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POLARIMETRIC SIGNATURES AND MICROPHYSICAL PROCESSES IN TORNADIC SOUTHERN AND HIGH PLAINS CLASSIC SUPERCExplore

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UNIVERSITY OF OKLAHOMA
GRADUATE COLLEGE

POLARIMETRIC SIGNATURES AND MICROPHYSICAL PROCESSES IN
TORNADIC SOUTHERN AND HIGH PLAINS CLASSIC SUPERCELLS

A THESIS
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MATTHEW SCOTT VAN DEN BROEKE
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Abstract

Preliminary schematics of polarimetric signatures are developed for classic, tornadic supercells at low, mid, and upper levels for the Southern and High Plains. Schematics are developed for pre-tornado, tornado, and tornado demise times from a small collection of cases, most of which were cyclically tornadic. Characteristic signatures and patterns are identified for reflectivity factor ($Z_{HH}$), differential reflectivity ($Z_{DR}$), correlation coefficient ($\rho_{hv}$), specific differential phase ($K_{DP}$), and linear depolarization ratio ($LDR_{VH}$), and signatures likely related to the tornado lifecycle are discussed.

Additionally, observed changes in four polarimetric variables ($Z_{HH}$, $Z_{DR}$, $\rho_{hv}$, and $K_{DP}$) and radial velocity are presented through the tornado lifecycle for three Southern Plains classic supercell cases, and evolution possibly related to tornado genesis and demise is discussed.

Primarily, the information presented herein should be useful for nowcasters as they use real-time polarimetric radar data to identify supercells and associated threats, notably the presence of large hail, tornadoes, and heavy rain. This information should also be useful in helping nowcasters interpret real-time evolution of the polarimetric variables in supercell storms, and may improve severe weather warnings, especially after the polarimetric upgrade to the national radar network.
1. Introduction

Supercell thunderstorms cause much damage and significant loss of life, especially on the Great Plains of the central and south-central United States. These long-lived convective storms produce numerous hazardous weather phenomena, most notably very heavy rain, large hail, damaging straight-line wind, and tornadoes. Nearly all long-lived tornadoes, and almost all strong to violent tornadoes, are produced by supercell thunderstorms.

Recognition of these organized precipitation systems and their associated threats is a priority for nowcasters, as they have significant potential to imperil life and destroy property. Weather radar has provided a superb way for nowcasters to identify and warn for dangerous thunderstorms. With the advent of polarimetric radar, nowcasters will have even more useful data on which to base their decisions, and much guesswork will be taken out of warning for specific severe weather threats.

A unified polarimetric schematic of supercell thunderstorms is necessary and overdue. Herein, we seek to develop preliminary polarimetric schematics for the primary polarimetric variables at pre-tornado, tornado, and tornado demise times. Schematics are developed for the Southern and High Plains at low, middle, and upper levels. All schematics are based on classic supercells, many of which were cyclically tornadic. This research should be useful for the operational community, especially after radars in the national radar network are upgraded with polarimetric capability.

While supercells are often described as quasi-steady-state systems, they are in reality constantly evolving (e.g. Klemp 1987). In particular, supercell evolution is often
rapid and dramatic during the near-tornado phase of the storm’s lifecycle, from the minutes leading up to tornadogenesis, to tornadogenesis, to tornado demise. This evolution is especially notable in the supercell’s “echo appendage” region (e.g. Browning 1965). No previous studies have looked at the evolution of polarimetric variables through the supercell’s near-tornado phase. Therefore, we herein seek to describe how the most commonly-used polarimetric variables change through the supercell lifecycle, utilizing raw data from three classic, cyclically tornadic central Oklahoma supercells. Raw data are presented since this is most representative of what a nowcaster would see in real-time. Polarimetric variables presented include reflectivity factor ($Z_{HH}$) and differential reflectivity ($Z_{DR}$), and in some cases specific differential phase ($K_{DP}$), correlation coefficient ($\rho_{hv}$), and radial velocity. Evolution of the polarimetric variables is discussed, primarily for low levels, through the tornado lifecycle, although for some cases the midlevels also showed repeatable evolution discussed herein. This information should be useful to operational nowcasters using polarimetric radar data to recognize classic supercells and their lifecycles. It should also yield insight into microphysical processes and changes as the supercell and low-level mesocyclone evolve, and may provide useful insight into the as-of-yet unanswered supercell tornadogenesis question once comparisons are made with non-tornadic cases.

Chapter 2 provides salient background for this study and a review of the applicable literature. In Chapter 3, the data are described, while in Chapter 4, terminology used herein and methodology used to obtain reported results are discussed. Chapter 5 provides a presentation of the low-level polarimetric schematics developed for the Southern and High Plains, while Chapter 6 examines low-level polarimetric evolution
in three Southern Plains storms. Chapter 7 provides middle- and upper-level polarimetric schematics for the Southern and High Plains, while Chapter 8 provides an overview of the most important conclusions of this study.
2. Background

a. Foundations of Supercell Structure and Evolution

Much research has been published containing conceptual models of supercell structure using radar reflectivity. A multi-layer conceptual model was first presented by Browning (1965; Fig. 2.1) showing the evolution of the hook echo based on storms that affected the Oklahoma City, Oklahoma, region. Lemon (1977) presented a supercell model showing reflectivity structure in two and three dimensions. Many aspects of Lemon’s conceptual model remain accepted. At low levels, the supercell’s key features include a core of highest reflectivity just downwind from the cyclonically-rotating primary updraft and rear-flank downdraft (the mesocyclone), an echo appendage (often historically referred to as a “hook echo”) extending south and southwest from this region of highest reflectivity as precipitation wraps around an intensifying mesocyclone, and decreasing reflectivity downwind from the primary updraft. Reflectivity in the downwind precipitation region often exhibits extended regions of relatively high values, giving the supercell a “winged” appearance. The mechanism producing this winged shape remains unknown.

Brandes (1978) published a conceptual model of low-level mesocyclone structure during the tornadic phase (Fig. 2.2). His model shows a well-defined echo appendage with storm inflow wrapping into the low-level mesocyclone and tornado region from the southeast and east. In Brandes’ model, the tornado is typically located near or inside the tip of the echo appendage.
In 1979, Lemon and Doswell presented a modified conceptual model of a tornado-producing supercell thunderstorm (Fig. 2.3). Some new features of this model include the presence of forward- and rear-flank downdrafts and a flanking line of convection. The forward-flank downdraft (FFD) forms downwind from the mesocyclone under the supercell’s precipitation shield, while the rear-flank downdraft (RFD) forms within the echo appendage (see also Markowski 2002). A flanking line of convection, typically extending southwest from the storm and often marked by young developing cells, indicates the leading edge of the RFD-associated outflow. These may occasionally be seen on radar.

Several studies have investigated the mid- and upper-level structure of supercell thunderstorms. Barnes (1978) published observations of reflectivity factor from an Oklahoma supercell at various levels, including 4.5 km (lower midlevels) and 7.5 km (upper midlevels to upper levels) (Fig. 2.4). At midlevels, this study revealed storm structure still exhibiting hints of an echo appendage, with highest storm reflectivity just downwind from the primary updraft. Areas of higher reflectivity were evident extending away from the updraft region, and a strong reflectivity gradient was present along the storm’s forward flank. At upper levels, an echo appendage feature was no longer present, and a weak-echo region of reflectivity occurred above the low-level updraft. Reflectivity flares were present, although weaker than at midlevels, and the strongest reflectivity gradient was now along the southwest (back) side of the storm.

Lemon and Doswell (1979) published more details of supercell three-dimensionality. At midlevels, a bounded weak echo region (BWER) was present, coincident with the strongly rotating central portion of the primary storm updraft. The
rear-flank downdraft (RFD) had wrapped around the mesocyclone, with a reorganizing updraft core (Fig. 2.5).

Some work has also been published regarding supercell structural evolution through the tornado lifecycle. Brandes (1981) examined evolution of a supercell that affected central Oklahoma. His figure 10 (Fig. 2.6) shows a region of dry upper-level air intruding on the southwest side of the storm at the pre-tornado time, under which a rear-flank downdraft develops near the time of tornadogenesis. The swirling component of low-level flow is a maximum during the mature stage. By the time of tornado dissipation, storm inflow has been cut off by the rear-flank downdraft, and a new updraft may be forming downstream from the initial updraft.

Under different environmental conditions, different types of supercells are known to form. Moller et al. (1994) published the first unified description of the supercell spectrum. Rasmussen and Straka (1998) attributed some of this variability to the role of upper-level storm-relative flow in redistributing hydrometeors.

\textit{b. Weather Radar Polarimetry}

Despite much work conceptualizing supercell structure (e.g., Doswell and Burgess 1993) this problem has not been approached from the perspective of polarimetric radar. The most significant work thus far published describing supercell structure using polarimetric data is by Ryzhkov et al. (2005), in which some very preliminary polarimetric patterns are observed in a few tornadic supercells, along with some interpretation.
Dual-polarization Doppler radar, in which electromagnetic waves are transmitted and received with both horizontal and vertical polarization, yields much information in addition to that provided by single-polarization radars. Polarimetric data can be used to infer microphysical processes ongoing within storms via a hydrometeor classification algorithm (HCA) (e.g., Straka 1996, Straka et al. 2000), and offer great promise for learning more about supercell structure and microphysics. Unified polarimetric schematics of classic tornadic supercells will be presented herein, for what is thought to be the first time. Schematics will be presented for the Southern and High Plains, at several points through the tornado lifecycle, for several vertical levels, and, as available, for five of the most commonly used polarimetric variables ($Z_{HH}$, $Z_{DR}$, $K_{DP}$, $\rho_{hv}$, and $LDR_{VH}$).

A unified polarimetric schematic of supercell thunderstorms is needed because of the expected upgrade of the current WSR-88D network to polarimetric capability starting around 2009 or 2010 (personal communication, Dusan Zrnić, 2006). National Weather Service (NWS) and private sector forecasters looking at these data will benefit by knowledge of polarimetric supercell signatures and changes in the polarimetric variables through the supercell lifecycle. Nowcasters may be able to more accurately identify specific severe weather threats with the storms, especially the presence of large hail and tornadoes, primarily utilizing $Z_{HH}$, $Z_{DR}$, $K_{DP}$, and $\rho_{hv}$, which will be the available variables on the polarimetric WSR-88Ds (personal communication, Zrnić 2006).

It is also important to understand each of the primary polarimetric variables utilized in this study. For further discussion of the variables mentioned below, see Doviak and Zrnic (1993), Straka et al. (2000) or Bringi and Chandrasekar (2000).
Reflectivity ($Z_{HH}$) is the component of radar energy both transmitted and received with horizontal polarization, and is familiar from the current WSR-88D network. This variable represents reflection of a radar signal from hydrometeors and non-meteorological scatterers. It is proportional to hydrometeor cross-section integrated over the sample volume, and is affected by hydrometeor phase.

Differential reflectivity ($Z_{DR}$) is ten times the base ten logarithm of the ratio of horizontal to vertical reflectivity factor. Thus, it is a measure comparing the horizontally-polarized return signal to the vertically-polarized return signal, and gives an estimate of the oblateness or prolateness (axis alignment) of hydrometeors in a sample volume. This variable has shown significant usefulness in hail detection (Herzegh et al. 1992, Doviak and Zrnic 1993, Straka 1996; Straka et al. 2000 and Bringi and Chandrasekar 2000) and has real-time tornado recognition potential (Ryzhkov et al. 2005).

Correlation coefficient ($\rho_{hv}$) is a measure of the correlation between the horizontally- and vertically-returned radar signals at zero lag. Many factors affect correlation, such as the presence of particle mixtures, the distribution of hydrometeor orientations, and irregularity of particle shapes (Straka et al. 2000). Randomly tumbling, irregular particles, for instance, would have low values of $\rho_{hv}$, while round, smooth hydrometeors would have high correlation. This polarimetric variable has been found useful in hail and tornado detection (Ryzhkov et al. 2005).

Specific differential phase ($K_{DP}$) is a local measure of phase shift caused by a radar beam’s interception of scatterers, causing a change in the phase angle of the transmitted signal’s electric field vector. Each transmitted signal polarization is scattered differently by a given collection of hydrometeors (unless all are spherical), so the change
in phase angle will vary between different signal polarizations. This differential phase change is measured by the radar as $\varphi_{DP}$, the differential phase shift. From $\varphi_{DP}$, $K_{DP}$ is calculated by taking the difference of $\varphi_{DP}$ over a given range. Greater liquid water content and anisotropy of scatterers produce greater differential phase shifts, and therefore higher $K_{DP}$ values (Jameson 1985). This variable is potentially useful in determining the presence of hail and can be helpful in raising nowcasters’ confidence in the presence of an ongoing tornado.

Linear depolarization ratio ($LDR_{VH}$) is defined as ten times the base ten logarithm of the ratio of radar energy transmitted horizontally and received with vertical polarization, to $Z_{HH}$ (that both transmitted and received with horizontal polarization). It represents the depolarization of horizontally-transmitted energy as a ratio of cross-polar to co-polar terms. This variable is useful for detecting wobbling or tumbling hydrometeors, and can be used to detect scatterer phase and irregularly-shaped scatterers (Herzegh et al. 1992). High values are often associated with hail and wet snowflake aggregates, while values $<-24$ dB are typical in rain (Straka et al. 2000). $LDR_{VH}$ only was available for High Plains cases, so no preliminary schematics will be developed for the Southern Plains.

c. Polarimetric Structure in Supercells

Few studies have approached mid- and upper-level supercell structure from a polarimetric perspective. The presence of a differential reflectivity ($Z_{DR}$) column (Herzegh 1992) rooted in the WER and an $LDR_{VH}$ cap above the $Z_{DR}$ column was noted by Hubbert et al. (1998) in a Colorado hailstorm. Hubbert et al. also report a column of
high $K_{DP}$ just downwind from the mesocyclone and attribute it to shedding of liquid drops from hail. Tessendorf et al. (2005) note similar features, and attribute the $LDR_{VH}$ cap to freezing droplets at the top of the $Z_{DR}$ column. They also found high $K_{DP}$ in the lower levels of the $Z_{DR}$ column, attributed to large oblate drops. These were inferred to be effective hail nuclei if able to enter the updraft.

Perhaps the most significant paper thus far published containing polarimetric supercell structure is Loney et al. (2002). This paper investigates polarimetric signatures above the melting level, based on an Oklahoma supercell. At 5 km (midlevels), $Z_{DR}$ was found to have high values in the vicinity of the mesocyclone, with low values (near 0 dB and below) just downwind from the mesocyclone. Enhanced $K_{DP}$ was found to the east of the highest storm reflectivity. Loney et al. also present vertical cross sections of $Z_{HH}$, $Z_{DR}$, $\rho_{hv}$, and $K_{DP}$ from near the surface to 15 km taken by the Cimarron radar (Fig. 2.7). The reflectivity factor cross section shows expected structure, with a BWER extending upward to about 8 km and higher $Z_{HH}$ values above the BWER. $Z_{DR}$ exhibits highest values in the BWER, with values as high as 1 dB to an elevation of approximately 6 km. Low values above the melting level extend toward the surface in an inferred hail shaft. Although $\rho_{hv}$ values from the Cimarron radar are biased low (Ryzhkov 2005), general trends are still evident. A large area of low correlation atop the $Z_{DR}$ column is collocated with the storm’s reflectivity maximum in an area of near-zero $Z_{DR}$; this signature likely represents hail. Higher $\rho_{hv}$ values are present at the storm’s higher elevations ($> \sim 10$ km). Storm maximum correlation was present between about 5 and 7 km to the west of the primary updraft. Storm maximum $K_{DP}$ was located just east of the storm $Z_{HH}$
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Figure 2.5. The 1979 Lemon and Doswell model of midlevel supercell structure after the BWER has formed, valid for an elevation of approximately 7 km (their Figure 10).

Features noted by Lemon and Doswell include the forward-flank and rear-flank downdrafts (FFD, RFD), the updraft (UD), the old core of the original mesocyclone (L), the center of the developing mesocyclone (C), and an area of anticyclonic vorticity (A).

Arrows indicate storm-relative flow.
Figure 2.6. Tornadic-region characteristics of the 1977 Del City-Edmond supercell through the tornado lifecycle, presented by Brandes (1981). Arrows represent storm-relative low-level streamlines; hatched areas represent rainy downdraft; stippled areas represent regions of high vertical vorticity associated with the updraft. The region of high radar reflectivity is outlined in black, and gust front location is indicated by a dashed line. ‘I’ denotes a region of upper-level dry air at the pre-tornado time, while ‘RDD’ represents the rear-flank downdraft. The black dot in b), c), and d) represents the tornado location.
Figure 2.7. Loney et al.’s vertical cross sections of interpolated polarimetric variables (2002) obtained via aircraft pass through an Oklahoma supercell. Polarimetric fields included are: a) reflectivity factor ($Z_{HH}$), b) differential reflectivity ($Z_{DR}$), c) correlation coefficient ($\rho_{hv}$), and d) specific differential phase ($K_{DP}$).
3. Data

Datasets used in this study include Southern Plains tornadic supercell cases collected by the Cimarron (CIM) and Norman (KOUN) dual-polarized Doppler radars. Details on the Cimarron radar can be found in Zahrai et al. (1993). Information about KOUN can be found in Zrnic et al. (1999), Doviak et al. (2000), and Doviak et al. (2002). High Plains datasets were collected by the Colorado State University–University of Chicago–Illinois State Water Survey (CSU-CHILL) and the National Center for Atmospheric Research’s (NCAR’s) SPOL dual-polarized Doppler radars. Information on the CSU-CHILL radar is published in Brunkow et al. (2000), and NCAR’s SPOL radar is described in Lutz et al. (1995).

The Cimarron radar (no longer operational) was located about 40 km west-northwest of Norman, Oklahoma, and KOUN is located in Norman, Oklahoma. In Southern Plains cases collected by the Cimarron radar, $\rho_{hv}$ data were used with caution, since a signal processing error caused $\rho_{hv}$ to be negatively biased. Thus these data allow relative comparison of values, although absolute magnitude of values is not correct (Ryzhkov et al. 2005). Unfortunately, $K_{DP}$ was not collected or calculated in the same way for the Cimarron cases, so these are not included.

The CSU-CHILL radar is located just northeast of Greeley, Colorado, and about thirty-five km southeast of Fort Collins, Colorado. SPOL is a deployable s-band radar (10.7 cm wavelength) frequently deployed in northeast Colorado and western Kansas.
While the CSU-CHILL radar data does not include $K_{DP}$ computed from $\varphi_{DP}$ as in the Southern Plains cases, it did obtain measurements of $LDR_{VH}$ used in this study.

