A Preliminary Survey of Rear-Flank Descending Reflectivity Cores in Supercell Storms

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ABSTRACT

This paper develops a definition of a supercell reflectivity feature called the descending reflectivity core (DRC). This is a reflectivity maximum pendant from the rear side of an echo overhang above a supercell weak-echo region. Examples of supercells with and without DRCs are presented from two days during the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX), as well as one day with tornadic high-precipitation supercell storms in central Kansas. It was found that in all cases, tornado formation was preceded by the descent of a DRC. However, the sample reported herein is much too small to allow conclusions regarding the overall frequency of DRC occurrence in supercells, or the frequency with which DRCs precede tornado formation. Although further research needs to be done to establish climatological frequencies, the apparent relationship observed between DRCs and impending tornado formation in several supercells is important enough to warrant publication of preliminary findings.

1. Introduction

In the course of examining Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX; Rasmussen et al. 1994) data for 2 June 1995 we have identified a distinctive echo that appeared to have an association with tornado formation. This echo in the rear flank of supercells, which we shall call the descending reflectivity core (DRC), resembles a bloblike precipitation protuberance that is pendant from the echo overhang of the rear side of the weak-echo region, with a typical horizontal dimension of 2–3 km. In most cases, the precipitation protuberance was associated with a single-Doppler kinematic feature consistent with locally enhanced rear-to-front flow accompanied by counterrotating shear signatures. Markowski (2002, p. 853) documents many examples of counterrotation in the supercell rear flank and notes that this counterrotation is seldom commented upon in the literature. In some cases, tornadoes developed in proximity to the cyclonic shear signature.

An example of a DRC is shown in Fig. 1. This example is from the supercell on 2 June 1995 that produced a significant tornado in the vicinity of Dimmitt, Texas, commencing shortly after 0058 UTC. The time series of 40-dBZ isosurfaces clearly shows the descent of a column of locally larger reflectivity at the rear side of the storm updraft region. Note that this column is embedded in a larger appendage of weaker reflectivity, and thus in the constant-elevation angle depiction, the DRC appears as a local spot or dot of higher reflectivity. The Dimmitt storm was one of several that produced a DRC on this day.

An echo strongly resembling a DRC was first docu-
mented as one of the “distinctive echoes” associated with tornadoes (e.g., the Xenia, Ohio, tornado; Fig. 2) by Forbes (1981). Forbes (1978), using Weather Surveillance Radar-1957 (WSR-57) plan position indicator (PPI) data, noted that these echoes resembled either dots or annular sections of a cylinder (asc’s; Garrett and Rockney 1962)], and often evolved into hook echoes as they became attached to the nearby main echo of the supercell. He further noted that the asc echo is not always caused by debris; 62% of the asc echoes he documented were nontornadic. On the contrary, he inferred “that these echoes are due to precipitation, and that these echoes are tornado-cyclone-scale features.” He further concluded “echo dots occasionally developed laterally to form the hook echo” and “it is inferred that the presence of an echo dot indicates the potential for a localized downdraft on the periphery of the mesocyclone which can trigger formation of a tornado cyclone within the mesocyclone.” Forbes (1981) represents the only known documentation of an echo strongly resembling a DRC in the formal literature.

Prior to Forbes (1981), there was a mention of a downward echo protuberance (extending farther downward than the general echo overhang) called a “hook echo streamer” (Browning 1965; Browning and Donaldson 1963), which appears in the same storm-relative location as DRCs and when sliced vertically cross-wise in two dimensions, gives the appearance of a DRC. However, when combined with PPI views, their hook echo streamer is revealed to be an elongated vertical “sheet” of precipitation rather than a localized echo. It is believed to be the same thing as what we will call the appendage. Any localized reflectivity maximum that may have been present to constitute a DRC within the hook echo streamer was not discussed in those papers. Other papers that discuss general supercell airflow structure and precipitation (e.g., Lemon and Doswell 1979) do not describe anything resembling a DRC. In the intervening years after Forbes (1981), no attention has been paid to the DRC echo signature.

