10R.2 THE 15 MAY 2003 SHAMROCK, TEXAS, SUPERCELL: A DUAL-DOPPLER ANALYSIS AND EnKF DATA-ASSIMILATION EXPERIMENT

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1. INTRODUCTION

Gaining a detailed understanding of tornadogenesis in supercell thunderstorms is severely limited by the inability to observe the process consistently at a close distance. However, the capacity to collect observational data of tornadogenesis has increased greatly in the past ten years due to the advancement of mobile Doppler radar systems. More specifically, the use of dual-Doppler analysis techniques can provide fine-scale observations of wind fields in supercell thunderstorms. These studies use several methods to obtain dual-Doppler data of supercells.

Early attempts at collecting dual-Doppler datasets required a supercell to pass through an area where two non-mobile, Doppler research radars were located (e.g. Brandes 1978; Dowell and Bluestein 1997). Later attempts, during projects such as VORTEX, fitted airplanes with Doppler radars to obtain pseudo-dual-Doppler data as the planes flew in the vicinity of supercells (e.g. Wakimoto and Atkins 1996; Wakimoto et al. 1998; Wakimoto and Liu 1998; Ziegler et al. 2001; Dowell and Bluestein 2002; Wakimoto et al. 2003). Unfortunately, supercell passes through a non-mobile network of radars are rare and require a great deal of good luck. Furthermore, the non-mobile radars were widely spaced, thereby limiting the spatial resolution of the data. On the other hand, airborne radars experience significant ground clutter contamination near the surface, and traverses near the storm are separated by as much as five to ten minutes. This time separation makes a detailed study of a rapidly evolving tornado very difficult (Bluestein et al. 2003).

Perhaps the most successful and promising of these methods for obtaining tornadogenesis data are mobile, Doppler radars mounted on ground-based vehicles. As it became apparent by the mid-1990s that such radars were a viable way to obtain Doppler radar data in supercells, it was suggested first that one radar could be used to obtain pseudo-dual-Doppler data by moving the radar parallel to the motion of the tornado (Bluestein et al. 1994). Then, the idea of using multiple mobile, ground-based, Doppler radars to obtain a dual-Doppler wind field was suggested (Bluestein et al. 1995; Wurman et al. 1997). Since then, these radars have been used to assess the wind field near the ground in tornadoes and low-level mesocyclones at a much finer resolution than by previous methods (e.g., Bluestein and Pazmany 2000; Wurman and Gill 2000; Burgess et al. 2002; Wurman 2002; Bluestein et al. 2003). Ideally, multiple (two or more) mobile, Doppler radars would obtain data of the same tornadic supercell.

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In such a case, a dual-Doppler analysis could present a comprehensive look at the low-level mesocyclone and perhaps even the tornado itself with finer spatial and temporal resolution than is possible with non-mobile Doppler radars and airborne Doppler radars. Furthermore, a dual-Doppler analysis of tornadogenesis could provide a particularly useful map of the wind field before, during, and after the formation of a tornado near the ground. As a result, this analysis could lead to a better understanding not only of the structure of a tornado but also of the environments that are conducive for tornado formation and those that are not, in effect, figuring out why tornadoes form (Bluestein 1999).

As mobile, ground-based, Doppler radars increase in number and improve in quality, the possibilities for dual-Doppler data acquisition of tornadogenesis increase. One such example was the case on 15 May 2003 near Shamrock, Texas. This study is a dual-Doppler analysis of a tornadic supercell from 15 May 2003 that qualitatively assesses how the analysis relates to the current understanding of tornado formation, development, and dissipation. Those observations are then used in a data assimilation experiment trying to sustain a model simulation of the tornadic Shamrock supercell.

2. DATA COLLECTION

During the spring season of 2003, a mobile, dual-polarization, 3-cm wavelength Doppler radar (XPOL) was used to collect data near supercell thunderstorms (Pazmany et al. 2003). In addition, a mobile, Doppler, 5-cm radar (Shared Mobile Atmospheric Research and Teaching or SMART radar) was used at various times during the same time frame to collect data in convective storms (Biggerstaff and Guynes 2000). On the evening of 15 May 2003, both of these mobile radars were located south of Shamrock, Texas and scanned, in a coordinated manner, a supercell thunderstorm moving through Wheeler County, Texas.

The XPOL radar was located just outside the southern border of Shamrock and collected reflectivity, velocity, and rare dual-polarization data of the supercell thunderstorm from approximately 0240 to 0317 UTC on 16 May 2003. The SMART radar was located east of Samnorwood, Texas and collected reflectivity and velocity data of the supercell thunderstorm from 0202 to 0335 UTC on 16 May 2003. During this time period, the supercell moved through Wheeler County in the eastern Texan panhandle and later approached the Texas-Oklahoma border.

