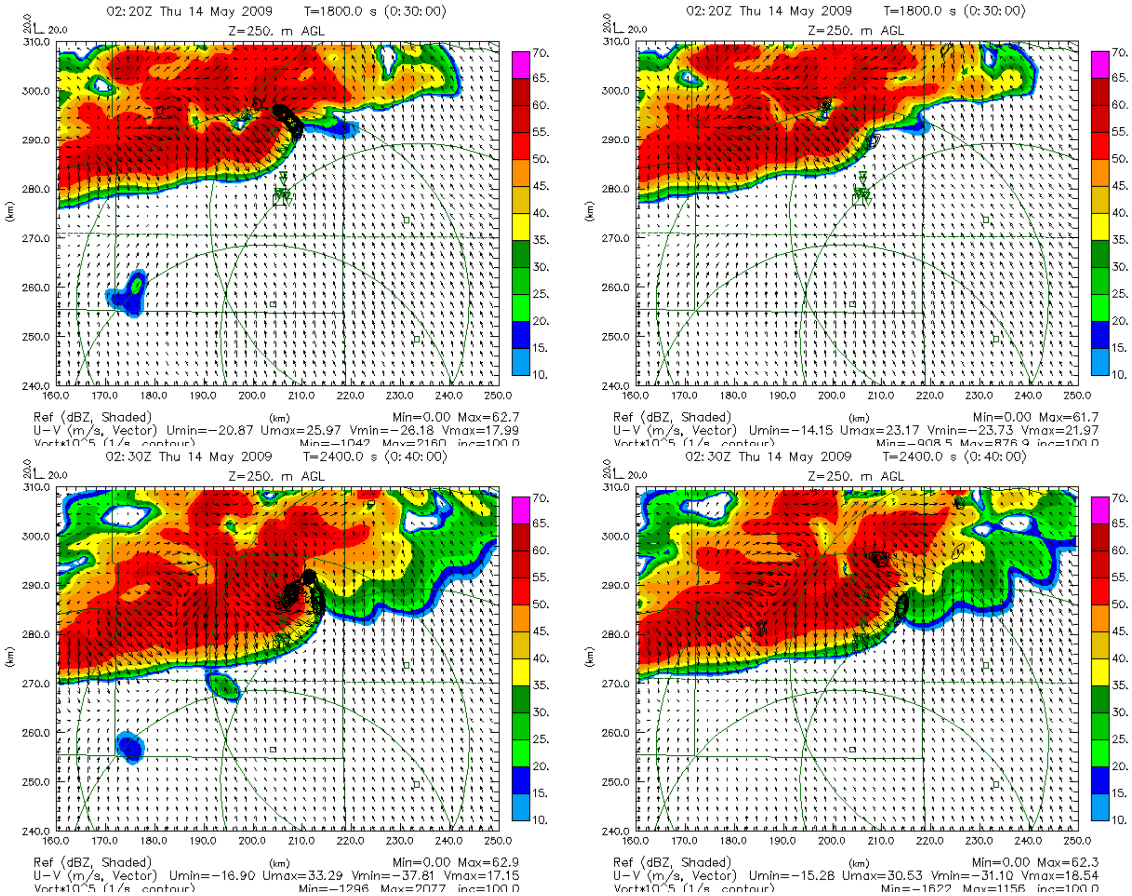

Figure 8 As in Fig 2., except Left: Reflectivity and vertical vorticity including CASA data, Right Reflectivity and vertical vorticity produced when CASA data are excluded from the assimilation. Upper: 02:20 UTC, Lower 02:30 UTC.

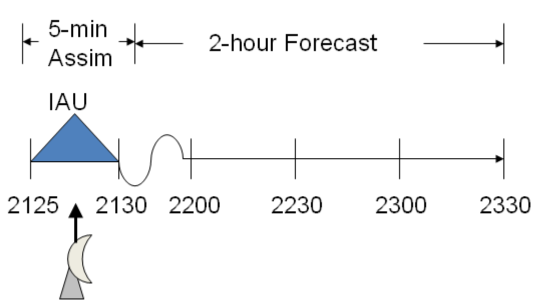

Figure 9. Assimilation and forecast timeline for the 2010 forecast configuration.

5. 2010 FORECAST CONFIGURATION

For 2010 there was an emphasis on getting much faster turnaround so the Emergency Managers could give immediate feedback on products and evaluate the forecasts for events in their jurisdictions, which are in and near the CASA radar network. A goal was established to return the forecast in 10 minutes or less and run forecasts continuously using two sets of processors.

The assimilation system was then re-designed to have only a single analysis with a short, 5-minute IAU spin-up, followed by a 2-hour forward forecast using ARPS. The domain size was reduced to 350 x 320 km and 800 processors were used for each assimilation and forecast. In this way the system is able to provide the 10-minute turnaround and is thus configured closer to what is considered a nowcasting/forecasting system.