A small sample of supercells was selected for this initial examination. Two studies have demonstrated that the events of 2 June 1995 provided an interesting sample of supercells for intercomparisons (Rasmussen et al. 2000; Gilmore and Wicker 2002, hereafter

**Fig. 1.** Three-dimensional perspective view from the south of the 40-dBZ isosurface prior to tornado formation in the Dimmitt, TX, tornadic storm of 2 Jun 1995. Times are (a) 0042, (b) 0047, (c) 0052, and (d) 0057 UTC. The descending reflectivity core is marked DRC.
GW02). On this day, large-scale conditions were rather uniform across western Texas, except that a pronounced mesoscale boundary was present and associated with enhanced tornado potential on its immediate cool side, while nontornadic supercells were favored in the warm air mass. Overall echo characteristics and reported severe weather were extensively documented in GW02, and those data will be utilized herein. Because high-precipitation (HP; Doswell and Burgess 1993) events were apparently absent from the sample of supercells present on 2 June 1995, we will also document two HP storms that produced tornadoes in Kansas on 21 April 2001, including the killer tornado at Hoisington. Further, several other cases of tornadic supercells are included to gain a preliminary sense of the variety of DRC morphologies that occur.

This paper is not a climatological study. That is, our sample is small and does not have sufficient statistical significance to draw broad conclusions about the association of DRCs with tornadoes. We have a much broader study in progress that utilizes dual-polarization radar and Weather Surveillance Radar-1988 (WSR-88D) data. The limited goal here is to establish, using radar data available to operational meteorologists, that

1) some supercells produce DRCs prior to low-level mesocyclone and tornado formation;
2) some supercells produce DRCs that are associated with low-level rotation intensification but not associated with tornadogenesis; and
3) some supercells do not produce DRCs and also do not produce associated low-level mesocyclone intensification.

These findings are presented to document a phenomenon that requires further research. Further, because our larger studies are indicating that this phenomenon is relatively common in tornadic supercells, we believe it is appropriate to bring it to the attention of the operational meteorological community at this time.

In section 2 of this paper, we present an objective definition of the DRC that is needed to compare the supercells in this sample. In section 3, we examine the sample of supercells for the occurrence of DRCs and compare those occurrences with low-level Doppler velocity shear intensity. We present three-dimensional isosurface visualizations of the supercells to give a more general sense of the storm structure. Findings are discussed in section 4, with conclusions presented in section 5.

2. Methodology

Examination of several supercells with DRCs indicates that some reflectivity level can be defined that, when viewed as an isosurface, depicts a bloblike echo protuberance that is pendant from the echo overhang of the weak echo region (WER) and located in the overall supercell echo appendage (e.g., Fig. 1). If viewed at a single level or on a single PPI scan, the DRC is sampled as a local maximum of reflectivity in the appendage. Of course, it should be expected that the reflectivity in the appendage would not be homogeneous and would include local maxima. However, when the maximum has vertical continuity, tapers toward the ground, descends with time, and is associated with a pronounced disturbance in the flow, it becomes of more scientific and operational interest.

It is common to call the supercell echo appendage a “hook echo” [a detailed review of the current knowledge of hook echoes can be found in Markowski (2002)]. However, the term appendage will be used herein for the following reason. The echo appendage at the supercell rear flank typically does not acquire a
hook shape until it is deformed by the flow associated with an intensifying vortex. Hence, the typical echo evolution would first involve an amorphous appendage, possibly containing a DRC. Then a velocity jetlet develops in the appendage, with associated cyclonic and anticyclonic vorticity centers straddling the jetlet. Typically, the cyclonic vorticity center dominates, deforming the appendage into a hook via advection of hydrometeors. In many cases, an anticyclonic precipitation flare is also present near the hook and is associated with the anticyclonic vorticity center. Because we are investigating the precipitation processes accompanying vortex formation at the rear flank, we prefer to be precise about the echo character instead of calling all appendages “hook echoes.” If it can be shown through later work that the DRC typically precedes hook echo formation, then clearly the DRC will provide greater lead time in diagnosing rear-flank vortex intensification.

To associate the presence or absence of a DRC with the evolution of the low-level flow, it is necessary to develop a definition that can be applied uniformly among the various supercells being examined. For the storms examined herein, the following definition is used. A DRC is an echo embedded in a supercell rear-flank appendage that, at any altitude or elevation angle sweep,

- is pendant from the echo cap above the WER or bounded weak echo region (BWER);
- following the path of greatest reflectivity from the DRC reflectivity maximum to the core, using constant azimuth or constant range steps, the DRC echo exceeds the minimum reflectivity along this path by at least 4 dB; and
- occurs in the right-rear quadrant of the supercell updraft (inferred from the WER).