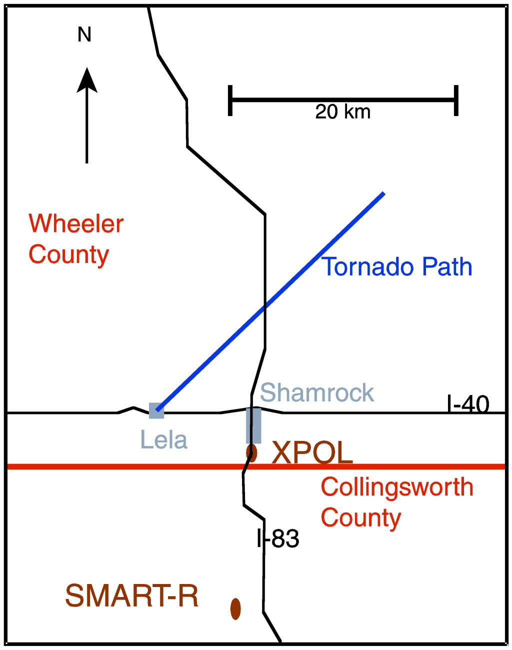

Figure 1. Diagram showing the NWS estimated tornado path and the approximate locations of the XPOL and SMART radars. The major highways and towns in the area are also depicted.

While data were being collected, a tornado formed approximately 10 km (20 km) away from the XPOL (SMART) radar. Since the sun had set by the time of apparent tornadogenesis, there could be no visual confirmation of a tornado. However, a National Weather Service (NWS) damage assessment indicates that the damage associated with the supercell was consistent with an F1 tornado. They further estimated the tornado formed at 0243 UTC in Lela, Texas (just west of Shamrock) and dissipated 29 kilometers northeast of Lela at 0320 UTC on 16 May 2003 (Fig. 1). An estimated $150,000 in damage was done in and around Lela, Texas including damaged homes, businesses, and several overturned vehicles on Interstate 40.

The Doppler velocities taken by both radars (not shown) support the formation of a tornado later than what the NWS indicated. Both radars show no discernible vortex signature until close to 0300 UTC. In any event, both radars were scanning the supercell prior to tornadogenesis. Furthermore, the NWS assessment of the location of the tornado path seems to fit qualitatively the location of the velocity couplet on both radars. Also, the indicated damage was consistent with the occurrence of a tornado, although the damage done to vehicles along Interstate 40 could have been caused by a rear-flank downdraft (C. Alexander, personal communication).

3. METHODOLOGY AND DATA ANALYSIS

Both sets of radar reflectivity and Doppler velocity were analyzed. The data were first edited using the SOLO software package (Nettleton et al. 1993; Oye et al. 1995). The editing consisted mainly of dealiasing radial velocities. The Nyquist velocity for the XPOL (SMART) radar was 16.0 ms^{-1} (19.95 ms^{-1}) which led to many folds throughout both sets of data and even some double-folds in the XPOL velocities.

Additionally, it was subjectively determined that there was a fairly large area of erroneous velocity returns from the SMART radar, most likely caused by a second-trip echo. The second-trip echo probably resulted from storms to the north of the Shamrock supercell, located outside the maximum unambiguous range of the radar. Both the reflectivity and the Doppler velocities were eliminated for this area which comprised the less important northern part of the supercell and did not affect the hook echo or the corresponding vortex signature/velocity couplet.

Finally, both the reflectivity and the velocity from both radars were de-speckled and ground clutter was removed. The de-speckling removed single data points not surrounded by other data points, essentially “cleaning up” the data. The removal of ground clutter that was clearly erroneous was based upon a threshold of reflectivity in close proximity to the radar.

3.1 *Dual-Doppler Methodology*

In order to run the dual-Doppler analysis software, a number of assumptions regarding both sets of data had to be made. First, it was assumed that the XPOL radar, which does not have a leveler, was level during data collection. This was a good assumption, since any lack of level ground was compensated for by the radar operator while collecting data. The SMART Radar collected data at multiple elevation angles, whereas the XPOL collected data at a single elevation angle. The exact elevation angle of the XPOL radar was not known, but for the purposes of this study, the elevation angle was assumed to be 0.5 degrees. It was also assumed that the SMART radar computer time was correct even though it could have been off by as much as one minute. The XPOL radar had its time calibrated when the data were initially collected. Finally, since the radars were at different ranges from the supercell and the antennas were most likely aimed at different elevation angles, the mean heights of the radar volumes were not the same. But, again, the mean heights were assumed to be equal in the analysis.

