12.6 THE STRUCTURE AND EVOLUTION OF HOOK ECHOES DURING TORNADOGENESIS AS REVEALED BY HIGH RESOLUTION RADAR DATA

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1. Introduction

Although hook echoes and rear-flank downdrafts have been hypothesized for decades to be important in producing supercell tornadoes, a recent review by Markowski (2001) illustrates that their role in tornadogenesis is still poorly understood. With recent advances in mobile Doppler technology and field programs (Bluestein and Pazmany 2000 , Wurman et al. 1997, Rasmussen et al. 1994), newly collected data sets on tornadic storms offer an unprecedented level of spatial and temporal detail of hook echoes and tornadoes. This study utilizes Doppler on Wheels (DOW) data to investigate the structure and evolution of hook echoes in tornadic storms. Five hook echoes from four tornadic storms are analyzed which produced tornadoes near Apache, OK (tornado A3 on 3 May 1999, F3 damage), Choctaw, OK (tornado A12 on 3 May 1999, F2), Thedford, NE (4 June 1999, F2), Throckmorton, TX (25 May 2000, F0), and Brady, NE (17 May 2000, F3).

The DOW data are the primary data set used in this study, though the analysis is supplemented with WSR-88D data in areas where DOW data are limited. Typical characteristics of the DOWs include a beam width of 1^{o}, an azimuthal sampling interval of 0.5 ^{o}, range gate spacing of 50m, and a nyquist velocity interval of 21.3 ms^{-1}. Variable scanning strategies and range from the storm create significant differences in the data available from case to case (see Table 1). For most of the cases the volume scan strategy was sectorized (except the Choctaw survey scans) with volume scans lasting 45-107 seconds. The actual time between useable volume scans, however, can be much longer due to sampling problems with beam blockage or positioning the radar (some data collection occurred while the radar was moving which also complicates the analysis). Ranges from the tornadoes varied from 3-17 km, yielding beam widths of 50-300 m between cases. One of the other significant differences between cases is the depth of the volume scans. The lowest beam heights at the lowest tilts ranged from 50-500m, and the beam heights at the highest tilts ranged from 900-5900m. Thus, some cases are more optimal than others to study the deep structure of the hook (i.e., Apache, Thedford, and Brady).

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Tornado	Vol. Scan duration	Beam Width	Lo-High Beam Heights (km)	Avg Hook Width (km)
Apache	107 s	300 m	0.3-2.6	0.7-1.0
Choctaw	13 s	50 m	0.5-1.0	0.1-0.4
Thedford	55 s	170 m	0.05-4.2	0.0-0.5
Throck.	105 s	150 m	0.2-0.9	0.2-0.5
Brady	45 s	300 m	0.3-5.9	1.0-7.0

Table 1. DOW data characteristics during tornadogenesis.

2. Hook Echo Structure During Tornadogenesis

Comparison of hook echo reflectivity structure during tornadogenesis between the five cases illustrates significant variability (see Fig. 1). For this study, tornadogenesis is defined as the time of appearance of a small and localized velocity couplet in the DOW data. Hook size and shape, position of the maximum reflectivities in the hook's precipitation streamer relative to the developing tornado, and the appearance of a local reflectivity maximum at the tornado location vary from case to case. In the Apache and Thedford cases, the position of the tornado is marked by an isolated reflectivity maximum, likely a weak debris cloud in the tornado circulation. It is interesting to note that the narrow area of maximum reflectivities in the hook echo precipitation streamer in low levels do not extend to the tornado location in either of these cases. There is an extension of very weak reflectivities to the tornado, but overall, the reflectivity maximum with the tornado is separate from the heaviest precipitation in the hook streamer. In the Apache case, the leading edge of the maximum reflectivities in the hook streamer is tilted cyclonically with increasing height (this will be discussed more in the next section). This is not the case in Thedford, where precipitation is not completely encircling the tornado in mid levels.