The first criterion ensures that the reflectivity maximum is not likely to have been caused by a discrete convective cell. The first and third criteria, together, ensure that the DRC is associated with the echo overhang. The second condition (illustrated in Fig. 3) ensures that the DRC has significantly larger reflectivity than those portions of the appendage closer to the core, and eliminates supercell appendages (such as hook echoes or hook echo streamers) that do not have significant embedded maxima. The degree to which the maximum exceeds the smallest reflectivity along the path to the core will be referred to as isolation, measured in decibels. All of the DRCs in this paper had isolation ≥4 dB, and typical isolation was 8–10 dB. The 4-dB criterion is arbitrary and was chosen to maximize the number of DRCs identified across this sample.

In conducting this investigation, we first examined the lowest three WSR-88D reflectivity scans (level II data) at each available time during the life cycle of a storm for the presence or absence of a reflectivity maximum as defined above. Further, we examined the lowest scan of Doppler velocity to measure the maximum differential velocity across the mesocyclone (if present), and the maximum gate-to-gate differential. Reflectivity data were objectively analyzed with the Barnes (1964) weighting function chosen to give approximately a 75% response at the worst four-sample wavelength (corresponding to four times the typical horizontal beam-to-beam separation at the range of the storm). The time-to-space vector used to advect individual tilts was computed from a multivolume-average centroid motion vector. With this scheme, the amount of detail preserved by the objective analysis varies according to the range of the storm from the radar. The objectively analyzed (gridded) data were visualized using 3D isosurfaces of two reflectivity levels separated by 10 dB. The high-reflectivity isosurface value was chosen to be somewhat lower than the maximum found in the DRC (typically ~40 dBZ), which varied from storm to storm. The same isosurfaces could not be used in every case because the overall reflectivity varied

1 Although the DRC can also be identified using research radars, herein we demonstrate DRC identification only with the operational WSR-88D because that is what is relevant to forecasters.
greater from storm to storm, and even more so for the DRCs themselves. The DRCs could be objectively identified in reflectivities <20 dBZ in some storms, to as large as >50 dBZ in others. The isosurfaces presented herein are perspective views produced by a custom Interactive Data Language based visualization program that shades surfaces from the objectively analyzed WSR-88D data. The viewing angle was chosen to provide the clearest depiction of the DRC, and varied from storm to storm based upon storm orientation and structure. Views are typically from an elevation of 15° above the horizon. The isosurfaces are not intended for quantitative comparisons but instead as tools to illuminate our understanding of the 3D structure that corresponds to features typically seen in PPI views. For example, one problem in using perspective views for quantitative work is that scale varies continuously throughout the image: a horizontal or vertical scale placed in one portion of the image would not apply to other portions. For this reason, the reader is encouraged to refer to the PPI depictions alongside the perspective views for scale information.

3. Rear-flank echo morphology

a. An example of DRC evolution

Before presenting several examples of DRCs, it is useful to provide an additional illustration of the evolution of a DRC from the base-scan PPI radar perspective. Figure 4 contains the PPI reflectivity and ground-relative Doppler velocity data for the 2 June 1995 Dimmitt, Texas, storm (cf. the isosurface plots in Fig. 1). In this case the DRC first appears at 0047 UTC to the south of the overall supercell appendage. The locations of shear associated with counterrotating vortices have been marked with the cyan arrow symbol. A maximum in gate-to-gate shear, the incipient Dimmitt tornado, developed in the northern edge of the DRC precipitation around 0052 UTC and, subsequently, moved leftward and more slowly than the DRC, and toward the main precipitation core. The Dimmitt tornado began at around 0058:40 UTC. As the tornado circulation intensified, the echo appendage became more hooklike, as can also be seen in the detailed Doppler-on-Wheels data presented by Wurman and Gill (2000). The DRC persisted after the development of this vortex and continued to be associated with a local jetlet flow and the Doppler signature of counterrotating vortices. Dual-Doppler analysis of research datasets in this storm (not shown) show that the DRC is associated with a cyclonic vortex on its left-front flank and an anticyclonic vortex on the right, both embedded in the DRC precipitation, with a westerly jet between the vortices. This storm is revisited in section 3b as one of a number of supercells that occurred on 2 June 1995.