Once the above assumptions were made, both sets of radar data were interpolated to a Cartesian grid. This grid consisted of 81 X 81 X 1 grid points; the location of the SMART radar was the origin of the grid. The grid points were separated every 250 m, making the grid 20 km wide in both horizontal directions. The one vertical level was located at 500 m above ground level. To interpolate the data to a grid, a Cressman scheme was used with a 500 m radius of influence. To synthesize the wind field, a standard iterative dual-Doppler wind-synthesis method was used in Cartesian coordinates. During each iteration, the horizontal divergence computed at 500 m AGL was assumed to be representative of the entire layer from 0-500 m AGL so that a boundary condition of w=0 could be employed at the ground. For a more detailed explanation of this method, see Brandes (1977), Ray et al. (1980), or Dowell and Shapiro (2003).

3.2 *Dual-Doppler Analysis*

The two sets of data were processed by dual-Doppler analysis software. The initial “test” run used data that appeared promising. This test was run to determine initially if the data were viable to use with the analysis software. The time of the chosen scan was 0304 UTC for both the XPOL and SMART radars. This time was chosen because both sets of radar data had clearly defined hook echoes and velocity couplets indicating the strong likelihood that a

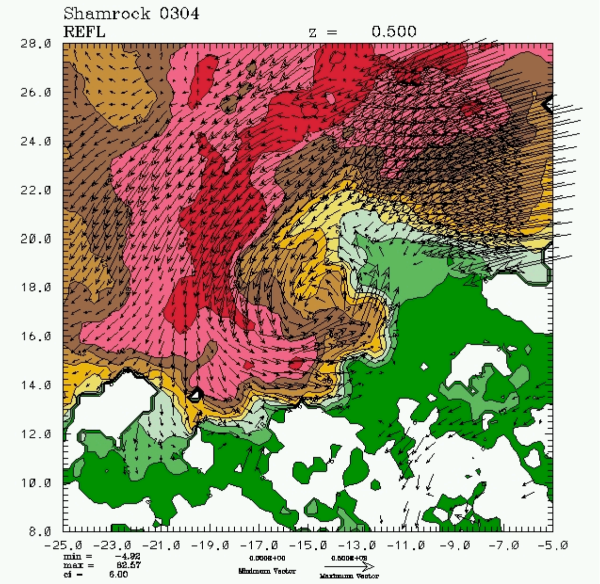

Figure 2. Dual-Doppler analysis showing horizontal, storm-relative wind vectors overlaid on reflectivity factor (dBZ) at 0304 UTC 16 May 2003. Origin indicates location of SMART radar with coordinate axes measuring distance (in km) north and west of the origin. Reflectivity factor from SMART radar, contoured every 6 dBZ starting with dark green (white is 0 dBZ). Storm motion was estimated as 12 ms^{-1} from 245 degrees.

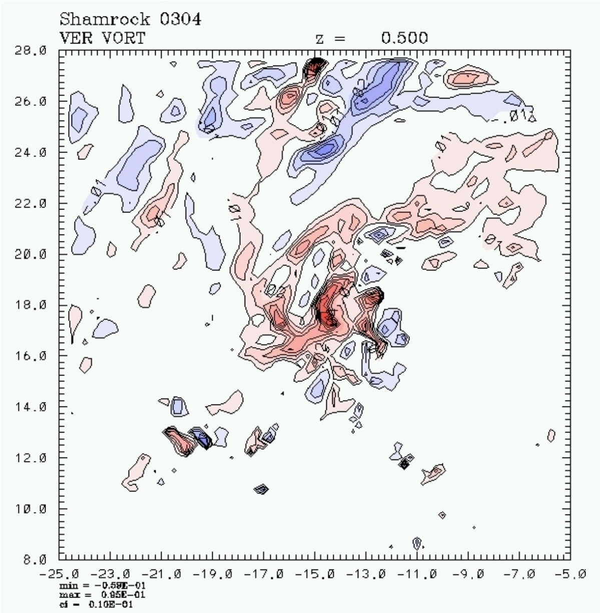

Figure 3. Dual-Doppler analysis showing vertical vorticity contoured every .01 s^{-1} with pink (blue) indicating cyclonic (anti-cyclonic) vertical vorticity at 0304 UTC 16 May 2003. Origin indicates location of SMART radar. Grid used matches that of Fig. 2.

tornado was occurring. Figs. 2 and 3 show the results of the initial, preliminary, dual-Doppler analysis. Subsequently, an additional 6 analyses were run beginning near the time of tornadogenesis and ending approximately 20 minutes later.

As was mentioned previously, due to the large number of assumptions and uncertainties associated with both data sets, the analyses are best viewed as a qualitative assessment of the variables plotted. Fig. 2 shows dual-Doppler, horizontal, storm-relative wind vectors plotted along with reflectivity factor. Fig. 3 shows the vertical vorticity that resulted from the analysis in the same location as Fig. 2.