In the present study, seven Southern Plains supercell cases were taken from central Oklahoma, all of which cyclically produced tornadoes. Schematics developed from these cases should also apply across much of the Southern Plains region of eastern and central Texas, the Texas and Oklahoma Panhandles, and eastern Kansas. It has been generally found that Southern Plains cases differ in some regards from High Plains cases, presumably because Southern Plains supercells are generally “warm based” (cloud base temperatures $T > 15^\circ C$), while High Plains supercells are generally “cold based” (cloud base temperatures of $T < 5^\circ C$), though there are exceptions. Unfortunately, perhaps because climatology favors fewer tornadoes on the High Plains, data were only available from three High Plains supercell tornado cases. Many similarities exist among the High Plains storms, which have polarimetric signatures quite different from those in the Southern Plains storms. Schematics developed for the High Plains storms should be valid across much of the high-elevation Plains of eastern Montana, Wyoming, and Colorado, the western Dakotas, and western Kansas.

Table 1 shows cases used in the present study. While radar data were often not available at a desired elevation angle for a particular time (e.g. the time a tornado was reported to have dissipated), the temporally closest scan was usually chosen. The temporally closest scan typically appeared quite representative.
<table>
<thead>
<tr>
<th>Table 1: Cases Used in the Present Study</th>
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<tbody>
<tr>
<td><strong>Southern Plains</strong></td>
</tr>
<tr>
<td>13 – 14 June 1998</td>
</tr>
<tr>
<td>5 October 1998</td>
</tr>
<tr>
<td>3 May 1999</td>
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<tr>
<td>8 – 9 May 2003</td>
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<td>9 – 10 May 2003</td>
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<tr>
<td>24 May 2004</td>
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<tr>
<td>29 – 30 May 2004</td>
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<tr>
<td><strong>High Plains</strong></td>
</tr>
<tr>
<td>1 August 1996</td>
</tr>
<tr>
<td>29 June 2000</td>
</tr>
<tr>
<td>21 May 2004</td>
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</tbody>
</table>
4. Terminology and Methodology

Preliminary schematics developed in this study are divided into pre-tornado, tornado, and tornado demise times. The pre-tornado time (PTT) was defined as approximately twelve to fifteen min before the initial tornado report, and was taken from the one to three low-level scans nearest this criterion. Tornado times (TT) were defined as those at which a tornado was reported to be occurring by an observer. The tornado demise time (TDT) was defined as the time of the radar scan temporally nearest observed tornado dissipation. Tornado times were chosen based on both the observations of scientists viewing the storms, and on the Storm Prediction Center’s (SPC’s) storm report database. Since times reported in the SPC database are only approximate, caution was used in defining tornado times based on the SPC tornado reports. Many storms used in this study produced well-known and well-documented tornadoes (e.g. storms on 3 May 1999, 8-9 May 2003, 9-10 May 2003), which aided in assuring the accuracy of chosen tornado times.

For each polarimetric variable at each time of interest, notes and schematic drawings were constructed, allowing compilation of the repeatable patterns reported herein. As only one previous study has looked at polarimetric data of supercell tornadoes (Ryzhkov et al. 2005), comparisons are frequently made to their findings.

In this study, the low levels were defined as the lowest elevation angle available at each time of interest. When the lowest-elevation scan was considerably contaminated by ground clutter near a supercell/tornado or the supercell/tornado was very close to the
radar (< 15 km), the next-higher scan was used. Therefore low-level scans were typically taken from the 0.0- and 0.5-degree elevation angles, although scans from 1.0 degree were infrequently used.

Midlevel data were chosen from an elevation angle such that known midlevel features were present, most importantly a BWER/weak-echo region (WER)/inflow notch above the low-level updraft. Upper-level data were typically chosen from the elevation angle immediately above the obvious BWER/WER/inflow notch, although this feature was sometimes present even at the storm’s highest elevations. In this case, upper level data were taken from well above the midlevel elevation angle at the same time, from a great enough altitude that storm reflectivity factor was taking on an oval-shaped outline. Because of varying radar-supercell geometry between cases and scan times, the elevation angle used for midlevel and upper-level data was highly variable. Thus, additional variability is introduced into the middle- and upper-level schematics.

To develop the preliminary polarimetric schematics presented herein, drawings and notes were constructed for each variable. Regions of high, medium, and low values were delineated. From these drawings and notes, composite schematics were created for each of the variables, at each vertical level, for each of PTT, TT, and TDT. On these schematics, regions of high (H), medium (M), and low (L) values are denoted, as well as areas denoted “V” where variability between cases was too great for a conclusion to be drawn about typical values. A denotation of “V” in a region of a supercell schematic does not mean the region is completely devoid of a somewhat repeatable pattern. A V(M/L) means the area was primarily a mix of medium and low values, while a V(H/M) means the area was primarily a mix of high and medium values. There were places
without repeatable patterns, and these are indicated as V(H/M/L). Many of the high, medium, and low thresholds were chosen based on thresholds presented in Straka et al. (2000), while others were defined based on observational experience. A bold supercell outline on the schematic drawings represents approximately the 20 dBZ reflectivity contour for the composite storm.

It is important to note that schematics were constructed from a relatively small number of cases. They are therefore limited, but should improve as more cases become available. A greater number of cases should allow the reduction of variability, and perhaps allow recognition of different storm evolutionary paths.

It is also noteworthy that the schematics presented herein were developed from cyclically tornadic supercells. Fewer non-tornadic cases exist, and these were not examined in the present study. Therefore, caution is advised when interpreting these schematics in the context of the tornado lifecycle. More non-tornadic cases need to become available, and be analyzed relative to the tornadic cases, before strong conclusions are reached about differences between tornadic and non-tornadic storms, and before we can state how robust the apparently tornado-indicative signatures actually are.

In this research, composites were constructed such that noted features were placed relative to the storm’s updraft at low levels, relative to its inflow feature at midlevels, and relative to the top of the updraft at upper levels. Repeatability of features was sought relative to the updraft/inflow region, and noted on the schematic diagrams. Throughout this study, “downwind” is defined as the direction in which a feature embedded in the storm-relative flow would move by advection.
In future studies, further quantification of these results may be helpful. To construct more quantitative schematics, an updraft could be pinpointed for each storm based on updraft indicators (e.g. low $Z_{HH}$, high $Z_{DR}$, low $\rho_{hv}$). Then, relative to the identified updraft, storm quadrants could be defined and typical values of each of the polarimetric variables defined in each of the quadrants across all available cases. In this approach, caution must be advised to maintain the smaller, repeatable features that appear, and to not let these features become washed out by the larger-scale analysis procedure.

In the text, the terms “schematic storm” and “schematic supercell” refer to the preliminary schematic drawing made for a given time period and polarimetric variable. In general, mid- and upper-level polarimetric structures were more variable than low-level structures. High Plains schematics tended to have more regions of variability than their Southern Plains counterparts, but this was thought due to the small number of available High Plains cases.

Polarimetric evolution is also presented for several central Oklahoma supercells in Chapter six. For each case, radar images were captured for the variables examined ($Z_{HH}$, $Z_{DR}$, $\rho_{hv}$, $K_{DP}$) and radial velocity through the tornado lifecycle. By comparing sequences of images, changes became apparent which are reported herein. Many of these changes appear related to evolution of supercell processes through the cycle of tornado genesis, maintenance, and demise.
5. Low-level Polarimetric Schematics

In this chapter, preliminary low-level polarimetric schematics are developed for the Southern and High Plains. Southern Plains schematics are developed for $Z_{HH}$, $Z_{DR}$, $\rho_{hv}$, and $K_{DP}$. For the High Plains, schematics are developed for the same variables plus $LDR_{VH}$. The preliminary nature of these schematics should be emphasized—more cases are needed for truly representative schematics. The upcoming advent of a dual-polarized Doppler radar network promises many more cases of classic tornadic supercells, thereby allowing refinement of the schematics presented herein.

a. Southern Plains Schematics

In this section, low-level dual-polarimetric Southern Plains schematics of tornadic supercells are developed for four of the most commonly used polarimetric variables.

1) REFLECTIVITY FACTOR ($Z_{HH}$)

i) Pre-tornado Times

A well-defined echo appendage was often found at pre-tornado times, although it often was wider and less cyclonically curved than at either tornado or tornado demise times (Fig. 5.1). At pre-tornado times, reflectivity $> 50$ dBZ was observed to cover much more of the spatial area of the echo appendage than at tornado times. A well-defined echo appendage, present at all times studied in the supercell lifecycle, was not found...
useful in distinguishing whether a supercell was in the process of producing a tornado, except it may appear more cyclonically curved while a tornado was ongoing or dissipating. The presence of the hook echo, however, seemed quite useful in indicating the presence of a maturing or well-developed mesocyclone (e.g., Forbes 1980; Markowski 2002).

In addition, the descending reflectivity core (DRC; Rasmussen et al. 2006) was also frequently found in the echo appendages. The location of these at the times considered is indicated on the reflectivity schematics with a circle. The circle’s size corresponds to the approximate size of the DRC central region (Fig. 5.1), though the entire DRC may be larger than indicated on the reflectivity figures, and DRC size depends on the reflectivity threshold used to define it. A study by Rasmussen et al. (2006) found that isolated tornadic supercells generally had a DRC, whereas a more comprehensive climatology by Kennedy et al. (2006) showed the occurrence of a DRC with isolated tornadic supercell storms to be less frequent than that found by Rasmussen et al (2006). Because of these studies we felt compelled to indicate where this feature might be found. Though the DRC is not shown with a reflectivity maximum in the schematics, if one were to occur, reflectivity would be at least 4 dB greater than in the surrounding hook echo (and not resolved by the reflectivity mapping thresholds used in this paper). An increase in reflectivity in the DRC relative to the surrounding hook echo reflectivity could be much more than 4 dB (Kennedy et al. 2006; and Rasmussen et al. 2006).

In addition, reflectivity maxima along the southern and northern storm flanks were significantly less frequent and less well defined. Maximum reflectivity was
typically concentrated just downstream from the primary storm updraft. The reflectivity gradient at the back edge of the echo appendage was typically not as strong as at tornado times, at least in the preliminary schematics of this sample of storms (Fig. 5.1).

ii) Tornado Times

During times when a tornado was ongoing, a well-defined hook echo was usually present, with high values of $Z_{hh} (> 50$ dBZ) often extending south into the echo appendage (Fig. 5.1). The appendage was typically thinner than at pre-tornado times, and often possessed greater cyclonic curvature. A sharp reflectivity gradient, seen more often than at pre-tornado times, was frequently located at its back (western) edge, attributed to the presence of a well-developed RFD. Highest storm reflectivity at low levels was typically located downwind from the primary updraft and extended northeast along the storm’s forward flank in regions of hail and heavy rain. Secondary maxima in reflectivity extended northeast from this region along the storm’s northern flank, giving the reflectivity pattern a ‘winged’ appearance.

A couplet of cyclonic-anticyclonic rotation was occasionally noted at the tip of the hook echo during tornado times, and was manifest in the reflectivity field as a quasi-symmetric pair of swirls. This feature was not observed during any pre-tornado or tornado demise times in the current study, and seems indicative of a supercell in the tornadic phase. During tornado times, regions of high reflectivity often extended prominently to the northeast away from the primary storm updraft region (Fig. 5.1).
It is believed that a reflectivity maximum may occur associated with a tornado, as debris is lofted and reflects energy back to the radar (Burgess et al. 2002; Ryzhkov et al. 2005). This signature occurred in approximately two-thirds of cases examined (Fig. 5.2). Care must be taken when interpreting this signature, however, since this reflectivity maximum could represent the DRC as described by Rasmussen et al. (2006). DRCs can be identified as descending reflectivity patterns in a series of PPI scans in the vertical or in three-dimensional images of storm reflectivity. In addition, they occur prior to tornadogenesis and therefore are not associated with debris.

iii) Tornado Demise Times

At demise times, the supercell hook echo region tended to exhibit more cyclonic curvature than at any other time (Fig. 5.1). Perhaps this occurs because the hook echo becomes wrapped around the tornado cyclone, sometimes into the body of the storm. Highest storm $Z_{HH}$ was typically located just downstream from the primary updraft, as expected, although a relatively thin filament of high values (> 55 dBZ) often extended well south into the echo appendage. Detached regions of high reflectivity were often found even farther away from the main storm body in the echo appendage (i.e., typically farther south).

Wings of high $Z_{HH}$ extending east and northeast from the updraft were sometimes visible at tornado demise times, but were usually not a prominent feature as at tornado times, perhaps indicating a weakening updraft. Also, at tornado demise times, the back of the supercell (typically its west side) tended to exhibit a lesser reflectivity gradient.
than at tornado times. Maximum $Z_{HH}$ gradient at the back of the storm was observed to occur while a tornado was ongoing (Fig. 5.1), likely related to a strong RFD at that time.

2) DIFFERENTIAL REFLECTIVITY ($Z_{DR}$)

i) Pre-tornado Times

Near-zero $Z_{DR}$ collocated with high reflectivity was used to infer the presence of low-level hail shafts in the supercells studied (Straka 1996, Straka et al. 2000). At pre-tornado times, this hail signature occurred much less frequently than at tornado times (Fig. 5.3). Medium values (1 - 2 dB) often covered a larger area of the echo appendage and extended more continuously to join a large area of medium values typically located on the northwest side of the schematic storm. High forward flank $Z_{DR}$ was present, caused by a concentration of large drops falling against storm inflow. Well-defined inflow maxima, although slightly less frequent, were about as common as at tornado times (Fig. 5.3).

ii) Tornado Times

A hail shaft, inferred from collocated high $Z_{HH}$ and low $Z_{DR}$, was identified in the lowest available elevation angle more often at tornado times than at pre-tornado times (Fig. 5.3). This implied hail shaft was most frequently located just downstream from the primary updraft, in a location favored for the fallout of hail (Moller et al. 1994). One
might speculate that this pattern change describes a storm updraft beginning to collapse during the tornadogenesis and tornado stage.

Forward flank values of differential reflectivity were high in nearly cases examined, with values typically exceeding 2-3 dB in this region (Fig. 5.3). Values of $Z_{\text{DR}}$ this high can indicate large, oblate raindrops, especially when reflectivity is not high (Straka et al. 2000). The forward flank tends to be an area of inflow and updraft, and the presence of high $Z_{\text{DR}}$ in this region implies ongoing drop sorting (Ryzhkov et al. 2005). Larger drops are able to fall against storm inflow, while smaller drops are advected into the storm. Thus, a region of sorted larger drops is theorized to develop along the storm’s forward flank, leading to the observed high $Z_{\text{DR}}$.

A well-defined differential reflectivity inflow maximum, the base of a $Z_{\text{DR}}$ column, was present at a slightly greater percentage of tornado times than pre-tornado times, but the relatively small difference was not thought significant. The hook echo region typically contained medium values of $Z_{\text{DR}}$ (1 - 2 dB), though larger values were not uncommon (Fig. 5.3). Larger values are probably most common in the echo appendage when average drop size there is larger, which may indicate evaporation of small drops.

Ryzhkov et al. (2005) observe the occasional presence of comma-shaped areas of high $Z_{\text{DR}}$ in the supercell inflow region. This pattern has been attributed to a centrifuging effect of the low-level mesocyclone, causing larger drops to move outward in cyclonically curved bands. It could also indicate storm inflow bands containing large drops. These bands of large drops would be visible to a radar operator as cyclonically curved bands of high $Z_{\text{DR}}$. Such curved bands were not prevalent, but did occur in
several of the tornado cases examined. Ryzhkov et al. (2005) suggest possible use of this
signature to infer updraft rotation strength, since greater centrifuging, and inflow, tends to
occur with stronger rotation.

As discussed in Herzegh et al. (1992), $Z_{DR}$ can exhibit low values near the tip of
the hook echo if a tornado is present, since tumbling debris behaves much the same as
large hail in that it tends to tumble randomly and present roughly equal horizontal and
vertical surface area to a scanning radar. Ryzhkov et al. (2005) define a “$Z_{DR}$ debris
signature” as a pixel containing $45 \text{ dBZ} < Z_{HH} < 55 \text{ dBZ}$ and $Z_{DR} < 0.5 \text{ dB}$. Such a
signature was indeed found in at least nine of the twelve Southern Plains tornado cases
examined, and this signature was thought to be a good indicator of an ongoing tornado
(Fig. 5.2). One case even exhibited the $Z_{DR}$ debris signature when the tornadic region
was approximately 100 km from the radar, perhaps (depending on the radar beam path
and therefore on atmospheric conditions) possibly indicating a rather tall and wide debris
column. This signature must be used with caution, since differential attenuation of the
horizontally- and vertically-polarized signals could result in local $Z_{DR}$ minima
unassociated with tornadic debris. Therefore, confidence in an ongoing tornado is
increased when additional tornado-indicative signatures are simultaneously present.
Lower $Z_{DR}$ has been known to trail the tornadic region as lofted debris is left behind
(Ryzhkov et al. 2005).
iii) Tornado Demise Times

For reasons discussed above, high $Z_{DR}$ (> 2 dB) was again located along the forward flank of the schematic storm, with medium values (1 – 2 dB) typically just downwind from this region (Fig. 5.3). Low $Z_{DR}$ regions in the storm core, collocated with high $Z_{HH}$ and associated with hail shafts, occurred in a few cases but were typically not large or well defined, and were sometimes not present at all.

Extended regions of higher $Z_{DR}$ to the east in the main storm were often present, but not typically well defined (Fig. 5.3) as at earlier times. In the hook echo region, $Z_{DR}$ values were typically medium (1 – 2 dB), but could exhibit large regions with low values, perhaps indicating the presence of residual tornado-lofted debris.

3) CORRELATION COEFFICIENT ($\rho_{hv}$)

i) Pre-tornado Times

Low $\rho_{hv}$ (< 0.95) was typically associated with the storm’s hail shaft, if present, since correlation is lower in mixed and/or irregular hydrometeors (Straka et al. 2000). Nearly all cases with a hail shaft identified by collocated high $Z_{HH}$ and low $Z_{DR}$ also had low $\rho_{hv}$ in the same location, typically just downstream from the primary updraft. Since hail shafts were found to be more prevalent at tornado times than at pre-tornado times, the presence of an area of low $\rho_{hv}$ associated with large hail was less frequent at pre-tornado times (Fig. 5.4).
Low $\rho_{hv}$ values, though higher than those found in hail shafts, occurred with heavy rain as identified by collocated high $Z_{HH}$ and $Z_{DR}$ (Straka et al. 2000). Typical values of $\rho_{hv}$ in heavy rain were 0.95 to 0.98. These values could also be found in mixtures of rain and hail. The location of this signature was consistent with the theory of supercell structure, typically downstream from and surrounding the hail region.