b. 2 June 1995 boundary-crossing supercells: Olton–Hart–Tulia and Dimmitt storms

The Olton–Hart–Tulia and Dimmitt supercells became tornadic after crossing the mesoscale outflow boundary that was present on 2 June 1995. Cyclic mesocyclone behavior (Adlerman et al. 1999) occurred in the Olton–Hart–Tulia supercell, producing several intensifications of the low-level differential velocity (Fig. 5) and four tornadoes, as well as several DRC events. On average, a given reflectivity isosurface in the DRCs developed downward with time (bottom graph in Fig. 5) at a rate of ~4 m s⁻¹. Determining gate-to-gate differential velocity was very problematic in this storm because the DRCs were quite isolated in the nonprecipitating region of the storm near the main updraft. The DRC provided enough return power to estimate Doppler velocity but the adjacent precipitation-free returns were too weak for velocity estimates (see the velocity plots in Fig. 6). Hence, gate-to-gate Doppler velocity couplets were sometimes not observable. The arrival of DRCs at the ground (at the 30-dBZ level) was followed within about 12–22 min by the occurrence of reported tornadoes on three occasions. The last reported tornado (F1 damage intensity near 0130 UTC) produced little or no radar indication of a tornado in the Doppler velocity, and was not preceded by a DRC. Several DRCs arrived at the ground without producing reported tornadoes (e.g., around 2315, 2325, and 0010 UTC). However, some of these events were arguably associated with increases in base-scan gate-to-gate differential velocity. During the storm life cycle, low-level mesocyclone differential velocity varied less than gate-to-gate differential velocity.

The four most prominent DRCs are depicted in Fig. 6. The overall storm structure evolved considerably in terms of height and horizontal size. However, the presence of a large WER on the south side of the storm was a much more steady feature. The DRCs were very prominent with this storm, and occurred close to the main updraft region to the east of the rear-flank echo appendage. Several of the DRCs with this storm that appeared to be nearly detached from the storm from a low-level PPI perspective [reminiscent of the dot echoes described by Forbes (1978)] clearly were pendant from the echo overhang.

It can be seen (Fig. 6, right-hand column) that Doppler velocity disturbances were prominent within a few kilometers of the reflectivity-determined DRC. A lack of scatterers in the near-ground region below the echo overhang aloft often resulted in missing velocity data.
But the data that are present support the generalization that this region was dominated by strong receding velocities (south-southeasterly component). The exception was always found near the DRC, where weak approaching flow was observed. This general pattern can be described as the Doppler shear signatures of counterrotating vortices, with the complete signatures typically absent because of a lack of scatterers. This was perhaps most obvious at 2342 UTC when weak approaching velocities (dark green in Fig. 6) were collocated with the DRC, with receding velocities (dark red) immediately to the west, and very strong receding velocities (light red) 8–10 km to the east. The initial points of tornado damage tracks (not shown) were always to the immediate north of the DRC track.

With time, the storm transitioned toward an HP supercell structure (while arguably still classifiable as a classic storm), with much more precipitation occurring to the rear of the storm updraft. This radar-based finding is consistent with visual observations (C. Doswell 1999, personal communication). However, even with this structure (0037 UTC; Fig. 6d), a reflectivity maximum, associated with a DRC, can be identified in the PPI depiction of the supercell appendage.

The other supercell that crossed the mesoscale outflow boundary on 2 June 1995, and was close enough to a WSR-88D with available level II data to be examined herein, was the Dimmitt storm. This supercell had structure (Fig. 6a) very similar to the Olton–Hart–Tulia storm, with a prominent echo overhang above a WER. The DRC descended well to the south of the storm core near the apparent updraft region. As with the Olton–Hart–Tulia storm, the velocity signature in the vicinity of the DRC is one of flow much different than the apparent nearby flow.

c. 2 June 1995 warm-sector supercells: Denver City and McDonald storms

The Denver City and McDonald (referred to as “McDonald-RM” in GW02) supercells were long-lived storms with midlevel mesocyclones and produced large hail. These supercells did not cross the mesoscale outflow boundary and did not have reported tornadoes. The McDonald storm intensified rapidly during the half-hour prior to 0030 UTC. The mesocyclone and gate-to-gate differential velocities (Fig. 7) in the 0.5° “base scan” (near 2.2 km AGL) grew to values as large, or larger than, some of those observed in the tornadic storms discussed in the last section (these are not strictly comparable values because they were obtained at different levels in the storms). After the initial intensification, the rotational signatures subsided in strength.
to more modest values. At no time during its life cycle did the McDonald storm contain a feature that met the DRC criteria; in fact, there were no features that even approached the criteria. Further, this storm did not have any reported tornadoes associated with it. The typical morphology of the reflectivity isosurfaces was similar to that at the time of peak rotation intensity (0032 UTC), shown in Fig. 8b (note that a portion of the velocity measurements suffer from velocity aliasing). The storm contained a large, prominent echo overhang across the southern side, with relatively little precipitation descending at the rear side of the updraft. To our knowledge, there are no previous observational studies of supercell reflectivity isosurfaces, so we can only speculate that perhaps this is the morphology of a low-precipitation (LP) supercell (e.g., the assertion that LP supercells have little or no low-level precipitation in the immediate vicinity of the updraft; Rasmussen and Straka 1998).