6. RESULTS 10 MAY 2010

On 10 May 2010 thunderstorms formed on a dryline in western Oklahoma and some storms initiated within the CASA radar network. Wind speeds aloft were quite strong such that storm motion was 25 ms^{-1} or more, and by the time storms developed significant rotation they were outside the CASA radar network. Despite that fact, some good forecasts were generated by the system.

Figures 10 and 11 shows a sample set of forecasts initialized at nominal time of 2140 UTC using radar data collected in the preceding 5-minute window. By 2220 UTC, the middle column of Fig 11, a strong tornado has formed near the border of Cleveland and Oklahoma Counties associated with the storm labeled "Storm A" in the remapped 0.5 tilt scans shown in the lower rows of Fig 11. The model does a good job in maintaining Storm A, developing low-level rotation and tracking the cells to the northeast from their genesis within the CASA radar network. The track of the storm is biased a bit to the north compared to the observed, and the model weakens a secondary cell that forms south of this cell (Storm B) between 2210 and 2220. In reality that storm remained strong, and developed a tornado on the south edge of Norman between 2230 and 2235.

7. DISCUSSION & FUTURE WORK

The results for the 14 May 2009 case are very exciting and show great promise for the prospect of properly spinning-up storm-scale NWP using high resolution data. The runs were not returned in real-time however, because the event happened as the storms were just entering the CASA network, thus they were already peaking near the end of the assimilation period, so they did not provide any true lead time in this case. It is worth noting the evolving circulation in companion 400m 3DVAR winds did catch the eye of the Emergency Manager in this case, providing notice in advance of official NWS warnings.

When the processes is accelerated using the single 5-miunte IAU and using 600 processors we are able to achieve real-time results. The, system proved stable even in the face of a fast-moving, high CAPE event like 10 May 2010.. The forecasts on 10 May were fairly successful for Storm A, with a small phase error to the north of the true track. The model generally did not do a good job with the continued development of Storm B in the Norman area with this configuration and hence by the end of the 50 minute sequence shown here the south end of this series of supercells is too far north.

Objective scoring, including object oriented and ensemble (time-lagged ensembles using 5-6 members over an hour) methods will be performed in the coming months to quantify the accuracy of this and other forecasts of 10 May 2010.

We are aware of two possible things that could help improve the nowcast-forecast system. 1) the use of a more sophisticated microphysics package, 2) performing one or more cycles of forecast and analysis in initializing the model.

Recent work has shown there is great sensitivity of the cold pool strength to the details of the microphyiscs in the model. Most notably forecast improvement has been seen in case studies when multi-moment microphysics schemes are employed (Dawson et al., 2009). The model will be re-run with the Milbrandt and Yau multi-moment schemes that are currently supported in the ARPS (Milbrandt and Yau, 2005a, 2005b). Timings will be compared to see if this upgrade is feasible for future real-time experiments.

One or more additional cycles may improve the initial condition of the forecast. While in the case of 10 May 2010 there was error in the storm development that occurred after the initial modeled storms left the CASA network, it is still possible that some improvement to the initial winds, clouds and updraft strength may improve the ensuing forecast. Schenkman et al. (2010) have done experiments for other CASA cases in which an hour or more of cycling is done. While such long cycles would add to the turnaround time, in time we believe it will one day be possible to maintain a continuously assimilated state that is corrected every 5 or 10 minutes and then forecasts could be launched from this state as needed. One stumbling block to the current cloud analysis methods is that they are well suited for adding clouds and small scale features to a large scale background but it can be more challenging to remove erroneous small-scale perturbations in the fields during cycling of the cloud analysis. Removing precipitation is relatively straightforward, but removing the resulting small-scale temperature and humidity perturbations is more challenging.