Highest low-level storm $\rho_{hv}$, typically $>0.98$ and ranging up to $\sim 1$ (perfect correlation between horizontal and vertical signals), was usually located in the large, light-precipitation region of the supercell, far downwind from the primary updraft (Fig. 5.4). In this region, reflectivity was also typically low ($<40$ dBZ), indicating lighter rain. Lighter rainfall is often composed of relatively spherical droplets (Jameson 1982), allowing correlation to be high (Straka et al. 2000).

ii) Tornado Times

Composite storms at tornado times were not easily distinguished from their pre-tornadic counterparts by $\rho_{hv}$. The hail and heavy rain regions, denoted by low correlation, were in approximately the same locations (Fig. 5.4). Since a hail shaft was found to be more common at tornado times, this low correlation signature was more prevalent at tornado times. The region of high $\rho_{hv}$ collocated with light rain may have been larger, but this was difficult to judge.

Outside the large hail and heavy rain regions, another area of low $\rho_{hv}$ was the updraft itself. Ryzhkov et al. (2005) note that $\rho_{hv}$ will be low in the updraft when strong inflow produces a mixture of raindrops and light debris such as leaves and grass. Such a
Depression of \( \rho_{hv} \) was seen in nearly all tornado cases examined. Ryzhkov et al. suggest the magnitude of the \( \rho_{hv} \) depression and its vertical extent may be useful as a possible means of evaluating updraft strength. Such a signature could also occur in non-tornadic storms with a sufficiently strong wind field.

Low \( \rho_{hv} \) is theorized to occur with the tornado vortex, since the horizontally- and vertically-received signals in tumbling randomly-shaped debris and particles will not be closely related. Ryzhkov et al. (2005) define a “\( \rho_{hv} \) debris signature” as a pixel containing \( 45 \text{ dBZ} < Z_{HH} < 55 \text{ dBZ} \) and \( \rho_{hv} < 0.8 \). For the Cimarron cases, since a signal processing error affected \( \rho_{hv} \) values, this threshold was lowered to 0.6. Such a signature was found at the storm location favorable for tornadogenesis in about two-thirds of the tornado cases examined (Fig. 5.2). In most cases, this region contained the lowest \( \rho_{hv} \) in the entire supercell, usually < 0.75 and sometimes as low as 0.4. Values as low as 0.2 have even been reported from the raw radar data in the 8 May 2003 tornado case (Ryzhkov et al. 2005). Worthy of note, two cases not exhibiting such a signature were the two most distant from the radar (> 70 km distant), so the radar beam may have passed above any debris column. It is theorized that the \( \rho_{hv} \) debris signature will not be as prevalent if the tornado is moving over an area of low debris availability and if the tornado is weaker. Ryzhkov et al. (2005) indicate a lower strength limit of F3 for this and other polarimetric tornado signatures to be well-defined, although we hypothesize the existence of a spectrum of tornado signature strengths rather than the presence or absence of such signatures. Another necessary consideration is the typically shorter life of weaker tornadoes, inferred by their much shorter average path lengths (Brooks 2004); a tornado with a short life is less likely to be sampled while producing debris.
iii) Tornado Demise Times

Major differences existed between the cases in all supercell regions, so the composite storm was completely designated as having high variability (Fig. 5.4). A majority of cases, however, did contain lower $\rho_{hv}$ just downwind from the primary updraft in the region favored for hail and large raindrops, as seen previously. More data would have to be obtained to ascertain whether an anomalous case, which had high values (> 0.98) in the same region, was representative of some supercells going through tornado demise, or if it truly was an outlier.

iv) Supercell Wake Region

Ryzhkov et al. (2005) define the supercell “wake” signature as an area trailing a supercell with $Z_{HH} < 30$ dBZ, $\rho_{hv} < 0.7$, and average $Z_{DR}$ between 1 and 2 dB. They attribute this signature to the residual presence of light debris lofted in the supercell’s wind field. The reader is referred to their paper for an excellent discussion of why lofted debris is the most likely source of the supercell wake signature. Tornadic debris could result in such a signature, as could any other light debris that could be lofted even by a non-tornadic storm (e.g. grass, leaves). Of our tornado cases, two strongly exhibited this signature, while two additional cases exhibited it marginally (Fig. 5.5). Three negative cases were distant from the radar (> 70 km; including the 24 May 2004 storm which only produced weak, short lived tornadoes), and the region of the wake signature would have
been even more distant and behind the storm. We speculate that the supercell wake signature may increase following a tornado, or following an increase in the near-storm wind field. It may be useful to investigate potential operational significance of this signature.

4) SPECIFIC DIFFERENTIAL PHASE (K_{DP})

i) Pre-tornado Times

At pre-tornado times, supercells examined exhibited a similar spatial pattern of high and low values. Temporally, however, there were differences. One pre-tornadic case had a temporal maximum, one had a temporal minimum, and two had no discernible trend. This lack of a clear K_{DP} temporal signature seems characteristic of the pre-tornado cases examined.

Also characteristic of the pre-tornado times was the presence of medium K_{DP} (typically 0.25 – 2 deg/km) along the back (northwest) side of the composite storm, whereas at tornado times K_{DP} was typically < 0.25 deg/km in the same region (Fig. 5.6). We cannot easily speculate about the meaning of this difference—perhaps it is caused by evaporation due to ingestion of dry air near the tornado time, leaving smaller, more isotropic hydrometeors.
ii) Tornado Times

At tornado times, there was a temporal $K_{DP}$ maximum downwind from the primary updraft in the storm’s reflectivity core more often than at pre-tornado times, indicating water-coated hail and/or large drops. As expected, low values ($< 0.25$ deg/km) were located in the large region of light precipitation downwind from the main storm core (Fig. 5.6) where hydrometeors are more isotropic and liquid water content is lower. High values ($> 2$ deg/km) were typically located in the same region as the hail shaft identified by collocated high $Z_{HH}$ and low $Z_{DR}$, just downwind from the primary updraft. The presence of high $K_{DP}$ extending away from the updraft region, similar in character to the previously described reflectivity factor ‘wings’, were present more often at tornado times than at other times.

Particular care is necessary when using $K_{DP}$ in the echo appendage region. Since this variable is calculated as the rate of change of $\varphi_{DP}$ (differential phase shift) over a given range, potential problems exist in $K_{DP}$ estimation for small ranges. If ranges too small are used, $K_{DP}$ values will be unreliable. In the echo appendage and tornado region, data in some range gates may be rejected due to debris contamination, or only a small number of gates may be available for the calculation. Therefore, $K_{DP}$ signatures potentially related to an ongoing tornado should be viewed with caution. Observations made when the tornado region is embedded within the echo appendage are more likely correct, although are still suspect because of the potential effect of rejected data.

Scattering can occur in the Mie regime if particles are much larger than the radar wavelength divided by sixteen, which can lead to negative $K_{DP}$ values (Ryzhkov et al.)
Typical wavelengths for the Doppler radars used to collect these cases are on the order of ten centimeters (10-11 cm), and many tornado debris particles are significantly larger than this value. Values of $K_{DP} < 0 \text{ deg/km}$ are, therefore, theoretically associated with a tornado vortex. About half of the cases for which $K_{DP}$ was collected during tornado times showed significantly negative values associated with the tornado vortex (Fig. 5.2), while the other cases showed values near zero deg/km. No cases showed significantly positive $K_{DP}$, which was generally prevalent in the echo appendage. Thus the presence of an area of significantly low $K_{DP}$ at the storm location favorable for a tornado seems a potentially useful diagnostic of an ongoing tornado, although caution must be used in interpreting this signature as described above. This signature should be less in areas with low availability of larger debris particles. Tornado strength may not significantly change this effect as long as the tornado is picking up sufficiently large debris to the elevation of the radar beam. Thus the effect may become greater as the tornado approaches the radar, since size sorting of debris should occur in the tornado vortex as lighter/smaller debris is lofted to greater altitudes (Dowell et al. 2005). One case, for reason of data contamination or the presence of tornado debris, showed a well-defined $K_{DP}$ minimum with a tornado nearly 100 km from the radar.

iii) Tornado Demise Times

At tornado demise times, high $K_{DP}$ ($> 2 \text{ deg/km}$) was typically present in a small region to the north of the primary updraft (Fig. 5.6). This local $K_{DP}$ maximum could indicate the presence of wet hail (relatively anisotropic hydrometeors) and heavy rain
(high liquid water content) in this area. Low $K_{DP} (< 0.25 \text{ deg/km})$ was present in the large region of small drops far downwind from the primary updraft. This was expected, since small drops are more isotropic and liquid water content is lower. Between these regions of high and low values, intermediate values ($0.25 - 2 \text{ deg/km}$) were found.

Extended regions of high $K_{DP}$ were occasionally present, although they varied from highly conspicuous to nonexistent. Their strength seemed somewhat proportional to the strength of similar extended regions of high $Z_{HH}$. In the hook echo, low to medium $K_{DP} (< 2 \text{ deg/km})$ was present. Well-defined and strong $K_{DP}$ minima associated with clouds of large tornado debris were not typically found at tornado demise times. Otherwise, $K_{DP}$ patterns seemed quite variable between the small number of available cases (Fig. 5.6).

\textit{b. High Plains Schematics}

In this section, low-level dual-polarimetric High Plains schematics of tornadic supercells are developed for five commonly used polarimetric variables. Extensive comparisons are made between these and the Southern Plains schematics developed above, since more Southern Plains cases were available.

1) \textsc{Reflectivity Factor} ($Z_{HH}$)

Although few High Plains cases exist, some comparisons can be made between them and the Southern Plains cases examined. At pre-tornado times, High Plains supercells were very similar to their Southern Plains counterparts. The primary
difference was a much larger region of light precipitation ($Z_{HH} < 35$ dBZ) downwind from the storm’s main precipitation region in the High Plains composite storm (Fig. 5.7). This trend could easily have been caused by environmental winds on the days of the two cases (or a similar effect), so should be taken with caution given the small sample size. Distinctive flares of high reflectivity were noted to extend from the updraft region, as in Southern Plains storms.

At tornado times, flares of higher reflectivity extending away from the primary updraft region were less well-defined, although they may be present (Fig. 5.7). The inflow notch between the hook echo and primary body of the storm was typically better defined in High Plains cases. One case had a reflectivity maximum at the storm location favored for a tornado, while the other did not. This signature can, therefore, still occur in sparsely-populated areas, given sufficient debris availability.

At tornado demise times, High Plains storms were virtually identical in $Z_{HH}$ structure to their Southern Plains counterparts (Fig. 5.7). In one High Plains case, the hook echo region became so cyclonically curved that it wrapped northward into the main body of the storm. $Z_{HH}$ was typically less variable between cases at tornado demise times than at other times studied.

Range Height Indicator (RHI) scans were available for the two CHILL cases. The cross sections most representative of storm structure were compared at tornado and pre-tornado times. In two tornado cases, a double weak-echo region (WER) feature was seen at the onset of the tornado time, but at no other time in the remainder of available RHI data for those cases. This double WER feature may be related to the presence of both a low-level updraft associated with the developing tornado vortex, and with the parent
mesocyclone. In general, RHI scans for tornado times showed a larger, broader WER volume than at pre-tornado times.

2) DIFFERENTIAL REFLECTIVITY ($Z_{DR}$)

High Plains cases often exhibited much more detailed $Z_{DR}$ structures because of beamwidth and data processing considerations. The most pronounced difference between Southern and High Plains cases, both at tornado and pre-tornado times, was the presence of a much larger area of low values (< 1 dB). This makes sense since hail and graupel are more frequent on the Colorado High Plains (Changnon 1977). At tornado times, low $Z_{DR}$ extended through most of the hook echo (Fig. 5.8). Widespread low hook echo values such as these were not noted in any Southern Plains cases. This may indicate a more frequent occurrence of hail and melting graupel advecting around the low-level updraft in High Plains storms.

Forward-flank $Z_{DR}$ at both tornado and pre-tornado times (Fig. 5.8) was generally higher than in the rest of the storm, but not necessarily > 2 dB as in all observed Southern Plains cases. This may have been caused by the presence of more melting graupel and/or hail in the High Plains cases owing to a relatively colder vertical atmospheric temperature profile. Generally, though, a similar drop sorting mechanism appeared to be at work.

At pre-tornado times, larger areas of high $Z_{DR}$ were typically present along the forward flank, and values exceeded 2 dB in all cases (Fig. 5.8). Other than this maximum
and the presence of medium values (1 - 2 dB) at the back of the hook echo, however, no clear pattern existed for where high/low values would be located at pre-tornado times.

At tornado demise times, values along the forward flank of the schematic storm were typically much lower than in Southern Plains cases; often only a small and isolated region of high values (> 2 dB) was present (Fig. 5.8). The only region with high values in both cases was the center of the storm, perhaps indicating large raindrops. The composite drawing of low-level $Z_{\text{DR}}$ at tornado demise times for the High Plains contains many regions of high variability between the three available cases. More data would be necessary to improve on this schematic.

RHI scans of $Z_{\text{DR}}$ show some interesting patterns. In one case, the inferred hail core occurred over a larger area at the pre-tornado time and became a more concentrated hail shaft at the tornado time. Although it may not be meaningful to discuss a “$Z_{\text{DR}}$ column” at the lowest levels (Tuttle et al. 1989, Conway and Zrnic 1993), there was often a $Z_{\text{DR}}$ maximum at the location of the storm’s primary updraft, representing the base of a $Z_{\text{DR}}$ feature of continuous and substantial vertical extent. In one case, this local low-level maximum was observed to not be present at the pre-tornado time, but attained highest values (~8-9 dB) about six minutes before the first tornado report. Such high $Z_{\text{DR}}$ values are likely caused by a torus of liquid water forming around the equator of melting graupel or small hail (Straka et al. 2000). The appearance of this signature may indicate increasing updraft strength and, through mass conservation, greater low-level convergence in the minutes leading up to tornado formation. The WER was associated with high values, presumably because the largest drops, being the heaviest, were most difficult for the updraft to loft and thus were present in the WER. One case showed a
divergence signature in the velocity field at the back of the storm with higher $Z_{DR}$ around it. This may represent a visualization of the storm’s cold pool triggering new convection (Weisman et al. 1988) or of insects caught along an outflow boundary, since $Z_{DR}$ is high for many types of insects (Achtemeier 1991).

3) CORRELATION COEFFICIENT ($\rho_{hv}$)

At pre-tornado times, High Plains supercells had correlation signatures virtually identical to the Southern Plains cases (Fig. 5.9). At tornado times, the High Plains $\rho_{hv}$ signatures were also very similar to their Southern Plains counterparts. Low values associated with regions of hail typically extended farther into the main body of the composite storm (away from the primary updraft), although they were not exceptionally larger than in Southern Plains cases (Fig. 5.9). $\rho_{hv}$ minima were not observed as frequently with a tornado, possibly due to less debris availability on the High Plains and/or the less intense nature of the High Plains tornadoes represented.

At demise times, low values of $\rho_{hv}$ (< 0.95) occurred in the storm region favored for hail and large raindrops, just downwind from the primary updraft (Fig. 5.9). High values of $\rho_{hv}$ (> 0.98) were located in the part of the storm farthest downwind from the primary updraft, in the region of light precipitation and generally low $Z_{HH}$ (< 35 dBZ). This is consistent with the presence of small, nearly spherical drops. High variability existed between these regions; however, a small area of intermediate $\rho_{hv}$ (0.95-0.98) surrounded the low values near the mesocyclone. At tornado demise times, the High
Plains cases showed more structural similarity than the Southern Plains cases, although this may be due to the small sample size. Again, more data are needed.

4) SPECIFIC DIFFERENTIAL PHASE ($K_{DP}$)

One supercell case, collected by the SPOL radar, was available and is described in Tessendorf et al. (2005). $K_{DP}$ schematics for this case are presented in Figure 5.10. Worthy of note, this storm’s primary updraft and hook echo feature were located on its northwest side.

Among the three selected points in the supercell lifecycle, the pre-tornado time showed lowest $K_{DP}$. $K_{DP}$ then increased at the tornado time, and remained about the same at the tornado demise time. A well-defined temporal maximum was not present as in many Southern Plains storms, although more High Plains cases would be needed to definitively state the presence of such a difference.

Weak $K_{DP}$ flares occurred during the tornado time, although not at any other sampled point in the supercell lifecycle. Maximum $K_{DP}$, as in Southern Plains storms, typically occurred in a core downwind from the primary updraft, with diminishing values toward the light precipitation region. Magnitude of values was not significantly different from the Southern Plains cases examined—overall, $K_{DP}$ of High and Southern Plains storms was not found to be noticeably different. No well-defined $K_{DP}$ minimum was found with the tornado for the SPOL case, perhaps indicating low availability of sufficiently large debris with this tornado.
5) LINEAR DEPOLARIZATION RATIO ($LDR_{VH}$)

i) Pre-tornado Times

Large regions of low values ($<-28$ dB) were not found along the northwest side of the composite storm as at pre-tornado times, but rather tended to be found more within the central portion of the supercell (Fig. 5.11), presumably in heavy rain. High values were confined to the region just downstream from the primary storm updraft along the forward flank very near the echo appendage in regions of hail. Intermediate values were along nearly the entire forward flank, in the southern portion of the echo appendage, along the back of the composite storm nearest the echo appendage, and in the storm’s northwest quadrant. This $LDR_{VH}$ pattern does not differ substantially from the tornado cases except in the northwest quadrant of the supercell, where low $LDR_{VH}$ predominates at tornado times but intermediate values are present at pre-tornado times.

In RHI scans of $LDR_{VH}$, this variable was found to show exceptionally high values ($-5$ dB to $-10$ dB) in the updraft region where $Z_{HH}$ was less than about 30 dBZ. This may be consistent with large raindrops, large wet hailstones, or the presence of a mix of hydrometeors and light ingested debris (Straka et al. 2000). $LDR_{VH}$ seemed an excellent tracer of storm inflow, and often exhibited higher values in the updraft to high altitude.
ii) Tornado Times

Low $\text{LDR}_{\text{VH}} (< -28 \, \text{dB})$ was located along the northwest side of the schematic supercell at tornado times, extending east and southeast to form a large area of low values through the region of light precipitation well downwind from the primary updraft (Fig. 5.11). High values ($> -24 \, \text{dB}$), typically associated with hailstones (Straka et al. 2000), were again found immediately downstream from the primary updraft, along the forward flank of the supercell very near the echo appendage. These high values could exhibit slight cyclonic curvature into the echo appendage, likely because cyclonic flow in the region could advect hail around the mesocyclone. A small region of low values was found to its west, along the western edge of the composite storm. Intermediate $\text{LDR}_{\text{VH}} (-28 \, \text{dB} \text{ to } -24 \, \text{dB})$ was typically located in the southern portion of the echo appendage, along the back of the storm nearest the echo appendage, and along most of the supercell’s forward flank. These values likely represent rain or a rain/graupel mix (Straka et al. 2000).