In the three other cases (Choctaw, Brady, Throckmorton), the developing tornado is along or within the leading edge of a blob of reflectivity at the end of the arm of the high reflectivities in the hook streamer. The average width of the arm of the hooks in these cases

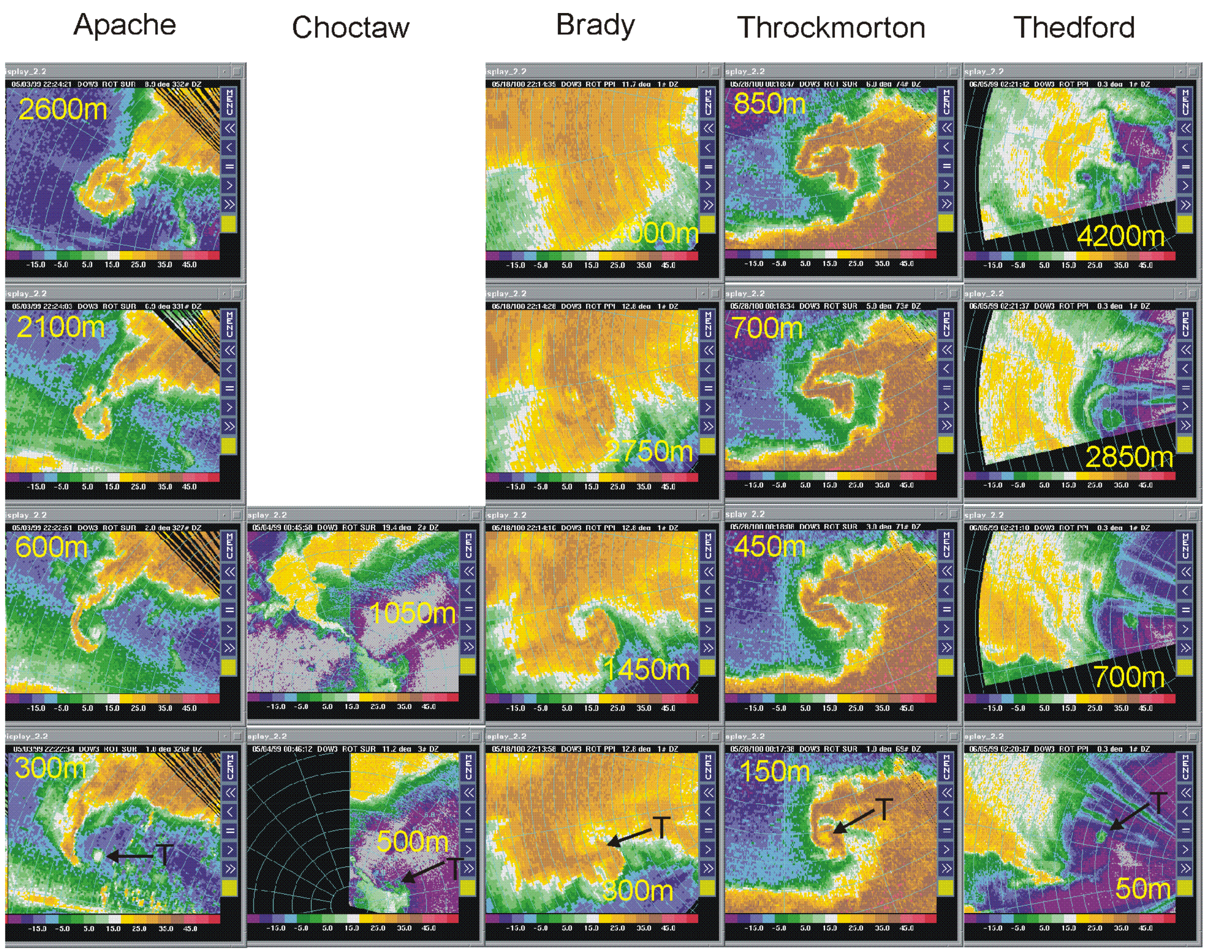

Figure 1. Radar reflectivity during tornadogenesis. Beam height at tornado location is given in meters. Tornado location illustrated with arrow at lowest tilt. Range rings are every 1 km. Images are oriented relative to the truck position (north is not necessarily up).

varies from 100s of meters (or less in places) in Choctaw and Throckmorton, to 1000s of meters in Brady (see Fig. 1 and Table 1). The hammerhead signature in the Brady storm is co-located with a well-defined cyclonic/anticyclonic vortex pair, though this is not well defined in the other cases at the times displayed in Fig. 1.

3. Hook Echo Streamer in the Apache Case

The hook echo streamer accompanying the Apache tornado shows an interesting structure and evolution. As discussed in the previous section, the maximum reflectivities in the streamer tilt upward and cyclonically with increasing height. The slope of the streamer in this case is somewhat similar to the "hook streamer" analyzed by Browning (1965). In Browning's analysis, the hook streamer, which is less occluded aloft than the Apache storm, is located on the west side of the mesocyclone during the analysis time. The leading edge of the streamer is tilted to the south (cyclonic) with increasing height. Browning concluded the hook streamer resided in updraft, but there are too many differences in precipitation distribution between the two storms to warrant drawing the same conclusion in the Apache storm without further detailed analysis. The hook in the Browning analysis is much larger than the Apache hook, particularly in mid levels where the hook is a broad extension of the main precipitation core. The Apache hook is much thinner, and it is narrowly attached to the main precipitation core aloft.