There are a number of readily apparent observations that can be gained from this preliminary analysis. First and foremost is the appendage of reflectivity, usually referred to as the hook echo, that can be seen in Fig. 2. In addition, it is interesting to note the extremely strong wind speeds (relatively speaking) located at the upper right of the figure (near -9.0, 23.0) suggesting strong storm inflow. The quantitative data, which has some degree of error, indicates wind speeds over 50 ms^{-1}. One of the interesting observations noted by many in the vicinity of this storm was the exceptionally strong inflow.

Also of interest is the presence of a strong low-level mesocyclone. The mesocyclone would be expected if, at the time indicated, a tornado was in progress as is believed for the analysis. This feature is shown in the strong horizontal wind gradient located in the center of Fig. 2 (near -14.0, 18.0), showing the distinct appearance of a strong cyclonic circulation. It is valuable to point out that the largest area of concentrated cyclonic vertical vorticity (Fig. 2) is also centered near the hook (-14.0, 18.0). This observation is somewhat elementary, however, in that there is little disagreement that stretching and tilting of vertical vorticity provides much of the necessary rotation seen in the low-level mesocyclone, though there is some difference in opinion as to how this vertical vorticity is generated (Rotunno and Klemp 1985; Walko 1993; Wicker 1996). A more detailed look at Fig. 3 shows that the isolines of strong cyclonic vertical vorticity in the location of the low-level mesocyclone are shaped as an annulus. This is consistent with previous observations of an annulus or "horseshoe-shaped" structure to vertical vorticity in the low-level mesocyclone seen in tornadic supercells (Wakimoto and Liu 1998).

3.3 *Data Assimilation*

The final part of this study employs the use of the SMART Radar data in a data assimilation experiment. First, a model simulation of the Shamrock supercell was attempted using an environmental sounding and a numerical cloud model, the NSSL Collaborative Model for Multiscale Atmospheric Simulation (NCOMMAS; Wicker and Wilhelmson 1995; Coniglio et al. 2005). The selection of a sounding that accurately represented the environment near Shamrock at the time the supercell became tornadic offered some challenges. Real soundings were launched in Amarillo, TX and Norman, OK at 00Z on 16 May 2003. However, both Norman and Amarillo are a significant distance from Shamrock, about 275 km and 160 km respectively. Also, at these locations, soundings were launched three hours before tornadogenesis. Instead, archived profiles from the Rapid Update Cycle (RUC) were obtained near the time and location of storm initiation (40 km S of Amarillo at 00Z) and tornadogenesis (near Shamrock at 03Z). Following considerable comparisons between the two RUC profiles, the actual soundings mentioned above, and other RUC profiles at nearby locations, it was determined that the two profiles were most likely the best representation of the environment where the storm initiated and became tornadic respectively.

Next, two simulations were run, one each with the two soundings. Using a 5 K warm bubble and the storm initiation sounding, the model was able to produce a short-lived cell with radar reflectivity factors up to 50 dBZ. Using the sounding from Shamrock resulted in more difficulty producing a storm with this idealized model configuration and initialization method. Future work involves using an ensemble Kalman filter (EnKF) (Dowell et al. 2004) in an effort to assimilate SMART Radar data into NCOMMAS, and it is hoped that through this method, a storm can be sustained in the model. Pressure and wind fields will be retrieved using both soundings to initialize the model. It is hoped that through the pressure and wind field retrievals, further insight can be gained into tornadogenesis. Verification of the two assimilation experiments will center on the estimates of storm motion, comparisons of the retrieved wind field to that obtained by the dual-Doppler analyses, and how the model's short-term forecast matches up with observation.

4. CONCLUSIONS

The ability to observe tornadogenesis, while rare and difficult to achieve, has been made easier in the last several years with the advancement of ground-based, mobile, Doppler radars. With the increase in the number of such radars, the opportunities for dual-Doppler analyses of tornadogenesis will increase, providing extremely useful observations of the tornadic environment. The increase in observations may also lend to more accurate data assimilations using a variety of different techniques.

In this case, the radars, one a 3-cm wavelength Doppler radar and the other a 5-cm wavelength Doppler radar, were able to capture the life-cycle of an F1 tornado that formed just west of Shamrock, Texas in the evening hours of 15 May 2003. The data from both radars were edited to remove problem areas and, with a variety of underlying assumptions, were analyzed to determine if the results were useful. The analysis software provided storm-relative wind vector data and vertical vorticity that, at least qualitatively, agreed with conventional theory regarding the structures of tornadic supercell thunderstorms.

At the conference, several additional dual-Doppler analyses will be shown, both prior to and during the development of the tornado, to provide a greater opportunity to analyze not only the parameters shown in the figures, but also how those parameters progress throughout the development of the tornado. Results of the assimilation experiments and the corresponding verification techniques also will be presented at the conference.

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