Higher $\text{LDR}_{\text{VH}}$ is hypothesized to occur with tornado debris (Ryzhkov et al. 2005). Two High Plains cases exhibited no $\text{LDR}_{\text{VH}}$ maximum at the storm location favored for a tornado, while the other had a spike of higher $\text{LDR}_{\text{VH}}$ extending southeast away from this region, but no local maximum at the inferred location of the tornado.
iii) Tornado Demise Times

High LDR$_{VH}$ (> -24 dB) was found in two supercell regions at tornado demise times. One was located just downwind from the primary updraft in the region of hail and large raindrops. The other, detached from the first, was located in the hook echo region (Fig. 5.11). Low values (< -28 dB) were found in the region of light precipitation well downwind from the primary updraft, while intermediate values (-24 dB to –28 dB) were found between. Intermediate values were especially prominent along the forward flank, to the east of the primary updraft region.

High LDR$_{VH}$, typical in the region just downwind from the primary updraft, was noted to exhibit cyclonic curvature into the hook echo region while a tornado was ongoing, and this extension of higher values appears to have broken away from the primary maximum by tornado demise time. Otherwise, no dramatic changes were noted in the LDR$_{VH}$ structure of a typical High Plains tornadic supercell as it evolved through its lifecycle (Fig. 5.11).
Figure 5.1. Schematics of reflectivity factor (Z_{HH}) for the Southern Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values (Z_{HH} < 35 dBZ), hatched areas represent high values (Z_{HH} > 50 dBZ), blank areas represent intermediate values (35 dBZ ≤ Z_{HH} ≤ 50 dBZ), and checkerboard-filled area represents a variable region. Circles represent the possible location of a descending reflectivity core (DRC), if present. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 5.2. Tornado signatures visible in the 8 – 9 May 2003 central Oklahoma supercell at 22:30 UTC: a) a local $Z_{HH}$ maximum, b) a local $Z_{DR}$ minimum, c) a local $\rho_{hv}$ minimum, and d) a local $K_{DP}$ minimum. Tornado region is denoted by bold black circle.
Figure 5.3. Schematics of differential reflectivity ($Z_{DR}$) for the Southern Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($Z_{DR} < 1$ dB), hatched areas represent high values ($Z_{DR} > 2$ dB), blank areas represent intermediate values ($1$ dB $\leq Z_{DR} \leq 2$ dB), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 5.4. Schematics of correlation coefficient (ρ_{hv}) for the Southern Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values (ρ_{hv} < 0.95), hatched areas represent high values (ρ_{hv} > 0.98), blank areas represent intermediate values (0.95 ≤ ρ_{hv} ≤ 0.98), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 5.5. Example of a supercell wake signature from the 9 – 10 May 2003 central Oklahoma supercell showing a) reflectivity factor, b) radial velocity, c) differential reflectivity, and d) correlation coefficient. Region of the wake signature is inside the black oval. In the wake signature, \(Z_{HH}\) is low (< 30 dBZ), \(Z_{DR}\) is intermediate (1 – 2 dB), and \(\rho_{hv}\) is low (< 0.7).
Figure 5.6. Schematics of specific differential phase ($K_{DP}$) for the Southern Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($K_{DP} < 0.25$ deg/km), hatched areas represent high values ($K_{DP} > 2$ deg/km), blank areas represent intermediate values ($0.25$ deg/km $< K_{DP} < 2$ deg/km), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 5.7. Schematics of reflectivity factor \( (Z_{HH}) \) for the High Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values \( (Z_{HH} < 35 \text{ dBZ}) \), hatched areas represent high values \( (Z_{HH} > 50 \text{ dBZ}) \), blank areas represent intermediate values \( (35 \text{ dBZ} \leq Z_{HH} \leq 50 \text{ dBZ}) \), and checkerboard-filled area represents a variable region. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 5.8. Schematics of differential reflectivity ($Z_{DR}$) for the High Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($Z_{DR} < 1$ dB), hatched areas represent high values ($Z_{DR} > 2$ dB), blank areas represent intermediate values ($1$ dB $\leq Z_{DR} \leq 2$ dB), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 5.9. Schematics of correlation coefficient ($\rho_{hv}$) for the High Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($\rho_{hv} < 0.95$), hatched areas represent high values ($\rho_{hv} > 0.98$), blank areas represent intermediate values ($0.95 < \rho_{hv} < 0.98$), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 5.10. $K_{DP}$ in the 29 June 2000 High Plains supercell, at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($K_{DP} < 0.25$ deg/km), hatched areas represent high values ($K_{DP} > 2$ deg/km), and blank areas represent intermediate values ($0.25$ deg/km $\leq K_{DP} \leq 2$ deg/km). Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 5.11. Schematics of linear depolarization ratio (LDR_{VH}) for the High Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values (LDR_{VH} < -28 dB), hatched areas represent high values (LDR_{VH} > -24 dB), blank areas represent intermediate values (-28 dB ≤ LDR_{VH} ≤ -24 dB), and checkerboard-filled area represents a variable region. Bold outline represents approximately the 20 dBZ reflectivity contour.
6. Low-level Polarimetric Evolution

In this chapter, three cyclically tornadic central Oklahoma supercells are analyzed in terms of polarimetric evolution. In addition to the four polarimetric variables presented in Chapter 5 for which Southern Plains schematics were developed ($Z_{HH}$, $Z_{DR}$, $\rho_{hv}$, and $K_{DP}$), this chapter will also present evolution of the radial velocity ($V_r$) field. While a set of schematics is a useful nowcasting asset, it cannot capture the complexity of a real-life, rapidly evolving situation. Tornadic supercells are just this: rapidly and often dramatically evolving, and unique. Therefore, it is hoped the presentation of several real cases in this chapter, along with a discussion of the observed polarimetric evolution, will be useful to those using such data in diagnosing real-time weather situations.

a. 13 – 14 June 1998 Supercell

On 13-14 June 1998, a supercell moved across central Oklahoma, producing significant damage in the Oklahoma City, Oklahoma area. Two transitions from PTT to TT and two transitions from TT to TDT were captured with the Cimarron dual-polarimetric radar and are analyzed here.

1) FIRST PTT ➔ TT TRANSITION: 0029 – 0043 UTC

The first transition from pre-tornado to tornado time in the 13/14 June 1998 supercell is represented by three low-level radar scans, taken at 0029 UTC, 0036 UTC,
and 0043 UTC. Although full data is not available for the 0029 UTC sweep, reflectivity factor ($Z_{HH}$) in the storm is seen to have undergone some significant changes (Fig. 6.1a) during this time. Regions of highest $Z_{HH}$ were observed to decrease in areal coverage, and generally moved away from the back of the storm (eastward progression). The storm’s forward flank became more linearly organized, with a more unbroken northwest-to-southeast line of high $Z_{HH}$ along the forward flank at the tornado time than earlier in the storm’s lifecycle. This could indicate increasing storm-relative inflow during the time leading up to tornadogenesis, with more efficient drop sorting. A similar sharpening of storm boundaries was noted on the west and northwest side of the supercell, leading to an increased $Z_{HH}$ gradient on the storm’s west side. Although it is not possible to infer the extent of any echo appendage at 0029 UTC, at 0036 UTC only weak appendage-like features were present along the storm’s southwest side. By 0043 UTC, however, the time when tornadogenesis occurred, two well-defined echo appendages were noted. Reflectivity of 40 – 45 dBZ extended well south of the main storm into the echo appendages.

In the velocity field (Fig. 6.1a), a broad region of cyclonic circulation was evident at the pre-tornado time (0029 UTC) where a mesocyclone would be expected, although it was weak. A divergence signature was noted to the west of this circulation under the west side of the supercell; this divergence could be associated with a rear-flank downdraft (RFD, Markowski et al. 2002). Flow was otherwise strongly directed toward the radar. By 0036 UTC, the rotation had appeared to increase in intensity, and the magnitude of the inbound and outbound radial velocities had increased. A divergence signature was still evident under the supercell’s west side. By the tornado time (0043
UTC), rotational signatures were evident associated with both echo appendages, although neither rotation was very strong (< 20 knots shear) or occurring over a very large area. It is noted that ground clutter presented a significant impediment to interpreting the low-level velocity field in this case.

Pre-tornado time $Z_{DR}$ shows a well-defined region of hail, identified as low $Z_{DR}$ (~0 dB) collocated with high $Z_{HH}$ (> 50 dBZ) (Straka et al. 2000), extending through much of the highest-reflectivity portion of the storm. Values of $Z_{DR}$ from 4 – 6 dB were common along the storm’s forward flank, and these high values were especially prominent in the mesocyclone area. Values in much of the remainder of the storm were typically 2 – 5 dB. Echo appendage values ranged from 1.5 to 2.5 dB. By 0036 UTC, the hail core had decreased in size, and was prevalent more immediately downstream from the mesocyclone than at the earlier time. A band of $Z_{DR}$ ranging from 4 – 6 dB was more prominent along the storm’s forward flank, with a local maximum in the vicinity of the developing echo appendage. At tornado time (0043 UTC), $Z_{DR}$ values near 0 dB, indicative of hail when collocated with high $Z_{HH}$, had become quite rare, and were confined to a small region immediately downstream from the primary updraft. Thus the trend was for increasing values of $Z_{DR}$ in the storm reflectivity core from pre-tornado to tornado time, attributed to lessening hailfall toward the tornado time. Values within the main storm and along the forward flank were similar to the previous times. The echo appendages, however, showed up at the tornado time as appendages of high $Z_{DR}$ (3 – 6 dB), consistent with large liquid drops or melting graupel (Straka et al. 2000).

Correlation coefficient must be treated cautiously with the Cimarron radar, as a data processing error caused Cimarron’s $\rho_{hv}$ to be biased low (Ryzhkov et al. 2005).
Relative comparison of values, however, is still possible. At the pre-tornado time (0029 UTC), correlation values of 0.65 – 0.75 were prevalent through much of the central portion of the storm, with higher values (0.85 – 0.93) in the region of light precipitation well downwind from the primary updraft. Highest storm correlation of 0.94 – 0.96 occurred in the storm’s $Z_{HH}$ core, and was typically collocated with the highest $Z_{HH}$. At 0036 UTC, the areas of especially high $\rho_{hv}$ were located in the same storm region, but covered much less area than at the preceding time. In addition, values in the central portion of the storm had lowered to 0.6 – 0.7, perhaps indicating greater hail prevalence. The developing echo appendage region was marked by relatively high correlation (0.9 – 0.95). By tornado time (0043 UTC), observed trends had continued: the region of high correlation associated with the storm $Z_{HH}$ core had continued to decrease in areal extent, values were lower over more of the central portion of the storm, and the echo appendage represented a local correlation maximum.

2) SECOND PTT $\rightarrow$ TT TRANSITION: 0057 – 0112 UTC

The second pre-tornado to tornado transition in the 13/14 June 1998 had some differences compared to the earlier transition. Low-level scans from 0057 UTC, 0104 UTC, and 0112 UTC were used. A strong reflectivity maximum was located in the central portion of the storm, as previously (Fig. 6.2a). It did not, however, tend to migrate eastward with time, and sharpening of the reflectivity gradient on the storm’s west and southwest sides was not noted. Echo appendage evolution was also somewhat different. During its second tornadic phase, the storm only contained one distinct echo
appendage, and typically had more $Z_{\text{HH}}$ characteristics readily thought of for a supercell with an ongoing tornado (e.g. Barnes 1978). The developing echo appendage was visible at the pre-tornado time (0057 UTC) as a growing region of reflectivity, typically 30 – 50 dBZ, south and west of the supercell’s inflow region and barely attached the storm’s echo appendage. Temporal resolution is regrettably poor, but at 0104 UTC the echo appendage has apparently gained higher values of reflectivity and become more substantially attached to the echo appendage. By the tornado time (0112 UTC), a dramatic hook echo had developed, compete with cyclonic-anticyclonic flares and strong overall cyclonic curvature of the echo appendage. Values of $Z_{\text{HH}}$ continued to increase in the echo appendage throughout this time.

The radial velocity progression through these times suggests the supercell possessed a stronger, better-developed mesocyclone during this second cycle of tornado production. All three scans (Fig. 6.2a) depict well-defined cyclonic rotation in the storm location favored for a mesocyclone (Lemon and Doswell 1979). This rotation was weakest at 0104 UTC, about ten minutes before the next tornadogenesis occurrence. By tornado time, the rotational couplet had tightened and become more indicative of an ongoing tornado. Divergence appeared to be ongoing in the western quadrant of the storm at 0057 and 0104 UTC (prior to tornadogenesis), but appeared to be more prevalent within the storm core at the tornadogenesis time.

Differential reflectivity showed some interesting patterns during this pre-tornado to tornado transition. In the storm core, where $Z_{\text{HH}}$ was high (> 50 dBZ), a small hail shaft was present at 0057 UTC. It became much larger and better-defined at 0104 UTC (~ten minutes prior to tornadogenesis), but decreased spatially and in intensity at the
tornadogenesis time. This may indicate a low-level fallout of hail in the minutes leading up to tornadogenesis, which we speculate may affect the storm’s buoyancy balance and/or wind distribution in a manner favorable for tornadogenesis. As in the previous pre-tornado to tornado transition, values of $Z_{DR} 4 – 6 \text{ dB}$ were common along the forward flank throughout this time. A relatively small and well-defined $Z_{DR}$ maximum developed in the hook echo region at the time of tornadogenesis.

Correlation coefficient showed a similar pattern of generally decreasing values in the storm core from pre-tornado to tornado time; however, this trend was most pronounced from 0057 to 0104 UTC and did not continue to 0112 UTC. Values in the central portion of the supercell ranged from 0.7 – 0.8 throughout this time, and did not decrease as seen in the previous pre-tornado to tornado transition. Correlation remained high in the downwind light precipitation region (typically 0.9 – 0.95). The developing echo appendage was again marked by high correlation (0.85 +), but values $\geq 0.94$ were not found as during the previous pre-tornado to tornado transition.

3) FIRST TT $\Rightarrow$ TDT TRANSITION: 0043 – 0050 UTC

After producing its first tornado, the parent supercell of the 13/14 June tornadoes rapidly cycled and quickly produced a second tornado. Because of the poor temporal resolution of low-level radar scans for this dataset, only two scans were chosen as representative of this tornado to tornado demise transition. A tornado was occurring at 0043 UTC, while it dissipated by about 0050 UTC.
At 0043 UTC, as seen before, the supercell possessed two well-defined echo appendages. By 0050 UTC, both were still present, although each had developed greater cyclonic curvature (Fig. 6.3a). Higher values of $Z_{HH}$ had moved south into the echo appendages; typical maximum values increased from $\sim$40 dBZ at 0043 UTC to $\sim$50 dBZ at 0050 UTC. The area of the storm containing $Z_{HH} > 55$ dBZ had increased toward the demise time, and had moved westward relative to storm center.

Radial velocity at 0043 UTC exhibited the previously-described pair of weak rotational couplets associated with the echo appendages (Fig. 6.3a). The same pattern existed at 0050 UTC, although the rotation associated with the westernmost echo appendage strengthened and became more apparent relative to that of the other rotational couplet. This may suggest a cyclic mesocyclone process through which the eastern mesocyclone was weakening and the western mesocyclone was becoming dominant. Radar-relative storm inflow appears to have increased from 0043 to 0050 UTC, although this may be an effect of the strong clutter signal.

Differential reflectivity appeared to undergo little change from 0043 to 0050 UTC. A hail core toward storm center, implied by collocated near-zero $Z_{DR}$ and high $Z_{HH}$ ($> 50$ dBZ), appeared to become smaller and less intense as time progressed (Fig. 6.3b). Values of $Z_{DR}$, as typical, were 4 – 6 dB along the storm’s forward flank. At the demise time, the echo appendage clearly stood out as a local $Z_{DR}$ maximum. This may indicate large average drop size in these areas. By this time, the low-level mesocyclone and associated tornado was beginning to wrap northward into the main storm.

A region of relatively high correlation (0.94 – 0.96) was observed to increase in areal extent from tornado to tornado demise time (Fig. 6.3b). A large area of very low
values (0.6 – 0.7) near storm center, probably associated with hail and heavy rain, was observed to generally decrease in area. High correlation in the downwind region of light precipitation increased markedly from tornado to tornado demise time. Through both times, locally high correlation was observed to persist in the echo appendage region.

4) SECOND TT → TDT TRANSITION: 0112 – 0124 UTC

After producing its longer-lived second tornado, the 13/14 June 1998 supercell underwent a classic transition to the demise phase, as described in Chapter 5. At 0112 UTC, the well-defined hook echo was solidly attached to the main storm via a thin reflectivity channel exceeding 45 dBZ (Fig. 6.4a). By 0117 UTC, the end of the hook echo had become partially detached from the primary storm reflectivity outline, but by 0124 UTC it was again solidly connected with the main storm. As observed in Chapter 5 as typical of Southern Plains supercells undergoing tornado demise, the echo appendage gained greater cyclonic curvature through this sequence of times and moved inward closer to the storm core. Reflectivity > 55 dBZ remained concentrated in the main body of the storm near the echo appendage throughout this time, and appeared to increase in areal extent. At the tornado time, the supercell possessed strong reflectivity “wings,” regions of higher $Z_{\text{HH}}$ values extending downwind away from the primary updraft. These diminished and finally went away completely by the demise time.

Very strong cyclonic rotation existed in the supercell’s mesocyclone region throughout this time. A tighter rotational couplet possibly indicative of a tornado-strength low-level vortex was evident at 0112 and 0117 UTC (Fig. 6.4a).
very strong rotation continued to be present, and although a tornado was not reported to have been occurring at this time, the author suspects (because of this and signatures in $Z_{DR}$ and $\rho_{hv}$) a tornado may have still been ongoing. Flow in the remainder of the storm was relatively constant through these times.

$Z_{DR}$ shows interesting patterns through this tornado to tornado demise transition. Only a small area of hailfall was implied at 0112 UTC (Fig. 6.4b). The supercell appeared to drop a major hail core at 0117 UTC, as the region of near-zero $Z_{DR}$ collocated with high $Z_{HH}$ became very large, and the magnitude of reflectivity increased. At about this time, in fact, 2.50” hail was reported at the ground, some of the largest hail to be reported with this supercell. Interestingly, only seven minutes later at 0124 UTC, nearly no hail was implied. Values of $Z_{DR}$ generally decreased in the echo appendage through this transition, but the change did not appear very significant—perhaps drops were, on average, becoming slightly smaller. High $Z_{DR}$ values of 4 – 6 dB persisted along the forward flank throughout.

Correlation in the supercell core did not exhibit strong evolution through this transition. Values by the demise time were lower than at the tornado time, but this transition to lower values mostly occurred from 0112 to 0117 UTC (Fig. 6.4b), probably as the hail core descended. Low values toward the center of the storm did not significantly change in magnitude or extent, nor did the high correlation values in the downwind light precipitation region. Correlation remained high in the echo appendage throughout this time, but these high values became more detached from high values in the main storm toward the demise time.

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b. 9 – 10 May 2003 Supercell

On 9/10 May 2003, a supercell moved across central Oklahoma, producing significant damage in the Oklahoma City/Edmond areas. Two transitions from PTT to TT and one transition from TT to TDT were captured by KOUN and are analyzed here.