If the high reflectivities in the hook streamer are advected by the strong winds of the mesocyclone, the structure seen in Fig. 1 could be explained by stronger rotation at 2600 m compared to 300m. To begin to evaluate the role of rotation in the evolution of the hook echo streamer, the volume scan prior to tornadogenesis is studied. Figure 2 shows the hook structure for the two volume scan times, 2218 and 2223 (~ 4.5 minutes apart). The large gap between volume scans is due to data collection problems. During the 2218 volume scan, the hook echo streamer is relatively straight in the lowest 2 km, and it is beginning to develop significant cyclonic curvature at 3100 m, where rotation is

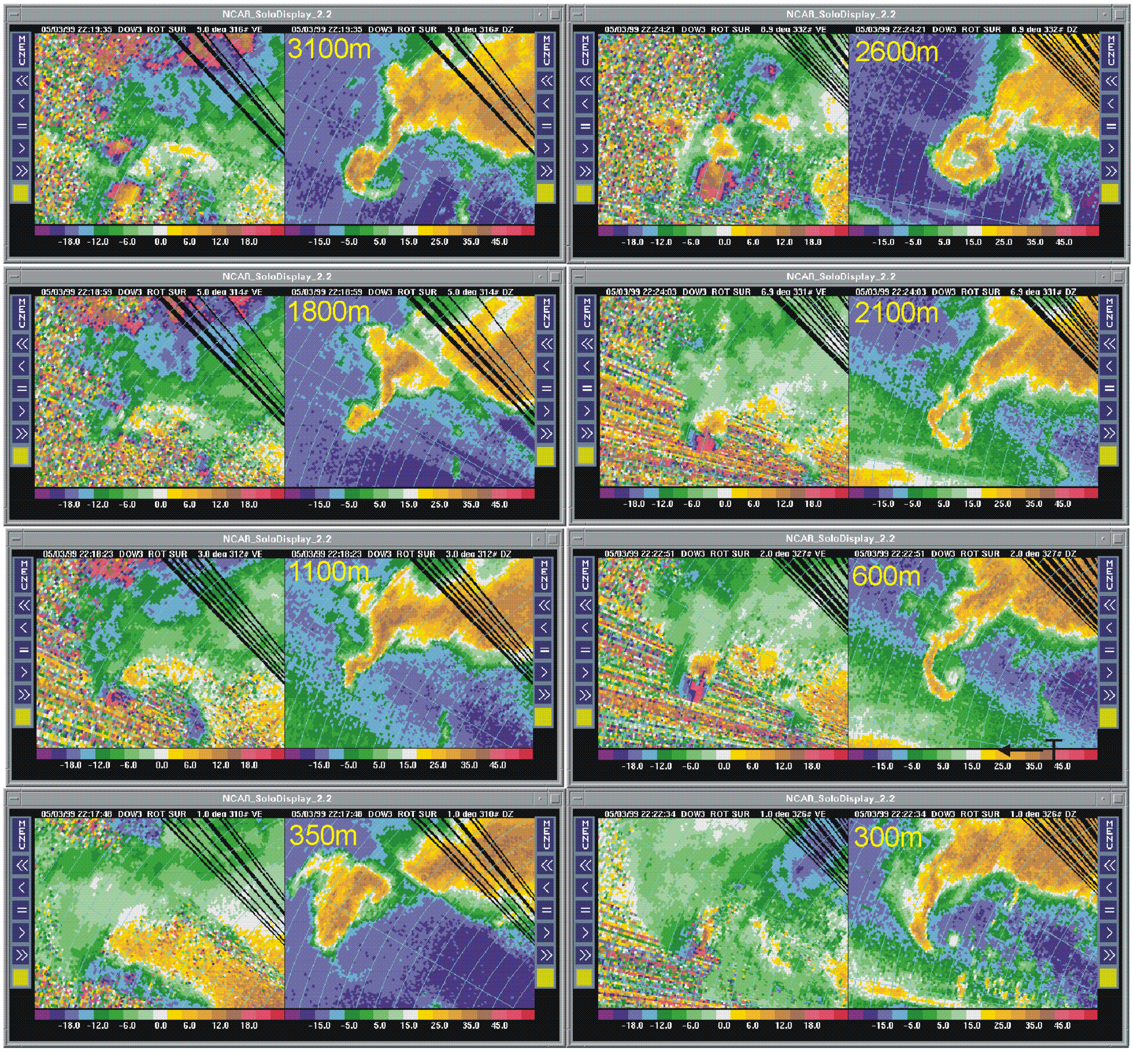

Figure 2. 2218 UTC (left) and 2223 UTC (right) volume scans during Apache tornadogenesis. Radar reflectivity (right) and base velocity (left) are displayed for each volume scan. Beam height at tornado/mesocyclone location is given in meters. Range rings are every 1 km.

strongest. By the 2223 volume scan, the hook echo streamer develops significant cyclonic curvature from 300-2600m.