The reflectivity structure of the Denver City supercell appeared similar to the McDonald storm during most of its life cycle (typical morphology illustrated in Fig. 8c). It was somewhat smaller and the overhang was often less extensive. The reflectivity maximum near the rear of the supercell at 0012 UTC (left side of the reflectivity plot, center column) did not meet the DRC criterion that it be pendant from the supercell echo overhang. Instead, it appeared that this feature was associated with a new cell that was growing at the immediate rear of the Denver City storm, an event that occurred several times. The Denver City storm did produce one echo meeting the DRC criteria (0047 UTC; Fig. 8d), and this is shown for completeness. However, this feature was only apparent during one volume scan, and did not appear to descend, as did many of the DRCs documented herein. The differential velocities in this storm could not be quantified well because of a gap in the velocity data between 0037 and 0107 UTC caused by range folding. The data that were available revealed an evolution similar to the McDonald storm with initial intensification of the mesocyclone differential velocity to 30–35 m s\(^{-1}\), subsiding to ~15 m s\(^{-1}\) through much of the life cycle. Gate-to-gate differential velocities exceeding 10 m s\(^{-1}\) typically were not present. The Denver City supercell was visually observed as having an initial LP appearance and then transitioned toward a visual HP appearance (G. Moore 1999, personal communication) after 0047 UTC.

Fig. 5. (top) The differential velocity at 0.5° elevation (ordinate) vs time (UTC; abscissa) for the mesocyclone in the Olton–Hart–Tulia supercell of 2 Jun 1995 (open symbols), as well as gate-to-gate differential velocity (filled symbols). The radar data are from the Lubbock WSR-88D. Times and damage intensities of tornadoes are shown with shaded bars in the bottom of the differential velocity graph. (bottom) The DRC maximum reflectivity, with the ordinate being the height above ground (‘N’ denotes no DRC present; no value is plotted where data are missing). Contours are for 30 (thin line) and 40 dBZ (thick lines, filled).
Fig. 6. Three-dimensional perspective views of (left) reflectivity isosurfaces of supercells discussed in the text, (center) 0.5° elevation PPI reflectivity plots, and (right) 0.5° ground-relative Doppler velocity plots. For the isosurfaces, the reflectivity levels are given in the upper part of each panel for the yellow (outer, lower value) surface and redder (inner, higher reflectivity) surface. Viewing azimuth is labeled in the lower-right part of each left-hand panel; north is toward the top of the center and right-hand panels. All perspective views share approximately the same scale. Lines below the storm are roads and are included to improve the perspective and give a sense of scale (gridlike roads are typically spaced 1 mi apart). All PPI plots have the same scale, shown by the length arrow, with an open circle marking a DRC location. Approximate heights (AGL) of the scan near the DRC are labeled in each reflectivity plot. Reflectivity levels are given by the scale at the top of the middle column; velocity levels by the scale at the top of the right column. Thin arrows in the right-hand plots give radar pointing angle. Circles correspond to the DRC if present. The radar data are from the Lubbock WSR-88D.
d. 2 June 1995 cool-sector supercell: Matador storm