1) FIRST PTT \(\rightarrow\) TT TRANSITION: 0247 – 0300 UTC

The first pre-tornado to tornado transition in the 9/10 May 2003 supercell is represented by three low-level radar scans, taken at 0247 UTC, 0253 UTC, and 0300 UTC. Reflectivity through this transition showed some important changes. Although the magnitude and extent of high \(Z_{HH}(>50 \text{ dBZ})\) did not change significantly in the supercell through these times, flares of higher reflectivity became better-defined extending to the northeast away from the primary updraft region (Fig. 6.5a). Another convective cell located north of the primary supercell weakened dramatically, from \(-55 \text{ dBZ at 0247 UTC to } -40 \text{ dBZ at 0300 UTC}\). The character of the echo appendage changed dramatically through this pre-tornado to tornado transition. At 0247 UTC, the echo appendage was not very distinct from the main body of the storm, exhibited little cyclonic curvature, and was marked by \(Z_{HH}\) generally \(\geq 50 \text{ dBZ}\). By 0253 UTC, new development had occurred to the east of the echo appendage’s previous location, and a strongly cyclonically-curved early hook echo feature now existed. At 0300 UTC, when a tornado was observed to be occurring in the Yukon/Oklahoma City, Oklahoma, area, the hook echo had developed further and exhibited its greatest cyclonic curvature.
At 0247 UTC, the radial velocity field (Fig. 6.5a) shows both large-scale rotation associated with the supercell’s mesocyclone and a tight rotational couplet at the tip of the echo appendage, indicating a strong mesocyclone at low levels at this time. Although an ongoing tornado may be inferred from this tight rotational couplet, no tornado was visually reported at this time. In addition, signatures characteristic of a tornado were not present in the $Z_{\text{DR}}$, $\rho_{hv}$, or $K_{\text{DP}}$ fields (Ryzhkov et al. 2005, Chapter 5 of this thesis). This is a good example of a time when polarimetric data could be useful to an operational nowcaster trying to decide if a tornado were ongoing—although velocity data strongly indicated a tornado, polarimetric signatures were more consistent with field observations. As this was a cyclic, tornadic supercell storm, the storm was likely in the process of producing a tornado around 0247 UTC, but the low-level mesocyclone may have encountered unfavorable conditions. By 0253 UTC, strong mesocyclonic rotation is still noted, but the tight rotational couplet has diffused and is no longer impressive. At 0300 UTC, when a tornado was finally reportedly occurring, a tight rotational couplet had again developed within the hook echo, and the magnitude of radar-relative inbound velocities had increased. Moderate to strong divergence was noted under the west side of the storm throughout these three times, perhaps indicative of the RFD.

Differential reflectivity undergoes an interesting evolution through this pre-tornado to tornado transition. At 0247 UTC, high $Z_{\text{DR}}$ (4 – 6 dB) was located along the storm’s forward flank and for a significant distance north into the storm (Fig. 6.5b). No hail shaft (or, in fact, no $Z_{\text{DR}} < \sim 1$ dB) was noted. At 0253 UTC, a few pixels of near-zero $Z_{\text{DR}}$ were found in the storm’s reflectivity core, perhaps suggesting some hailfall. Additionally, high $Z_{\text{DR}}$ values did not extend as far north into the storm as several
minutes before. At 0300 UTC, a few pixels of inferred hail seemed to be present, although no significant hailfall was likely occurring. No severe hail reports were received from this time, consistent with the $Z_{DR}$ signature. Perhaps most strikingly, $Z_{DR}$ had decreased to 3 – 5 dB along the storm’s forward flank, and values throughout the central portion of the storm were lower than previously. Values of 1 – 2.5 dB were typical throughout most of the storm away from the forward flank. The hook echo showed up well as a region of high $Z_{DR}$. These signatures indicate the presence of hail and/or graupel becoming more prevalent in the center of the storm, and large drops becoming more prevalent in the echo appendage region, toward the tornado time.

Correlation coefficient at 0247 UTC is rather uniformly high (0.98 +) throughout most of the supercell (Fig. 6.5b), with a few areas of 0.94 – 0.96 associated with heavy rain in the storm core. At 0253 UTC, the $\rho_{hv}$ field was dramatically different. A region of much lower values (0.9 – 0.96) had developed in the storm core, perhaps related to the hail fallout noted previously. Rain could have also been increasing in intensity in the storm core. The echo appendage was highly visible as an area of locally higher $\rho_{hv}$ (values 0.95 – 0.99). By 0300 UTC, $\rho_{hv}$ had continued to drop in the storm core, with values of 0.84 – 0.88 associated with a small hail shaft. Values were otherwise similar to those at 0253 UTC.

At 0247 UTC, $K_{DP}$ exhibited typical values of 1.5 – 2.5 deg/km in the storm core, with values highest just downwind from the primary updraft and associated with a stronger cell on the storm’s north side (Fig. 6.5c). By 0253 UTC, $K_{DP}$ values as high as 4 deg/km were noted in the storm core, apparently associated with the previously-described hail shaft which was most intense at this time. $K_{DP} \geq 2$ deg/km covered a larger portion
of the storm’s area. By 0300 UTC, the tornado time, $K_{DP}$ values were down to about 3 deg/km in the storm core, perhaps because the hail shaft and heavy rain diminished in intensity at this time owing to storm weakening. Perhaps most dramatic, $K_{DP}$ at the tornado time exhibited well-defined “wings” of higher values extending northeast away from the primary updraft. In the echo appendage region, values of $K_{DP}$ around 0.5 deg/km were common, but these decreased toward 0 deg/km at the tornado time, consistent with Mie scattering of radar energy off large debris particles (Ryzhkov et al. 2005, Chapter 5 of this thesis).

2) SECOND PTT $\rightarrow$ TT TRANSITION: 0311 – 0346 UTC

The second pre-tornado to tornado transition in the 9/10 May 2003 supercell is represented by four low-level radar scans, taken at 0311 UTC, 0322 UTC, 0328 UTC, and 0346 UTC. While the scan at 0311 UTC is relatively close to the previous tornado time (0300 – 0301 UTC), the supercell was in the process of rapidly producing a new updraft. Some influence from the previous tornado may be present, but should not overwhelm the processes leading up to tornadogenesis. The second tornado was observed to begin around 0329 UTC, and was rated F3. The 0346 UTC scan was included as an excellent example of a supercell in the tornadic phase.

From 0311 to 0322 UTC, maximum reflectivity decreased in the storm core from ~58 dBZ to ~55 dBZ, and reflectivity $> 55$ dBZ covered less area (Fig. 6.6a). At 0328 UTC, about when tornadogenesis was observed, reflectivity again increased, especially along the storm’s forward flank. At 0346 UTC, after an intense tornado had been
ongoing for some time, $Z_{HH}$ was still very high over a large area of the storm core.
Extended regions of higher reflectivity were quite prominent at 0311 UTC, but diminished over time. At 0311 UTC, a hook echo was left over from the previous tornado time. It diminished in definition and cyclonic curvature by 0322 UTC, but by 0328 UTC a large portion of the western side of the supercell began to curve cyclonically around a newly-developing updraft circulation. Thus, a very large echo appendage was present. After the tornado had been ongoing for some time (0346 UTC), the echo appendage was still large, was much more cyclonically curved, and possessed a strong and obvious $Z_{HH}$ maximum at the tornado location.

At 0311 UTC, radial velocity showed a relatively tight rotational couplet embedded in the mesocyclone circulation (Fig. 6.6a). This rotational couplet may have been associated with the tornado that dissipated around ten minutes previously. By 0322 UTC, only a mesocyclonic rotation was noted, but it occurred over a very broad region. At 0328 UTC, the strength of the mesocyclonic rotation had appeared to increase, and strong inbound/outbound velocities were becoming closer together. The 0346 UTC radial velocity scan shows the strong and well-defined circulation of a tornado cyclone embedded within the mesocyclonic rotation. Throughout the radial velocity progression in this pre-tornado to tornado transition, divergence was noted under the west side of the supercell.

Differential reflectivity showed interesting evolution through this pre-tornado to tornado transition (Fig. 6.6b). At 0311 UTC, values of $Z_{DR}$ were high (3.5 – 5 dB) along most of the storm’s forward flank. A small core of near-zero values occurred in the high-$Z_{HH}$ region along the forward flank well downwind from the primary updraft. By 0322
UTC, $Z_{DR}$ had generally decreased both in areal coverage of high values and in magnitude, although no hail was inferred at this time. Values had especially diminished in the region around the primary updraft, just north of the poorly defined echo appendage.

By 0328 UTC, values had dramatically risen to 4 – 7 dB along a portion of the forward flank, likely representing very large raindrops or melting graupel, and apparently related to a simultaneous increase of $Z_{HH}$ in the same location. Also at this time, $Z_{DR} > 3$ dB had expanded to cover much more of the storm, and values were increasing in the developing hook echo region. At 0346 UTC, after a tornado had been ongoing for some time, highest storm $Z_{DR}$ (5 – 6.5 dB) was located within the mesocyclone, just north of the tornadic region. High values along the forward flank had deceased somewhat, but still covered a large area. A dramatic region of low $Z_{DR}$ (-1 to 0 dB) was present at the tornado location.

Correlation also underwent some dramatic changes during this pre-tornado to tornado transition. At 0311 UTC, correlation was relatively low (0.9 – 0.96) in the storm’s $Z_{HH}$ core, associated with heavy rain or rain/hail mix (Fig. 6.6b). Values of $\rho_{hv}$ were typically 0.96 – 0.98 near the forward flank, where heavier rain was occurring, and $> 0.99$ in much of the remainder of the storm in lighter rain. By 0322 UTC, correlation had risen in the storm core, coincident with a general lowering of reflectivity (and decrease of heavy rain/hail). At 0328 UTC, $\rho_{hv} \leq 0.97$ again began occurring commonly along the storm’s forward flank as heavier rain developed. At 0346 UTC, the correlation pattern was quite dramatic: values were quite low (0.9 – 0.95) through much of the forward flank region where very heavy rain and rain/hail mix was occurring, high values ($\geq 0.97$) were found through much of the rest of the storm, and a region of very low
values (~ 0.5) was found associated with the tornado. These low near-tornado values have been turned gray in the figure, as they were too low to be on the color bar. No other significant changes were noted as the supercell evolved through this transition.

Specific differential phase at 0311 UTC was at a local maximum in the storm core’s region of heavy rain; values there were up to 4.5 deg/km (Fig. 6.6c). Absolute storm maximum $K_{DP}$ (~ 6 deg/km) occurred in the hook echo region. As negative or near-zero $K_{DP}$ is expected with large tornado-lofted debris (Ryzhkov et al. 2005, Chapter 5 of this thesis), and since a tornado dissipated in this storm region about ten minutes before, it is hypothesized that this region of high $K_{DP}$ is associated with residual tornado-lofted debris not large enough for Mie scattering to result in negative values. As residual tornadic debris would likely be exceedingly anisotropic, very high $K_{DP}$ could be expected. At 0322 UTC, values in the storm core had diminished to 1.5 – 3 deg/km, but values > 1.5 deg/km covered about the same percentage of the storm. Increasingly heavy rainfall at 0328 UTC along the supercell’s forward flank led to higher $K_{DP}$ there, with values climbing back up toward 4 – 4.5 deg/km. Values of $K_{DP} > 1.5$ deg/km extended far south into the developing echo appendage. By 0346 UTC, much of the hook echo contained $K_{DP} > 1.5$ deg/km. A striking $K_{DP}$ dipole occurred in the tornado region, with values around –2.5 deg/km at the tornado location and values as high as +5 deg/km about 2.3 km to the tornado’s southeast.
3) TT ⇒ TDT TRANSITION: 0300 – 0306 UTC

The tornado occurring in the 0300 – 0301 UTC timeframe was apparently quite short-lived, causing difficulty because of the low temporal resolution of operational radars. Although the timing is not optimal to best analyze this tornado to tornado demise transition, a radar scan at 0300 UTC was used to represent the tornado time and the following scan at 0306 UTC was taken as representative of tornado demise. Note that trends in the polarimetric variables may be difficult to judge over this transition because of its short duration.

From 0300 to 0306 UTC, the storm percentage with $Z_{HH} \geq 55$ dBZ increased, especially north of the mesocyclone (Fig. 6.7a). By 0306 UTC higher reflectivity (45 – 55 dBZ) had started wrapping into the hook echo, and the hook echo was better defined at this time than earlier. Extended regions of higher $Z_{HH}$ were present at both times, but were perhaps better defined at 0306 UTC.

At both times, the radial velocity field showed strong rotation in a mesocyclonic sense and depicted an embedded tighter, smaller rotational couplet (Fig. 6.7a). Rotational velocity at the storm location favored for a tornado did, however, decrease from 0300 to 0306 UTC, probably indicating the ongoing tornado demise. A divergence signature, likely associated with an RFD, remained strong under the west side of the supercell through both times.

Differential reflectivity underwent some changes from 0300 to 0306 UTC. The areal extent of high values along the forward flank increased, and $Z_{DR}$ from 4.5 dB to 5 dB became more common (Fig. 6.7b). At 0300 UTC, when a tornado was known to be
ongoing, $Z_{DR}$ was commonly 3 – 4.5 dB in the hook echo, indicating large raindrops, and the hook echo was an obvious feature. By 0306 UTC, however, $Z_{DR}$ had decreased to 1 – 2 dB in the hook echo, and this feature was no longer obvious. This indicates a smaller average drop size in the echo appendage by the tornado demise time. A few near-zero pixels in the storm core, indicating hail, were present at 0300 UTC, while at 0306 UTC the near-zero pixels were spread out through a larger part of the storm core but still not prevalent.

At 0300 UTC, correlation in the hail shaft reached ~0.84, a dramatic local minimum. Values of $\rho_{hv} < 0.96$ are common through a large portion of the storm downwind from the mesocyclone in heavy rain, with $\rho_{hv}$ generally $> 0.97$ in the downwind light precipitation region. At 0306 UTC, $\rho_{hv}$ was similar, but the very low values associated with the hail core had risen to 0.85 – 0.88.

$K_{DP}$ increased from tornado to tornado demise, with maximum values in the storm core rising from ~3 deg/km to ~4.5 deg/km. ‘Wings’ of higher $K_{DP}$ extended northeast away from the primary updraft at both times. A large area of high $K_{DP}$ values trailed the supercell at 0306 UTC; this region was also characterized by low $Z_{HH}$ (< 30 dBZ), midrange $Z_{DR}$ (1 – 2 dB), and low $\rho_{hv}$ (< 0.7). These polarimetric characteristics are consistent with the “supercell wake signature” (Ryzhkov et al. 2005), when light debris lofted in the storm’s wind field is left behind to slowly settle out.
On 8/9 May 2003, a supercell moved across central Oklahoma, producing significant damage in Moore and Oklahoma City. One transition from PTT to TT and one from TT to TDT were captured by KOUN and are analyzed here. Electricity was cut to KOUN for much of the time the tornado was ongoing in Moore because of a lightning strike, but this did not affect the transitions analyzed here. In the tornado-to-tornado demise transition, a beam blockage caused the loss of some useful information in the hook echo region, but meaningful results can nonetheless be obtained.

1) PTT $\rightarrow$ TT TRANSITION: 2159 – 2211 UTC

The pre-tornado to tornado transition in the 8/9 May 2003 supercell is represented by three low-level radar scans, taken at 2159 UTC, 2205 UTC, and 2211 UTC. Reflectivity ($Z_{HH}$) underwent changes similar to those noted in other cases. The echo appendage at 2159 UTC began to take on greater cyclonic curvature at 2205 UTC and had become strongly cyclonically curved with hints of a cyclonic-anticyclonic rotational couplet by 2211 UTC (Fig. 6.8a). A cell began to split off the storm at 2159 UTC, and by 2211 UTC, had become separate to the north of the primary supercell. $Z_{HH}$ distribution did not change significantly between 2159 and 2205 UTC, but by 2211 UTC the region of highest reflectivity ($>52$ dBZ) had shifted eastward and concentrated along the storm’s forward flank downwind from the primary updraft. Extended regions of
higher $Z_{HH}$ extending away from the primary updraft were not as evident as in other cases.

Radial velocity underwent interesting evolution during this sequence from pre-tornado to tornado time. At 2159 UTC, radar-indicated flow in southern portions of the echo appendage was primarily convergent, with ~24 m/s inbound velocity converging with ~18 – 21 m/s outbound velocity under the echo appendage (Fig. 6.8a). By 2205 UTC, the area covered by the highest inbound and outbound velocities had expanded, and the flow became more rotationally convergent in the developing echo appendage. Finally, at the tornado time (2211 UTC), the areal coverage of strong inbound and outbound velocities had decreased, but a concentrated cyclonic rotational couplet had formed near the tip of the echo appendage. Overall, areal extent of inbound velocities through the west side of the supercell increased from the pre-tornado to tornado time, perhaps indicating RFD intensification or a more favorable radar viewing angle.

A well-defined hail shaft, indicated by collocated near-zero $Z_{DR}$ and high $Z_{HH}$, is never found in this sequence. Some hail may have been falling at 2159 UTC in the storm core well north of the mesocyclone, and some hail was likely falling at 2211 UTC, the tornado time, in a similar location but slightly closer to the mesocyclone (Fig. 6.8b). Values of $Z_{DR}$ were typically very high along the storm’s forward flank, with values averaging 4 – 7 dB through this transition. Spatially, the forward-flank $Z_{DR}$ maximum tends to move east with time (away from the primary updraft), and by the tornado time, $Z_{DR}$ had lowered substantially in the near-echo appendage portion of the forward flank. Values of 1 – 3 dB were common in the echo appendage through this transition, although a local maximum of 3 – 5 dB developed at the tornado time, likely indicating larger
average drop size as smaller drops evaporated. Values on the supercell’s north side were observed to drop dramatically through this transition, from 4 – 6 dB at pre-tornado time to 1 – 4 dB at the tornado time. The cell splitting off the parent storm to the north was characterized by a local $Z_{\text{DR}}$ maximum, typically 3 – 5 dB.