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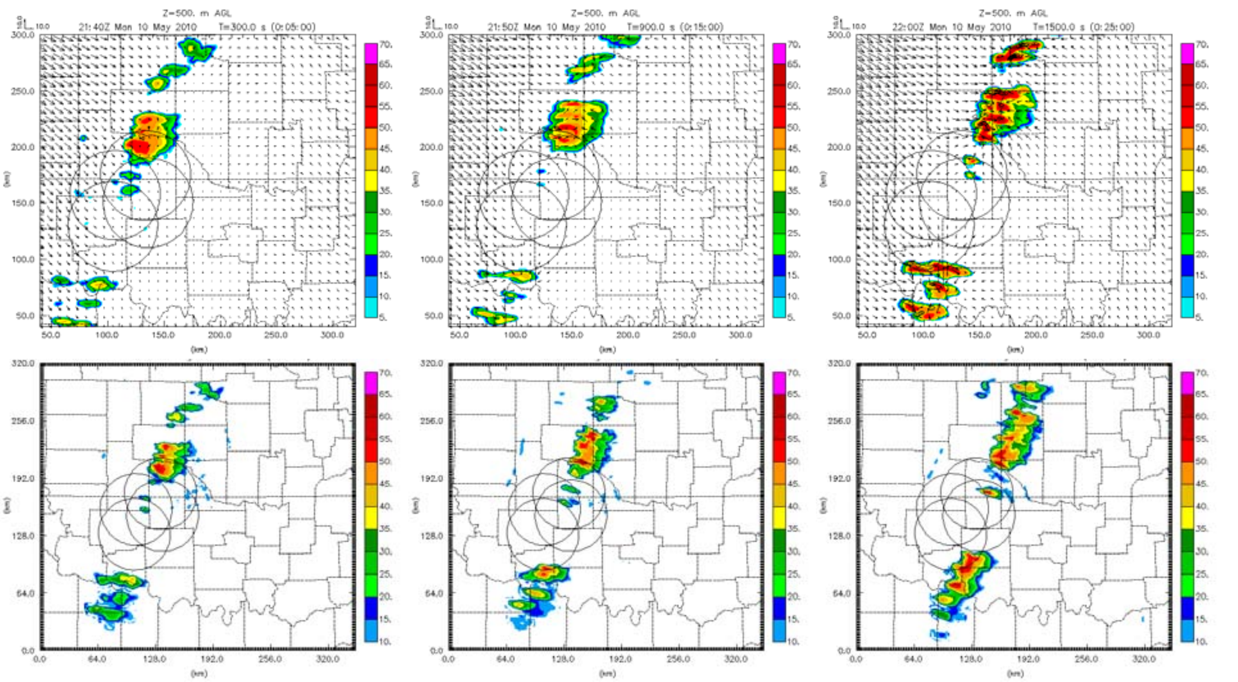

Figure 10. Forecast Perturbation winds and reflectivity (dBZ) at 500 m AGL (upper row) and verifying 2d remapped 0.5 degree scan radar from KTLX (lower row) for 2140 UTC, 2150 and 2200 UTC 10 May 2010, left to right.

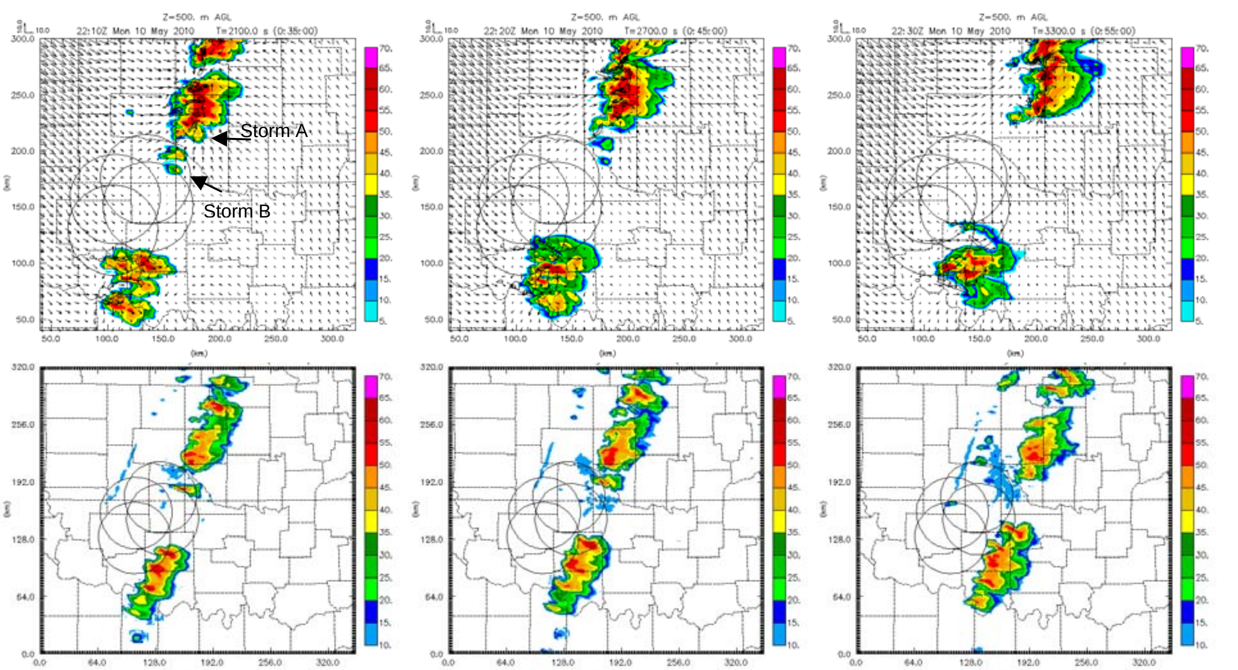

Figure 11 Forecast results (upper row) and verifying 2d remapped 0.5 degree scan radar from KTLX (lower row) for 2210 UTC, 2220 and 2230 UTC 10 May 2010, left-to-right. As in Figure 10.

8. ACKNOWLEGMENTS

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