To determine the horizontal advection potential of the mesocyclone aloft, the rotational velocity can be combined with the size of the reflectivity annulus and the time difference between volume scans. The diameter of the annulus in mid levels (2600-3000m) is ~ 2.0 km, and the rotational velocity is ~ 22 ms^{-1} during the 2218 and 2223 volume scans. Given a rotational velocity of 22 ms^{-1}, in the 286 seconds (~ 4.5 minutes) between observations, the leading edge of the high reflectivities in the streamer could be advected along a circular distance of 6292 m, which is almost exactly the circumference of a 2km diameter vortex (6280m). Thus, if reflectivity is conserved, the leading edge of the high reflectivities of the hook echo streamer could circle the vortex completely. Figure 2 suggests this did not happen. The position of the leading edge of the high reflectivities changed by only ~ 180 degrees during that time (note that the leading edge of the high reflectivities in the streamer are on the northeast side of the circulation, and it has not joined the high reflectivities in the arm of the hook during the 2223 volume scan).

4. Conclusions

A comparison of multiple hook echoes in tornadic storms with high-resolution DOW radar data yields interesting insight into the structure and evolution of hook echoes. Significant differences are observed in hook size and shape, position of the maximum reflectivities in the hook's precipitation streamer relative to the developing tornado, and the occasional appearance of an isolated reflectivity ball at the tornado location separate from the high reflectivities in the hook precipitation streamer. The significant differences in precipitation distribution around the mesocyclones in these cases may have important implications for tornadogenesis dynamics.

One of the unique cases studied here (Apache) suggests the hook echo streamer evolution in that case is not easily explained by a 2D process of horizontal advection in the peak winds of the mesocyclone and conservation of precipitation. The potential reasons for this are many, and are the subject of ongoing analysis in the Apache hook echo and the other hook echoes. The evolution of the hook echo is likely a 3D process with potentially important contributions from updraft, downdraft, and mixing.

The high-resolution data illustrate a whole new scale of structure and evolution not resolved using the current WSR-88D radar network. With the shortest duration volume scan of five minutes and reflectivity resolution of 1km, much of the evolution of tornadogenesis is likely inadequately resolved, thus inhibiting the ability to understand and predict tornadoes. Analysis of one case suggests that volume scans of less than one minute that extend into middle and upper levels may be required to optimally track the evolution of significant features in the hook echo.

Analysis of the current data sets are ongoing to better understand the structure and evolution of hook echoes and their relation to tornadogenesis. With a better understanding of the structure and evolution of features apparent in these high-resolution datasets, a better understanding of the process of tornadogenesis is likely along with an assessment of current limitations in operational data sets. Such understanding can contribute to future enhancements in radar hardware and radar use in warnings.

5. Acknowledgements

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6. References

Bluestein, H. B., A. L. Pazmany, 2000: Observations of tornadoes and other convective phenomena with a mobile, 3–mm wavelength, Doppler radar: the spring 1999 field experiment. *Bull. Amer. Meteor. Soc*, **81**, 2939–2952.

Browning, K. A., 1965: Some inferences about the updraft within a severe local storm. *J. Atmos. Sci.,* **22**, 669-677.

Markowski, P. M., 2001: Hook echoes and rear-flank downdrafts: a review. *Mon. Wea. Rev.*, **130**, 852–876.

Wurman, J., J. M. Straka, E. N. Rasmussen, M. Randall, A. Zahrai, 1997: Design and deployment of a portable, pencil-beam, pulsed, 3-cm Doppler radar. *J. Atmos. and Oceanic Technol.*, **14**, 1502–1512.

Rasmussen, E. N., J. M. Straka, R. P. Davies-Jones, C. A. Doswell III, F. H. Carr, M. D. Eilts, D. R. MacGorman, 1994: Verification of the origins of rotation in tornadoes experiment: VORTEX. *Bull. Amer. Met. Soc.*, **75**, No. 6, pp. 995–1006.