The correlation coefficient shows strong evolution through this pre-tornado to tornado transition, and in some ways makes storm changes more evident than the reflectivity field. At 2159 UTC, $\rho_{hv}$ was uniformly 0.97+ throughout the storm, except in a small location in the storm core north of the mesocyclone, where hail was possibly inferred using $Z_{\text{DR}}$ and $Z_{\text{HH}}$ (Fig. 6.8b). Values of $\rho_{hv}$ in this region of possible hailfall were 0.88 – 0.95, with most values 0.92 – 0.94. In addition, values of $\rho_{hv}$ along the supercell’s forward flank were uniformly high as in the rest of the storm. By 2205 UTC, a few changes had occurred. The small region of lower values in the storm core was still in place north of the mesocyclone, although it had shifted east and values had generally risen. The lowest values found in this region at this time were around 0.91; these observed trends suggest lessened hailfall, consistent with $Z_{\text{DR}}$ observations. At this time, the storm’s central region of low $\rho_{hv}$ was associated with heavy rainfall, as $Z_{\text{DR}}$ and $Z_{\text{HH}}$ were both high. Values along the forward flank were beginning to drop immediately north of the mesocyclone. By 2211 UTC, the tornado time, a dramatic and large region of low $\rho_{hv}$ had expanded to fill much of the forward flank near the primary updraft; this region extended well into the storm core and contained typical $\rho_{hv}$ values of 0.8 – 0.95. Since some minor hailfall was inferred at this time, the lowest values are likely associated with hail, while the other low values are likely occurring in heavy rain. At the tornado time, the hook echo shows up very well in $\rho_{hv}$ as a cyclonically-curved feature containing
high values (typically 0.97+). A cyclonic-anticyclonic rotational couplet near the tip of the echo appendage appears in this field. Lower correlation is present on the north side of the rotational couplet associated with a tornado lofting debris in Moore, Oklahoma.

Location of highest storm $K_{DP}$ tends to shift eastward with time, similar to the evolution of $Z_{HH}$ (Fig. 6.8c). At the pre-tornado time (2159 UTC), $K_{DP}$ in the storm core ranged from 2 – 4 deg/km, with values from 0 – 2 deg/km typical in the rest of the supercell, including the echo appendage. By the next scan time (2205 UTC), maximum $K_{DP}$ in the storm core had increased to ~5.5 deg/km, with values also 2 – 3 deg/km in a reflectivity core on the storm’s north side. These higher values had tended to shift southward, becoming closer to the forward flank near the mesocyclone, and likely indicated increasingly anisotropic hydrometeors such as large raindrops. At the tornado time (2211 UTC), the pattern was very similar to the previous scan. The $K_{DP}$ maximum with the reflectivity core on the storm’s north side had diminished, although maximum values were still ~5 deg/km in the storm core near the forward flank. Values through the echo appendage remained similar through this sequence, although at the tornado time a large region of negative values became evident on its north side. This was likely caused by debris larger than the radar wavelength being lofted from Moore, Oklahoma, allowing Mie scattering to cause negative $K_{DP}$ in the debris (Ryzhkov et al. 2005; Chapter 5 of this thesis).
2) TT → TDT TRANSITION: 2230 – 2242 UTC

The tornado-to-tornado demise transition in the 8/9 May 2003 supercell is represented by three low-level radar scans, taken at 2230 UTC, 2235 UTC, and 2242 UTC. Through this transition, reflectivity showed a trend toward loss of echo appendage definition and distancing of storm maximum $Z_{HH}$ from the echo appendage region (Fig. 6.9a). At 2230 UTC, while the tornado was still ongoing, a well-defined hook echo was still present, and $Z_{HH} > 52$ dBZ was mostly located just north of the echo appendage and along the forward flank near the primary updraft. By 2235 UTC, an echo appendage was still present, but much of it had wrapped northward into the storm. Finally, by tornado demise (2242 UTC), a better-defined hook echo was again present, although the region of $Z_{HH} > 52$ dBZ had become located primarily well north and east of the primary updraft, and not near the echo appendage.

Radial velocity through this tornado-to-tornado demise transition showed the expected trend of decreasing tornado-related rotation, and also seems to indicate mesocyclone weakening (Fig. 6.9a). At 2230 UTC, strong mesocyclone rotation was evident, with an embedded tornado-related tight rotational couplet. By 2235 UTC, the radial velocity pattern was similar, but the tornado-related tight rotational couplet appeared to be moving away from the larger mesocyclonic circulation. Finally, at tornado demise (2242 UTC), a surprising lack of rotation, either on the tornado or mesocyclone scale, was noted. No tight tornado-related radial velocity couplet was noted, the magnitude of the mesocyclonic circulation was significantly diminished, and the areal extent of the mesocyclone’s circulation appeared to have lessened.
As in the previously discussed pre-tornado to tornado transition, very little hail was noted during this sequence. At 2230 UTC, a small region of hailfall, associated with near-zero $Z_{DR}$ and high $Z_{HH}$, was located in the storm core just north of the mesocyclone, although no hail was inferred at 2235 or 2242 UTC (Fig. 6.9b). Forward-flank $Z_{DR}$ values were typically 4 – 7 dB throughout this transition, although the band of $Z_{DR} > 4$ dB became thinner along the forward flank by the demise time (2242 UTC). In the echo appendage region, $Z_{DR}$ was fairly consistently 2 – 4 dB. Moving from tornado to tornado demise time, $Z_{DR}$ was observed to increase in the downwind light precipitation region.

Correlation at 2230 UTC showed a large area of low values (0.85 – 0.94) in the storm’s reflectivity core associated with heavy rain and light hailfall (Fig. 6.9b). Values in the remainder of the supercell ranged from 0.94 – 1, with possible contamination caused by beam blockage through much of the storm’s downwind light precipitation region. Most strikingly at this time, however, was the presence of a large region of very low $\rho_{hv}$ surrounding the tornado location, likely associated with a large amount of lofted debris. This $\rho_{hv}$ minimum was collocated with a local maximum of $Z_{HH}$. By 2235 UTC, the $\rho_{hv}$ pattern was very similar except for the lack of a minimum at the tornado location; the most dense debris has probably settled out or been left behind. Correlation values both higher in magnitude and in areal coverage of high values have filled in along the supercell’s forward flank by 2242 UTC (tornado demise), with values typically exceeding 0.98. This trend suggests replacement of large drops, hail, or rain/hail mix with smaller raindrops along the forward flank. Values in the large downwind region of light precipitation deceased significantly from 2235 to 2242 UTC.
Specific differential phase did not change much through this tornado to tornado demise transition. At the tornado time (2230 UTC), $K_{dp}$ values averaged 2 – 4 deg/km in the storm core and south portion of the hook echo, while values were typically 0 – 0.5 deg/km in nearly all the light downwind precipitation region (Fig. 6.9c). A large region of $K_{dp} < 0$ deg/km occurred on the north side of the hook echo likely associated with a large cloud of tornado debris. Five minutes later, the $K_{dp}$ pattern was virtually identical, although the region of below-zero values had become less negative and covered a smaller area. By the demise time (2242 UTC), the region of $K_{dp} > 2$ deg/km had become larger, and had shifted east relative to the primary updraft, similar to $Z_{hh}$. 
Figure 6.1a. Reflectivity factor ($Z_{\text{HH}}$, left column) and radial velocity (right column) through the first pre-tornado time to tornado time transition in the 13/14 June 1998 case. a) and d) represent 0029 UTC; b) and e) represent 0036 UTC; c) and f) represent 0043 UTC.
Figure 6.1b. Differential reflectivity ($Z_{DR}$, left column) and correlation coefficient ($\rho_{hv}$, right column) through the first pre-tornado time to tornado time transition in the 13/14 June 1998 case. a) and d) represent 0029 UTC; b) and e) represent 0036 UTC; c) and f) represent 0043 UTC.
Figure 6.2a. Reflectivity factor ($Z_{\text{HH}}$, left column) and radial velocity (right column) through the second pre-tornado time to tornado time transition in the 13/14 June 1998 case. a) and d) represent 0057 UTC; b) and e) represent 0104 UTC; c) and f) represent 0112 UTC.
Figure 6.2b. Differential reflectivity ($Z_{DR}$, left column) and correlation coefficient ($\rho_{hv}$, right column) through the second pre-tornado time to tornado time transition in the 13/14 June 1998 case. a) and d) represent 0057 UTC; b) and e) represent 0104 UTC; c) and f) represent 0112 UTC.
Figure 6.3a. Reflectivity factor ($Z_{HH}$, left column) and radial velocity (right column) through the first tornado time to tornado demise time transition in the 13/14 June 1998 case. a) and c) represent 0043 UTC; b) and d) represent 0050 UTC.
Figure 6.3b. Differential reflectivity ($Z_{DR}$, left column) and correlation coefficient ($\rho_{hv}$, right column) through the first tornado time to tornado demise time transition in the 13/14 June 1998 case. a) and c) represent 0043 UTC; b) and d) represent 0050 UTC.
Figure 6.4a. Reflectivity factor ($Z_{HH}$, left column) and radial velocity (right column) through the second tornado time to tornado demise time transition in the 13/14 June 1998 case. a) and d) represent 0112 UTC; b) and e) represent 0117 UTC; c) and f) represent 0124 UTC.
Figure 6.4b. Differential reflectivity ($Z_{DR}$, left column) and correlation coefficient ($\rho_{hv}$, right column) through the second tornado time to tornado demise time transition in the 13/14 June 1998 case. a) and d) represent 0112 UTC; b) and e) represent 0117 UTC; c) and f) represent 0124 UTC.
Figure 6.5a. Reflectivity factor ($Z_{HH}$, left column) and radial velocity (right column) through the first pre-tornado time to tornado time transition in the 9/10 May 2003 case. a) and d) represent 0247 UTC; b) and e) represent 0253 UTC; c) and f) represent 0300 UTC.
Figure 6.5b. Differential reflectivity ($Z_{DR}$, left column) and correlation coefficient ($\rho_{hv}$, right column) through the first pre-tornado time to tornado time transition in the 9 May 2003 case. a) and d) represent 0247 UTC; b) and e) represent 0253 UTC; c) and f) represent 0300 UTC.
Figure 6.5c. Specific differential phase ($K_{DP}$) through the first pre-tornado time to tornado time transition in the 9 May 2003 case. a) represents 0247 UTC; b) represents 0253 UTC; c) represents 0300 UTC.
Figure 6.6a. Reflectivity factor ($Z_{HH}$, left column) and radial velocity (right column) through the second pre-tornado time to tornado time transition in the 9/10 May 2003 case. a) and e) represent 0311 UTC; b) and f) represent 0322 UTC; c) and g) represent 0328 UTC; d) and h) represent 0346 UTC.
Figure 6.6b. Differential reflectivity ($Z_{DR}$, left column) and correlation coefficient ($\rho_{hv}$, right column) through the second pre-tornado time to tornado time transition in the 9 May 2003 case. a) and e) represent 0311 UTC; b) and f) represent 0322 UTC; c) and g) represent 0328 UTC; and d) and h) represent 0346 UTC.
Figure 6.6c. Specific differential phase ($K_{dp}$) through the second pre-tornado time to tornado time transition in the 9 May 2003 case. a) represents 0311 UTC; b) represents 0322 UTC; c) represents 0328 UTC; d) represents 0346 UTC.
Figure 6.7a. Reflectivity factor ($Z_{HH}$, left column) and radial velocity (right column) through the tornado time to tornado demise time transition in the 9/10 May 2003 case. a) and c) represent 0306 UTC; b) and d) represent 0311 UTC.
Figure 6.7b. Differential reflectivity ($Z_{DR}$, left column) and correlation coefficient ($\rho_{hv}$, right column) through the tornado time to tornado demise time transition in the 9 May 2003 case. a) and c) represents 0306 UTC; b) and d) represents 0311 UTC.
Figure 6.7c. Specific differential phase (K_{DP}) through the tornado time to tornado demise time transition in the 9 May 2003 case. a) represents 0306 UTC; b) represents 0311 UTC.
Figure 6.8a. Reflectivity factor (Z_{HH}, left column) and radial velocity (right column) through the pre-tornado time to tornado time transition in the 8/9 May 2003 case. a) and d) represent 2159 UTC; b) and e) represent 2205 UTC; c) and f) represent 2211 UTC.
Figure 6.8b. Differential reflectivity ($Z_{\text{DR}}$, left column) and correlation coefficient ($\rho_{\text{hv}}$, right column) through the pre-tornado time to tornado time transition in the 8/9 May 2003 case. a) and d) represent 2159 UTC; b) and e) represent 2205 UTC; c) and f) represent 2211 UTC.
Figure 6.8c. Specific differential phase ($K_{DP}$) through the pre-tornado time to tornado time transition in the 8/9 May 2003 case. a) represents 2159 UTC; b) represents 2205 UTC; c) represents 2211 UTC.
Figure 6.9a. Reflectivity factor ($Z_{HH}$, left column) and radial velocity (right column) through the tornado time to tornado demise time transition in the 8/9 May 2003 case. a) and d) represent 2230 UTC; b) and e) represent 2235 UTC; c) and f) represent 2242 UTC.
Figure 6.9b. Differential reflectivity ($Z_{DR}$, left column) and correlation coefficient ($\rho_{hv}$, right column) through the tornado time to tornado demise time transition in the 8/9 May 2003 case. a) and d) represent 2230 UTC; b) and e) represent 2235 UTC; c) and f) represent 2242 UTC.
Figure 6.9c. Specific differential phase ($K_{DP}$) through the tornado time to tornado demise time transition in the 8/9 May 2003 case. a) represents 2230 UTC; b) represents 2235 UTC; c) represents 2242 UTC.
7. Middle- and Upper-level Polarimetric Schematics

In this chapter, preliminary middle- and upper-level polarimetric schematics are developed for the Southern and High Plains. Southern Plains schematics are developed for $Z_{HH}$, $Z_{DR}$, $\rho_{hv}$, and $K_{DP}$, while for the High Plains, $Z_{HH}$, $Z_{DR}$, $\rho_{hv}$, and $LDR_{VH}$ are represented. Again, it is important to emphasize the preliminary aspect of these schematics, and the likelihood that they will be improved as more polarimetric supercell cases become available.

a. Southern Plains Midlevel Schematics

1) REFLECTIVITY FACTOR ($Z_{HH}$)

At midlevels, typical Southern Plains storms exhibited a hint of an echo appendage feature, although it was much less pronounced than at low levels (Fig. 7.1). A wide variety of storm shapes were represented, probably resulting from the use of slightly different elevations and from the presence of different storm structures and organization. The most prominent feature was a BWER, WER, or inflow notch above the location of the low-level updraft. Which is present likely depends on environmental factors, precisely where in its evolution the storm is, and on observational altitude. Highest storm reflectivity factor was typically located just downwind from the primary updraft, with a relatively large area of high reflectivity (> 50 dBZ). Extended regions of high reflectivity similar to those seen at low levels were typically present, although much less pronounced.
than at low levels. Low reflectivity (< 35 dBZ) was located along much of the storm periphery on the storm’s north and east sides, while a fairly large area of medium values (35 – 50 dBZ) was typically located between the areas of high and low values (Fig. 7.1).

Midlevel reflectivity factor at tornado times was fairly similar in appearance to that at pre-tornado times (Fig. 7.1). Areas of high (> 50 dBZ), medium (35 – 50 dBZ), and low (< 35 dBZ) reflectivity values were in similar locations. In the mean, however, the inflow notch had tended to become a BWER feature located over the low-level updraft. High reflectivity values often formed a conspicuous arc (or horseshoe) shape around the BWER. Also, the region of high reflectivity values was less likely to exhibit flares, although these could still be weakly present. A weak echo appendage could be present, although this only occurred in a small portion of cases.

Midlevel reflectivity factor at tornado demise times appeared very similar to the same field at tornado times (Fig. 7.1). A BWER was still present above the low-level updraft, and high $Z_{HH}$ values (> 50 dBZ) were still located downwind from this feature. The region of high values, however, did not exhibit as much cyclonic curvature around the BWER as at tornado times, perhaps indicating a reduction of midlevel updraft vorticity and updraft weakening. Medium reflectivity values (35 – 50 dBZ) were in the same location as at tornado times, although they tended to more readily reach the storm periphery. Consequently, low reflectivity values (< 35 dBZ), seen along much of the storm periphery at pre-tornado and tornado times, were typically restricted to the portion of the storm periphery farthest from the primary updraft at tornado demise times. Some cases possessed a well-defined cyclonically curved echo appendage, while most cases possessed no such feature.
2) DIFFERENTIAL REFLECTIVITY (Z\textsubscript{DR})

At pre-tornado times, midlevel differential reflectivity showed a region of high values (> 2 dB) just downwind from the primary updraft; this region of high values showed fairly great areal coverage (Fig. 7.2) and represented the Z\textsubscript{DR} column (e.g. Herzegh 1992), a region of liquid drops lofted above the freezing level in the mesocyclone. Few medium values (1 – 2 dB) were present, but when present, were located generally downwind from the region of high values. Low values (< 1 dB) covered the downwind half to two-thirds of the typical storm. Because of the greatly varied position of BWER/WER/inflow notch features, no conclusion could be reached about typical Z\textsubscript{DR} values along the storm’s west and south flanks near the primary updraft. Any BWER/WER/inflow notch present, however, was collocated with high Z\textsubscript{DR} (> 2 dB), or in one case where the storm was quite distant from the radar, medium values (1 – 2 dB). Once more cases are available, it may be possible to divide storms based on structure and develop more representative polarimetric schematics for each.

Differential reflectivity at midlevels changed significantly in Southern Plains supercells from pre-tornado to tornado times. High Z\textsubscript{DR} (> 2 dB) had shifted southwest toward the southwest flank of the storm (Fig. 7.2), likely representing updraft regeneration there. These were surrounded by a variable blend of high, medium, and low values, so a designation of variable was added to the composite schematic. Low values (< 1 dB) covered the downwind three-fourths to four-fifths of the composite supercell, attributed to a region of graupel. This pattern contrasts with the schematic of pre-tornado
time $Z_{DR}$, in which the larger area of high values was typically located closer to storm center (Fig. 7.2).

At tornado demise times, midlevel Southern Plains $Z_{DR}$ was quite similar to the tornado time cases (Fig. 7.2). High values ($> 2$ dB) were located through much of the echo appendage, across the BWER/WER/inflow notch, and along the storm’s forward flank very near the primary updraft. High values were typically more extensive than at tornado times, and appeared to be migrating back toward the center of the storm as seen at pre-tornado times. The northwest flank of the storm could contain a variety of values ranging from low to high, so was designated variable in the composite schematic.

Finally, roughly the downwind three-fourths of the composite supercell had low $Z_{DR}$ values ($< 1$ dB). This was also more consistent with pre-tornado times than with tornado times.

3) CORRELATION COEFFICIENT ($\rho_{hv}$)

Midlevel correlation coefficient patterns looked quite different from those developed for low levels (Chapter 5). A region of low values ($< 0.95$) was located just downwind from the primary updraft, or sometimes collocated with the primary updraft (i.e. with the BWER/WER/inflow notch) (Fig. 7.3). In some cases these low values were thought to represent hail, since large hail tends to have low correlation (Straka et al. 2000). The updraft region tended to have low correlation values, likely because a mix of hydrometeors and light debris (e.g. grass, leaves) was present. Because placement of the strongest portion of the updraft/inflow region was variable, $\rho_{hv}$ values ranged from low to
medium (≤ 0.98) in the echo appendage region, leading to a designation of variable in this area. Medium correlation (0.95 – 0.98) was typically located surrounding and just downwind from the region of low values, with high values (> 0.98) beyond the medium values. Another well-defined region of medium values was located along the storm’s southeast flank, a pattern not seen at low levels. Average $\rho_{hv}$ was higher at midlevels than at low levels, probably resulting from smaller average drop size farther aloft (and thus from greater hydrometeor sphericity—Jameson 1982).

Correlation in Southern Plains classic supercells looked very similar at tornado and pre-tornado times (Fig. 7.3). A small region of low values (< 0.95) was still present collocated with the BWER feature, surrounded by medium values (0.95 – 0.98). High values (> 0.98) still dominated storm center, while lower values occurred through much of the composite supercell’s southeast quadrant. The region of predominately medium correlation had expanded notably since pre-tornado times, and a small region of low values even showed up along the storm’s eastern (farthest downwind) flank. Correlation values along the storm’s western edge were typically quite variable between cases, and a full range of values were represented.

Low correlation (< 0.95) was still evident collocated with the BWER/inflow notch feature at tornado demise times (Fig. 7.3), although this feature may have represented a new updraft by the demise time. To its southwest, medium $\rho_{hv}$ (0.95 – 0.98) was present in rain or rain/graupel mix. High values typically extended to the north and east away from the BWER/inflow notch feature and covered much of the composite supercell’s north flank. Intermediate values (0.95 – 0.98) continued their trend of covering more area with each successive time, and now dominated much of the
southeastern two-fifths to half of the composite supercell. Correlation was highly variable along the forward flank near the primary updraft, and along the back of the storm to the northwest of the BWER/inflow notch.

4) SPECIFIC DIFFERENTIAL PHASE ($K_{DP}$)

At pre-tornado times, specific differential phase exhibited the expected pattern. A small core of high values (> 2 deg/km) was located just downwind from the primary updraft and BWER/WER/inflow notch feature, surrounded by an area of medium $K_{DP}$ (0.25 – 2 deg/km) (Fig. 7.4). This region of enhanced values was likely caused by the presence of large drops lofted to midlevels by the updraft, as it was generally collocated with the $Z_{DR}$ column. It could also represent drops shed from hail, as seen in Hubbert et al. (1998). Values in the echo appendage region could be medium or high if an inflow feature was present, but could also be low. Approximately the downwind two-thirds of the composite supercell had low $K_{DP}$ (< 0.25 deg/km), probably in dry graupel.

Tornado time $K_{DP}$ appeared very similar to the same field at the pre-tornado time (Fig. 7.4). A small core of high values (> 2 deg/km) was collocated with and immediately downstream from the BWER feature, with medium values (0.25 – 2 deg/km) covering the remainder of the echo appendage. Low values (< 0.25 deg/km) dominated the remainder of the composite supercell.

By tornado demise time, storm average $K_{DP}$ was rising after the tornado time minimum. There was, however, little spatial similarity between the three available cases. High and medium values (> 0.25 deg/km) were confined to the windward third of the
composite supercell, with scattered high, medium, and low values throughout this region. One case, very distant from the radar, did not have any high values. An area of medium values, relatively consistent between the cases, is denoted on the composite schematic (Fig. 7.4). Low values (< 0.25 deg/km) cover roughly the downwind two-thirds of the composite storm.

b. High Plains Midlevel Schematics

Midlevel data existed for two High Plains cases; therefore, schematics developed herein are particularly preliminary.

1) REFLECTIVITY FACTOR ($Z_{\text{HH}}$)

One case possessed a well-defined echo appendage while the other case had none. As in Southern Plains cases, a wide variety of observable structures likely exist. Inflow notches were present in each case, representing the primary region of midlevel inflow above the low-level updraft (Fig. 7.5). At pre-tornado times, the inflow notch did not yet possess significant cyclonic curvature. Regions of high, medium, and low values were in similar locations when compared to Southern Plains cases. In High Plains cases, however, the region of medium values (35 – 50 dBZ) tended to be smaller, and there was a larger region of light precipitation (and low reflectivity) on the storm’s downwind side. Caution is required when interpreting such differences, as they may result from differing environmental conditions (e.g. stronger wind aloft causing a larger downwind region of
light precipitation in these High Plains cases—environmental comparisons are necessary before conclusions are drawn).

High Plains reflectivity factor at tornado times was remarkably similar at midlevels to that of Southern Plains cases (Fig. 7.5). A strong inflow notch often extended far into the main storm, surrounded by a horseshoe-shaped region of high $Z_{HH}$ (> 50 dBZ). No echo appendage features occurred. More of the storm’s areal extent was taken up by medium $Z_{HH}$ values (35 – 50 dBZ) at tornado times than at pre-tornado times. Low values (< 35 dBZ) often covered a large area in the downwind precipitation region for High Plains cases, whereas in Southern Plains cases low values of $Z_{HH}$ were typically confined more to the storm’s edges. This may indicate a larger downwind region of graupel in the High Plains storms. Environmental effects may also have caused this trend, however, so caution in interpretation is advised.

At tornado demise times, both High Plains cases exhibited a well-defined inflow notch, although neither was as strong as those observed at tornado times (Fig. 7.5). In addition, high reflectivity values (> 50 dBZ) were less cyclonically curved around the inflow notch, again supporting weaker midlevel vorticity at tornado demise times. No echo appendage features were noted with either High Plains case. This may be caused by differing storm modes on the High Plains—especially, low-precipitation storms are more common in higher terrain where moisture is limited. Otherwise, tornado demise time $Z_{HH}$ was virtually identical at tornado demise and tornado times. For comparison, Southern and High Plains cases also had very similar structure at tornado demise times.
2) DIFFERENTIAL REFLECTIVITY (Z\text{DR})

Midlevel High Plains Z\text{DR} at pre-tornado times was dominated by low values (Fig. 7.6). A small core of high values (> 2 dB) was present, collocated with the farthest extension of the inflow notch and representing the Z\text{DR} column. A small region of medium values (1 – 2 dB) occurred along the back of the storm, and although somewhat suspect, may represent new cell development and liquid drops. In one case, that exhibiting a weak echo appendage feature, high and medium Z\text{DR} (≥ 1 dB) was present along the storm’s south side, likely representing new updraft development. Since the other case had no such pattern, this area was designated variable on the composite schematic.

For High Plains cases, tornado time Z\text{DR} showed some different midlevel patterns. High and medium values (≥ 1 dB) were typically located along the west (back) flank of the storm in the region favored for liquid drops, although values in much of the inflow area were too variable for a conclusion to be reached about typical values. Of the two cases, one showed high and medium Z\text{DR} values collocated with the inflow notch, as expected, while the other case contained low values in the same storm region. As anticipated, low values (< 1 dB) dominated much of the downwind region of the composite supercell where extensive graupel was likely present.

The two High Plains tornado demise cases exhibited slightly different patterns, probably a result of a different elevation being used for each. In one case, a small area of medium and high Z\text{DR} values (≥ 1 dB) was present in the storm region favored for an inflow notch/BWER feature, although the other case had low values (< 1 dB) throughout
the entire storm. As at all other times in the High Plains storms, any region of enhanced
differential reflectivity in the updraft vicinity was small and transitioned very quickly to
surrounding low values (Fig. 7.6). The Z_{DR} column may have been less pronounced on
average, indicating a weaker updraft by the tornado demise time.

3) CORRELATION COEFFICIENT (\(\rho_{hv}\))

For the two High Plains cases, midlevel correlation patterns were different from
those seen in the Southern Plains cases (Fig. 7.7). A well-defined region of low values (<
0.95) was collocated with the inflow notch, a consistent feature in the few available High
Plains cases. Medium \(\rho_{hv}\) values (0.95 – 0.98) occurred in small regions along the
forward flank and farther into the storm from the inflow notch. Medium values,
however, were less widespread than in Southern Plains cases, and their coverage was
variable in the two High Plains cases examined. High correlation values (> 0.98)
dominated most of the High Plains composite supercell at pre-tornado times, unlike in the
Southern Plains cases, where high values had a strong presence but were not as
widespread. The prevalence of high correlation values in High Plains cases is thought
related to the greater prevalence of small graupel and hail particles there compared to
Southern Plains storms (Changnon 1977).

Midlevel tornado time correlation in High Plains cases produced a striking
pattern. Since an inflow notch was well-defined in these cases, a strong incursion of low
correlation was present in the same area (Fig. 7.7). This incursion of low correlation was
roughly coincident with areas of low and medium reflectivity (< 50 dBZ), so tended to
appear more cyclonically curved and extend farther into the storm than the readily apparent low-reflectivity inflow notch. Medium correlation (0.95 – 0.98) tended to be located around the low-correlation incursion, although correlation throughout approximately the upwind fifth of the composite supercell was quite variable between high, medium, and low values. Away from this region, high correlation (> 0.98) dominated most of the downwind four-fifths of the composite storm in graupel, with some medium values along the southeast flank, much as seen in Southern Plains cases.

At tornado demise times, High Plains cases looked fairly similar to their Southern Plains counterparts (Fig. 7.7). A region of low correlation was collocated with the inflow notch, surrounded by medium values. Much of the composite storm’s northern and central sections were covered by high $\rho_{hv}$. Along much of the storm’s eastern flank, correlation tendency was toward a blend of medium and high values, so high variability was indicated on the schematic. This region of variability, however, tended to contain lower average correlation than the surrounding region designated as containing high values. Graupel likely dominated much of this region.

4) LINEAR DEPOLARIZATION RATIO (LDR$_{VH}$)

LDR$_{VH}$ tended to be a rather complex polarimetric field, although this was less true at pre-tornado times for midlevels than at other times examined. As noted in Chapter 5, high LDR$_{VH}$ at low levels was closely associated with storm inflow. This was also found true at mid and upper levels, especially at tornado and tornado demise times. At pre-tornado times, a region of high LDR$_{VH}$ (> -24 dB) was found along the south edge of
the echo appendage, with a secondary, small region of high values along the storm’s western flank (Fig. 7.8). These regions may represent areas of graupel or small hail. Low values (< -28 dB) were most commonly found well downstream from the primary updraft, within the northeast third of the composite supercell. Between these areas, a blend of high, medium, and low values occurred, necessitating a denotation of variable on the composite schematic.

Midlevel LDR<sub>VH</sub> appeared remarkably different at tornado times (Fig. 7.8). The inflow notch had become a much more well-defined region of high values extending into the storm, and was now a prominent feature. These high values may have resulted from light, irregular debris lofted in the storm’s inflow. A small region of low values was evident just downwind from the inflow notch. Most of the storm’s remainder was dominated by medium values (-24 to –28 dB). No low values were present in the northeast quadrant, as was true at pre-tornado times. The storm’s forward flank had a mixture of high and medium LDR<sub>VH</sub> in the two available cases.

LDR<sub>VH</sub> was significantly similar between tornado and tornado demise times. A well-defined, although perhaps less cyclonically curved, inflow notch was present and readily apparent as a region of high LDR<sub>VH</sub> (Fig. 7.8). The small area of low values immediately downwind of the inflow region, noted at tornado times, was also evident at tornado demise times. Values had decreased in the downwind section of the storm, with medium values (-24 to –28 dB) covering less area. In the area designated variable along the north side of the composite supercell, values ranged from low to medium. Along the forward flank variable area, LDR<sub>VH</sub> was occasionally observed to be high, medium, or low.
c. Southern Plains Upper-level Schematics

1) REFLECTIVITY FACTOR ($Z_{HH}$)

At pre-tornado times, upper-level $Z_{HH}$ structure of the typical Southern Plains classic supercell was very simple. The storm’s central core contained high reflectivity ($\geq$ 50 dBZ) in the region of highest hydrometeor concentration, surrounded by medium values (35 – 50 dBZ) with low values ($< 35$ dBZ) along much of the storm periphery (Fig. 7.9). Reflectivity flares extending from the region of highest values, commonly seen at low levels and weaker but often present at midlevels, were not readily observed at upper levels.

At tornado times $Z_{HH}$ structure remained quite simple, yet was more complex than at pre-tornado times (Fig. 7.9). A reflectivity weakness often extended into the main storm body above the midlevel BWER and lower level updraft; this feature was stronger than at pre-tornado times but still varied widely in strength from non-existent to very strong (possibly as a function of elevation viewed). High reflectivity factor values ($\geq$ 50 dBZ) began to exhibit some cyclonic curvature around the reflectivity weakness at tornado times, perhaps indicating stronger average vorticity in upper portions of the mesocyclone while a tornado was ongoing. The region of high reflectivity factor could exhibit weak extended regions, but this effect was never readily noticeable. Occasionally, scattered patches of high or low values were present well downwind from the primary updraft; these were thought to indicate regions of stronger rising motion.
(high values) and sinking motion (low values). Otherwise, features were virtually identical to those seen at pre-tornado times. Along the storm’s forward flank away from the updraft region, reflectivity values ranged from low to medium, so high variability was noted for typical reflectivity in this region.

Tornado demise time upper-level Southern Plains $Z_{HH}$ was more complex than at pre-tornado or tornado times. The composite schematic for tornado demise times (Fig. 7.9) is an especially general representation of typical $Z_{HH}$ structure, although it is still well representative of most cases.

High reflectivity values (> 50 dBZ) were confined to a relatively small portion of the storm center, and had tended to move farther into the main body of the storm (away from storm edge) compared to pre-tornado and tornado times (Fig. 7.9). The region of high values was surrounded by medium values (35 – 50 dBZ). Areal extent of these medium values was quite variable, leading to a surrounding area to be denoted variable. Low reflectivity was located through most of the downwind third of the storm. Another region of low $Z_{HH}$ values was located on the storm’s southwest side, perhaps representing remnants of an inflow notch.

2) DIFFERENTIAL REFLECTIVITY ($Z_{DR}$)

As expected, with the dominance of small icy particles (graupel and ice crystals) at upper levels, $Z_{DR}$ in typical Southern Plains storms at pre-tornado times was low (< 1 dB) (Fig. 7.10). A small core of high values (> 2 dB) was present, collocated with uppermost portions of the updraft and representing the uppermost extent of the $Z_{DR}$.
A very small area of medium values (1 – 2 dB) was typically present just north of this area, although the rest of the storm was dominated by low $Z_{DR}$ (< 1 dB). Often, the transition from high to low values was quite abrupt, indicating a distinct column of liquid drops. Most of the area of low values contained differential reflectivity between – 0.5 dB and +0.5 dB. Looking at a slightly higher elevation than that represented in the composite schematic, an area of very low $Z_{DR}$ (typically –0.5 to –2 dB) was located directly above the high-value column. This signature is thought to be caused by the formation of vertically-oriented graupel or hail at the top of the $Z_{DR}$ column.

At tornado times, a core of high $Z_{DR}$ values (> 2 dB) was located in virtually the same location for Southern Plains cases as at pre-tornado times (Fig. 7.10). A variable mixture of high, medium, and low values surrounded this high-value core, so no conclusions could be reached about typical $Z_{DR}$ values in much of the updraft region. Low values (< 1 dB) again dominated much of the downstream region of the storm, with lowest storm values (typically –0.5 to –2 dB) a short distance downstream from the high-value $Z_{DR}$ column.

Upper-level differential reflectivity at tornado demise times was very similar to the same field at tornado times (Fig. 7.10). A small core of high values (> 2 dB) was present, roughly collocated with the region of highest storm reflectivity just downwind from the primary updraft. Low values (< 1 dB) covered the downwind four-fifths of the composite supercell, with lowest storm values in a small core just northeast of the region of highest storm values. The region of very low values (< -0.5 dB) was smaller at tornado demise times than at tornado times, perhaps indicating a weakening of upward motion in the storm’s mesocyclone. An updraft weakening trend during tornado
occurrence has previously been theorized and documented in the literature (e.g. Lemon et al. 1975, Lemon and Doswell 1979, Ray et al. 1981, Dowell and Bluestein 1997).

3) CORRELATION COEFFICIENT (ρhv)

At upper levels, Southern Plains storms exhibited a region of low correlation toward the back of the storm reflectivity outline, located above the midlevel BWER/inflow notch and low-level updraft (Fig. 7.11). This region of low correlation (< 0.95) could represent the upper extent of the updraft or a region of large hail immediately downwind from the mesocyclone. Likely, the presence of a mixture of hydrometeor types also contributes to the low values. This region of low values was surrounded by medium values (0.95 – 0.98), with high values (> 0.98) farther downwind into the main storm body and along the forward flank. The farthest-downwind section of the composite supercell contained mostly medium correlation values. Between these regions of medium and high values, correlation varied widely between medium and high, so no conclusion was reached about typical ρhv.

At tornado times, high upper-level ρhv variability existed for large portions of the Southern Plains storms. High correlation (> 0.98) was located toward the center of the composite supercell, with medium values (0.95 – 0.98) located to the south and northeast of this area (Fig. 7.11). Elsewhere, ρhv varied widely between cases.

At tornado demise times, ρhv was the most inconclusive of any of the three examined times. Only a small region of medium values (0.95 – 0.98) near storm center and a small region of high values (> 0.98) along the storm’s northwest flank were
consistent through the three cases examined (Fig. 7.11). The reason for exceedingly variable correlation at tornado demise times is unknown, but may be an indication of a lower level of storm organization, or indicative of different elevations being observed. Regardless, more cases would be helpful in the development of more detailed schematics.

4) SPECIFIC DIFFERENTIAL PHASE (K\textsubscript{DP})

Two of three upper level, pre-tornado storms showed a small core of high K\textsubscript{DP} values (> 2 deg/km) centered on the mid-level BWER and low-level updraft, while the other case only showed scattered medium values (0.25 – 2 deg/km) in the same storm location. The composite schematic (Fig. 7.12) shows a region of medium values above the storm inflow region; however, a mixture of high and medium values may be present through the sections designated as medium values and as variable. This region of enhanced values likely represents the upper reaches of high hydrometeor concentration in the updraft, with a mix of rain and graupel/small hail. Other than a small section above storm inflow, K\textsubscript{DP} was low (< 0.25 deg/km) over the remainder of the composite supercell, consistent with dry graupel (Straka et al. 2000).

High K\textsubscript{DP} (> 2 deg/km) was more uncommon for Southern Plains storms at tornado times than at pre-tornado times, perhaps indicating the beginning of updraft weakening associated with the tornadic phase. Medium values (0.25 – 2 deg/km) were typical in the vicinity of the inflow region (Fig. 7.12). Of five cases, one showed a core of high values, one showed a few pixels of high values, and the remaining three showed no high values. Therefore, no conclusion could be reached about typical K\textsubscript{DP} values for
much of the windward fourth of the composite supercell. Overall, $K_{DP}$ was lower at
tornado times than at either pre-tornado or tornado demise times. The remaining three-
fourths of the composite storm consisted of low $K_{DP}$ (< 0.25 deg/km).

Upper-level $K_{DP}$ at tornado demise time was virtually identical to the same field at
tornado times. As at midlevels, a trend toward increasing storm values was evident in
two of three available cases. All medium and high values, as at midlevels, were confined
to a relatively small region along the storm’s windward side, and only a small region of
medium values (0.25 – 2 deg/km) was consistent between the cases and noted on the
composite schematic (Fig. 7.12). $K_{DP}$ in approximately the downwind four-fifths of the
composite supercell was low (< 0.25 deg/km).

d. High Plains Upper-level Schematics

1) REFLECTIVITY FACTOR ($Z_{HH}$)

The two High Plains cases had upper-level $Z_{HH}$ structure virtually identical to the
Southern Plains cases (Fig. 7.13). One case had a well-defined inflow notch. Overall
storm shape tended to be less stretched out along a west-east axis than the Southern
Plains storms; High Plains storms were more nearly round in outline than those on the
Southern Plains.

At tornado times, $Z_{HH}$ structure in the High Plains storms was somewhat more
variable than at pre-tornado times. Storms were, as at pre-tornado times, more oval or
circular in shape than Southern Plains cases. One case had a poorly-defined weak-echo
intrusion extending from the southwest flank, but the other case had no sign of a WER or inflow notch. In composite, therefore, no WER was noted on the High Plains upper-level schematic (Fig. 7.13). High reflectivity (> 50 dBZ) was typically located toward the center of the storm, surrounded by medium values (35 – 50 dBZ) with low values (< 35 dBZ) around much of the storm’s periphery. Between the two cases, significant variation existed regarding the areal extent of high values, and no conclusions could be reached about typical Z_{HH} along the storm’s southwest side. This lack of a decisive reflectivity trend is caused by the different shapes of storms observed, again likely related to the radar tilt angle chosen and to the exact evolutionary path of each storm.

Only one High Plains tornado demise case was available for upper levels. It appeared virtually identical to upper-level Z_{HH} at tornado times (Fig. 7.13).

2) DIFFERENTIAL REFLECTIVITY (Z_{DR})

In the two High Plains cases available, no high values of differential reflectivity (> 2 dB) were observed at pre-tornado times (Fig. 7.14). Scattered medium values (1 – 2 dB) occurred along the southwest (back) flank of each storm, collocated to varying extent with the inflow notch. In the composite schematic, the area designated as variable could contain medium or low Z_{DR} values, depending on the presence and extent of an inflow notch. Low values (< 1 dB) dominated the remainder of the storm, with lowest Z_{DR} values (typically –0.5 dB to –2 dB) in the south-central region downwind from the midlevel inflow area.
At tornado times, the two High Plains cases showed a core of lowest storm $Z_{\text{DR}}$ values in virtually the same location as for Southern Plains cases (Fig. 7.14). Highest storm values were located along the composite supercell’s western flank, although the only consistent region of medium values ($1 – 2$ dB) was slightly in from storm edge. Otherwise, $Z_{\text{DR}}$ was typically near 0 dB, consistent with dry graupel.

Only one tornado demise case is available at upper levels for the High Plains, greatly limiting what can be said about typical structures. This case was similar to the composite schematic for tornado times, however, with a small region of high values ($> 2$ dB) in the storm’s southwest corner (likely related to an updraft pulse) and low values ($< 1$ dB) everywhere else (Fig. 7.14). Lowest storm values were in a similar location, above the midlevel inflow region and low-level updraft.

3) CORRELATION COEFFICIENT ($\rho_{hv}$)

Large areas of high $\rho_{hv}$ variability existed for High Plains cases at pre-tornado times, although this was partially the result of the scarcity of available cases (Fig. 7.15). Low $\rho_{hv}$ ($< 0.95$) was evident in the inflow notch region, surrounded by a region of high values ($> 0.98$). Few regions of medium correlation ($0.95 – 0.98$) were consistently present, although one was located toward storm center and another was located on the composite supercell’s northeast edge. The eastern edge of the composite storm, in addition to this region of medium values, had scattered high correlation ($> 0.98$), although most of the eastern edge, and most of the storm interior, tended to be a diverse mix of medium and high values. This is consistent with dry graupel (Straka et al. 2000).
As in Southern Plains cases, correlation was quite variable for High Plains storms at tornado times (Fig. 7.15). A stripe of high values (> 0.98) was located through storm center, but otherwise, $\rho_{hv}$ tended to be a blend of high, medium, and low values. In one case, a well-defined area of low values was collocated with an inflow notch, and another area of low values to its north may have represented hail. The lesson to be learned is that individual cases often possess considerable structure fitting with accepted models of supercell organization, although a variety of structures are present with different storms. Thus, when only a small number of cases are available, a composite schematic will likely not be very useful because it cannot capture details of individual storms. More cases are necessary before we can state characteristic patterns. As seen in many natural systems, a spectrum of possibilities may be more representative than a single schematic.

Although only one upper-level High Plains case existed at tornado demise times, it showed interesting patterns in $\rho_{hv}$ (Fig. 7.15). Correlation in the single upper-level High Plains tornado demise case shows a rather eclectic mix of low, medium, and high values, with high values (> 0.98) dominating the western third of the storm, medium values (0.95 – 0.98) dominating its central half, and low values dominating along the remaining eastern periphery. This correlation gradient may be partially a result of increasing distance from the radar, but such an effect should have been less noticeable. Although a reflectivity inflow notch was not especially obvious in this case, low correlation along the storm’s southwest side created a pattern suggestive of storm inflow in this region.
4) LINEAR DEPOLARIZATION RATIO (LDR$_{VH}$)

Upper-level LDR$_{VH}$ at pre-tornado times was fairly similar to the same field at midlevels. A region of high values (> -24 dB) was evident in the inflow region (Fig. 7.16), with low and medium LDR$_{VH}$ (≤ -24 dB) typically present in the storm’s downwind region. Between these areas, values were mostly low and medium, with scattered pockets of high values.

The upper-level LDR$_{VH}$ field at tornado times had become relatively weakly-patterned and messy (Fig. 7.16). In both cases, a region of high values (> -24 dB) marked the inflow notch, likely related to the mix of hydrometeor types and light storm inflow debris present in this region. Typical LDR$_{VH}$ patterns in the remaining western half to two-thirds of the composite supercell were difficult to ascertain. The eastern third seemed dominated by medium values (-24 to –28 dB).

Unfortunately only one upper-level case was available at tornado demise times, and it was quite messy and lacked a readily distinguishable pattern (Fig. 7.16). The region of high values (> -24 dB) in the storm’s southwestern quadrant was associated with the remnants of an inflow notch. The northwest and southeast quadrants contained regions of low values (< -28 dB), consistent with dry graupel, while the storm’s central region tended to be an assortment of low and high LDR$_{VH}$ in a background of medium values. Regions in the composite schematic denoted as having low values also frequently contained a high number of medium-valued pixels, although low values were dominant.
Figure 7.1. Schematics of midlevel reflectivity factor ($Z_{\text{HH}}$) for the Southern Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($Z_{\text{HH}} < 35$ dBZ), hatched areas represent high values ($Z_{\text{HH}} > 50$ dBZ), blank areas represent intermediate values ($35$ dBZ $\leq Z_{\text{HH}} \leq 50$ dBZ), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.2. Schematics of midlevel differential reflectivity ($Z_{DR}$) for the Southern Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($Z_{DR} < 1 \text{ dB}$), hatched areas represent high values ($Z_{DR} > 2 \text{ dB}$), blank areas represent intermediate values ($1 \text{ dB} \leq Z_{DR} \leq 2 \text{ dB}$), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.3. Midlevel schematics of correlation coefficient ($\rho_{hv}$) for the Southern Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($\rho_{hv} < 0.95$), hatched areas represent high values ($\rho_{hv} > 0.98$), blank areas represent intermediate values ($0.95 \leq \rho_{hv} \leq 0.98$), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.4. Midlevel schematics of specific differential phase ($K_{DP}$) for the Southern Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($K_{DP} < 0.25$ deg/km), hatched areas represent high values ($K_{DP} > 2$ deg/km), blank areas represent intermediate values ($0.25$ deg/km $< K_{DP} < 2$ deg/km), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.5. Schematics of midlevel reflectivity factor ($Z_{HH}$) for the High Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($Z_{HH} < 35$ dBZ), hatched areas represent high values ($Z_{HH} > 50$ dBZ), blank areas represent intermediate values ($35$ dBZ $\leq Z_{HH} \leq 50$ dBZ), and checkerboard-filled area represents a variable region. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.6. Schematics of midlevel differential reflectivity ($Z_{DR}$) for the High Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($Z_{DR} < 1 \text{ dB}$), hatched areas represent high values ($Z_{DR} > 2 \text{ dB}$), blank areas represent intermediate values ($1 \text{ dB} \leq Z_{DR} \leq 2 \text{ dB}$), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.7. Midlevel schematics of correlation coefficient (ρhv) for the High Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values (ρhv < 0.95), hatched areas represent high values (ρhv > 0.98), blank areas represent intermediate values (0.95 ≤ ρhv ≤ 0.98), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.8. Midlevel schematics of linear depolarization ratio (LDR$_{VH}$) for the High Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values (LDR < -28 dB), hatched areas represent high values (LDR > -24 dB), blank areas represent intermediate values (-28 dB ≤ LDR ≤ -24 dB), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.9. Schematics of upper-level reflectivity factor ($Z_{HH}$) for the Southern Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($Z_{HH} < 35$ dBZ), hatched areas represent high values ($Z_{HH} > 50$ dBZ), blank areas represent intermediate values ($35$ dBZ $\leq Z_{HH} \leq 50$ dBZ), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the $20$ dBZ reflectivity contour.
Figure 7.10. Schematics of upper-level differential reflectivity ($Z_{DR}$) for the Southern Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($Z_{DR} < 1 \text{ dB}$), hatched areas represent high values ($Z_{DR} > 2 \text{ dB}$), blank areas represent intermediate values ($1 \text{ dB} \leq Z_{DR} \leq 2 \text{ dB}$), and checkerboard-filled areas represent variable regions. Regions denoted “LL” are where lowest storm values of $Z_{DR}$ were found. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.11. Upper-level schematics of correlation coefficient ($\rho_{hv}$) for the Southern Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($\rho_{hv} < 0.95$), hatched areas represent high values ($\rho_{hv} > 0.98$), blank areas represent intermediate values ($0.95 \leq \rho_{hv} \leq 0.98$), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.12. Upper-level schematics of specific differential phase \( K_{DP} \) for the Southern Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values \( K_{DP} < 0.25 \) deg/km, hatched areas represent high values \( K_{DP} > 2 \) deg/km, blank areas represent intermediate values \( 0.25 \) deg/km \( \leq K_{DP} \leq 2 \) deg/km), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.13. Schematics of upper-level reflectivity factor ($Z_{HH}$) for the High Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($Z_{HH} < 35$ dBZ), hatched areas represent high values ($Z_{HH} > 50$ dBZ), blank areas represent intermediate values ($35$ dBZ $\leq Z_{HH} \leq 50$ dBZ), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.14. Schematics of upper-level differential reflectivity ($Z_{DR}$) for the High Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas represent low values ($Z_{DR} < 1$ dB), hatched areas represent high values ($Z_{DR} > 2$ dB), blank areas represent intermediate values (1 dB $\leq Z_{DR} \leq 2$ dB), and checkerboard-filled areas represent variable regions. Regions denoted “LL” are where lowest storm values of $Z_{DR}$ were found. Bold outline represents approximately the 20 dBZ reflectivity contour.
Figure 7.15. Upper-level schematics of correlation coefficient ($\rho_{hv}$) for the High Plains at
a) pre-tornado times, b) tornado times, and c) tornado demise times. Stippled areas
represent low values ($\rho_{hv} < 0.95$), hatched areas represent high values ($\rho_{hv} > 0.98$), blank
areas represent intermediate values ($0.95 \leq \rho_{hv} \leq 0.98$), and checkerboard-filled areas
represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity
contour.
Figure 7.16. Upper-level schematics of linear depolarization ratio (LDR\textsubscript{VH}) for the High Plains at a) pre-tornado times, b) tornado times, and c) tornado demise times. Only one case was available at the tornado demise time. Stippled areas represent low values (LDR\textsubscript{VH} < -28 dB), hatched areas represent high values (LDR\textsubscript{VH} > -24 dB), blank areas represent intermediate values (-28 dB ≤ LDR\textsubscript{VH} ≤ -24 dB), and checkerboard-filled areas represent variable regions. Bold outline represents approximately the 20 dBZ reflectivity contour.
8. Primary Conclusions

This work is limited by the small number of available polarimetric datasets of tornadic supercells, and would be much more robust if many additional cases existed. This will be possible when dual-polarimetric capability is available in a large number of WSR-88D radars in the next decade. Despite this limitation, some useful conclusions have been reached.

Southern Plains supercells, at low levels, tended to exhibit numerous repeatable polarimetric features. Major findings in $Z_{HH}$ at tornado times include “wings” of higher values often extending away from the updraft region, a stronger gradient on the west side of the echo appendage, and a local maximum at the storm location favorable for a tornado. Increasing cyclonic curvature of the hook echo region was noted through the tornado life cycle. $Z_{DR}$ tended to indicate hail shafts most commonly at tornado times or immediately prior, with highest storm values typically located along the storm’s forward flank throughout the tornado life cycle. A $Z_{DR}$ minimum often occurred associated with the tornado, while low $Z_{DR}$ occasionally trailed the tornado region. Storm minimum $\rho_{hv}$ typically occurred associated with the tornado at tornado times, and in hail shafts or heavy rain areas at other times. Another region of low correlation was the storm updraft, while highest storm correlation was typically found in the light downwind precipitation shield. $K_{DP}$ typically exhibited a storm-core temporal maximum at tornado times, with highest storm values in regions of hail and heavy rain and lowest values in the downwind light precipitation region. Values at the storm location favorable for a tornado were typically near zero, and sometimes strongly negative.
At low levels, High Plains storms were found to vary in several important ways when compared to the Southern Plains cases. Importantly, however, since data were available from few High Plains storms, these results should be interpreted with particular caution. In $Z_{HH}$, a larger downwind light precipitation region was evident. RHI scans showed a distinct double WER feature at the onset of the tornado time in both High Plains cases for which RHI scans were available. $Z_{DR}$ averaged much lower for the High Plains storms, presumably because of the greater prevalence of graupel and hail. $\rho_{hv}$ was similar between Southern and High Plains cases, although tornado-associated minima were less pronounced on the High Plains. The single High Plains case with $K_{DP}$ data did not show significant differences when compared with the average Southern Plains storm.

In a study of three cyclically tornadic, classic supercells on the Southern Plains, polarimetric variables were found to change, often dramatically, though the tornado lifecycle, although these changes were not always consistent between cases. $Z_{hh}$ typically increased in magnitude and areal extent toward a demise time. Regions of higher reflectivity often became more pronounced extending away from the primary updraft toward a tornado time, and became less distinct as the supercell transitioned to tornado demise. The echo appendage became more cyclonically curved through tornado lifecycle. Radial velocity-indicated rotation in the mesocyclone and tornado cyclone increased toward tornado times, and generally decreased toward demise times. Divergence was often present under the west side of a supercell throughout the tornado lifecycle, perhaps indicative of a RFD. High forward-flank values of $Z_{DR}$ showed few changes, although areas of low $Z_{DR}$ associated with hailfall north of the updraft tended to decrease in the minutes immediately before a tornado time. $Z_{DR}$ in the echo appendage
tended to be quite high except in the vicinity of the tornado, when $Z_{DR}$ was observed to drop to near zero dB. Once a tornado dissipated, $Z_{DR}$ gradually increased in the echo appendage region as debris slowly settled out. $\rho_{hv}$ along the forward flank decreased, often dramatically, toward all tornado times, and increased toward demise times. A $\rho_{hv}$ minimum typically occurred along the forward flank while a tornado was ongoing. Little evolution was observed in the downwind light precipitation region, where values remained high throughout the tornado lifecycle. Values of $K_{DP}$ tended to reach a temporal maximum in the storm core just before the tornado time. Regions of higher $K_{DP}$ extending downwind from the primary updraft tended to develop toward a tornado time and decrease toward a tornado demise time, similar to the evolution seen in $Z_{HH}$. In the hook echo, medium values were replaced by near-zero or negative values with the tornado as tornadogenesis occurred; these low $K_{DP}$ values increased toward tornado demise times.

Finally, preliminary schematics were developed for classic, tornadic supercells at mid and upper levels on the Southern and High Plains. $Z_{HH}$ in Southern Plains storms could show an echo appendage at midlevels, which became less pronounced with height. At midlevels, a BWER, WER, or inflow notch was typically present above the low-level updraft, while at upper levels this feature was weaker if present. The midlevel inflow feature often showed most cyclonic curvature at tornado times, and was weakening by tornado demise times. Highest storm reflectivity, typically just downwind from the primary updraft and above the low-level updraft, formed an arc- or horseshoe-shaped region around the inflow feature at tornado times. High Plains cases were similar, although their reflectivity outline was less stretched out along an east-west axis. Also,
the downwind region of low reflectivity was more extensive in High Plains cases. Midlevel $Z_{DR}$ was high through a region near the updraft, representing large drops lofted upward in the $Z_{DR}$ column (Herzegh 1992). A sharp transition to downwind low values was common, often with few intermediate values present. At upper levels and in High Plains cases, low $Z_{DR}$ was much more widespread. Lowest storm $Z_{DR}$ was typically located just downwind from and above the top of the $Z_{DR}$ column in both Southern and High Plains cases. At tornado times, high $Z_{DR}$ had typically shifted toward the inflow side of the storm and covered less area. Low $\rho_{hv}$ was typically collocated with the primary updraft (entrainment of light debris) and immediately downstream (large hail or hail/rain mix). High correlation typically occurred in central portions of the storm, while the farthest-downwind portions often contained medium values. Average $\rho_{hv}$ at mid and upper levels tended to be lower than at low levels, likely because hydrometeors are on average smaller and more spherical farther aloft. High Plains cases had greater areal coverage of high correlation. Fewer conclusions could be drawn about typical correlation of High Plains storms, probably because of the few available cases. Upper-level correlation also tended to be more variable than at midlevels. $K_{DP}$ was only available for Southern Plains cases. A small core of high values was typically located just downwind from the inflow region at midlevels, with a smaller region of high values at upper levels. High $K_{DP}$ variability tended to occur in the inflow region. At upper levels, high $K_{DP}$ was most uncommon and areally restricted at tornado times, perhaps suggesting a weaker updraft. Values in the downwind region were virtually always low, at all times and in both locations. $LDR_{VH}$ was only available for High Plains cases, and tended to be a rather complex polarimetric field. High values were associated with the updraft and
inflow region, especially at tornado and tornado demise times. At pre-tornado times, low \( \text{LDR}_{VH} \) was concentrated in the storm’s northeast quadrant, although this region virtually disappeared at tornado times. At upper levels, messy \( \text{LDR}_{VH} \) fields characterized tornado and tornado demise times, although medium values tended to dominate.