Another supercell with morphology somewhat different than the two warm-sector storms was initiated on the cool side of the prominent outflow boundary in the area of Matador, Texas (see GW02 for details). This storm was reported to have the appearance of an LP supercell (C. Doswell 1999, personal communication). Its echo morphology was typified by that shown in Fig. 9a (2307 UTC). In this storm, large reflectivities were often observed to exist in a deep column very near the upshear end of the storm. We have also observed this structure in some of the 3 May 1999 tornadic supercells in Oklahoma (not documented in detail herein). This structure presents a difficulty because the objective criteria we used for DRC classification does not allow a single intense reflectivity column, not pendant from an echo upshear and not connected to a more classic downshear core, to be called a DRC. On the other hand, these quasi-columnar rear-side reflectivity maxima were generally not associated with the sort of local Doppler velocity patterns that were observed in the Dimmitt supercell or others reported herein. In the case of the Matador storm, the large reflectivity appeared to extend downward toward the north in an anticyclonic fashion, then east across the north side of the storm. This supercell had typical base-scan (600–800 m AGL) gate-to-gate differential velocities of 15–20 m s\(^{-1}\) (28 m s\(^{-1}\) maximum). Differential velocities in the mesocyclone were 20–25 m s\(^{-1}\), briefly reaching 30 m s\(^{-1}\) just prior to the formation of a deep hooklike appendage that persisted for about 30 min. This appendage never contained a reflectivity maximum meeting the DRC criteria. No tornadoes were reported for the Matador supercell, which was well observed by storm spotters.

e. 21 April 2001 Kansas supercells: Rush Center and Hoisington storms

All of the storms that occurred on 2 June 1995 in West Texas for which visual observations were available had the general characteristics of either LP or classic supercells for most of their life cycles. In only one storm was one DRC observed during an HP phase (Olton–Hart–Tulia) and that was associated with only a weak increase in rotation. This permits the hypothesis that HP supercells, with their propensity toward large amounts of precipitation trailing the updraft, are somehow different than the other categories and do not have the sort of DRC structure that was associated with most of the tornado occurrences on 2 June 1995. This possibility, along with the need to increase the number of samples of DRCs in HP storms, motivated us to compare and contrast an example of two tornadic HP supercells with the storms of 2 June 1995.

The Rush Center, Kansas, supercell produced a tornado of F2 damage intensity that was reported to begin around 0040 UTC on the evening of 21 April 2001 (NCDC 2001). Large gate-to-gate shear did not appear in the base-scan Doppler velocity from the Dodge City, Kansas (KDDC), radar until around 0045–0051 UTC. The DRC in this storm (Fig. 9b) was first identified by noting the occurrence of a locally intense rear-to-front flow signature (gate-to-gate couplets with counterrotating shear) around the time of tornado occurrence. A reflectivity maximum meeting the DRC criterion was found near the same location, and its development followed backward in time. Upon first inspection of base-scan PPI data, it appeared that this was just another shower in the large mass of precipitation that contained the Rush Center supercell. However, close scrutiny revealed that the precipitation maximum extended upward and northward, connecting with the echo upshear of the supercell. This configuration is considerably different than that shown for the Dimmitt and Olton–Hart–Tulia supercells, which tended toward LP in visual appearance. The interesting aspect of the HP supercell DRCs is that they were associated with the shear signatures of counterrotating vortices straddling locally intense rear-to-front flow. In the case of the Rush Center storm, the locally intense rear-to-front flow can be seen in the Doppler velocities about 4 km to the west of the objectively identified DRC. In the Rush Center supercell, as in the 2 June supercells, the DRC appeared to develop downward from aloft (Fig. 7).

![Graph of differential velocity at 0.5° elevation](http://journals.ametsoc.org/waf/article-pdf/21/6/923/4638679/waf962_1.pdf)
Fig. 8. As in Fig. 6. Radar data are from Lubbock WSR-88D.
Fig. 9. As in Fig. 6. Radar data are from the WSR-88Ds in Lubbock (Matador); Dodge City, KS (Rush Center and Hoisington early); and Wichita, KS (Hoisington late).
There was no differential velocity pattern at the lowest scan that could be termed a mesocyclone, and there were no significant gate-to-gate shears, when this feature formed aloft. After reaching the elevation of the lowest scan, during the two volume scans subsequent to that shown in Fig. 9b, differential velocities abruptly increased (Fig. 10), becoming very large (the differential velocity was in excess of 60 m s\(^{-1}\) by \(\sim 0050\) UTC). In this case, therefore, the flow associated with the DRC itself would appear to have been responsible for the abrupt development of the low-level mesocyclone and associated tornado. The differences in echo morphology between the Rush Center storm and the Dimmitt and Olton–Hart–Tulia storms could owe to significant differences in kinematic and microphysical processes. Work is ongoing to understand these differences. The common features of a rear-flank reflectivity maximum accompanied by a rear-to-front flow maximum have prompted us to include this HP storm in this set of examples.

The Hoisington, Kansas, supercell produced its first DRC (Fig. 9c) at about 0115 UTC in the vicinity of Vaughn, Kansas. This DRC had somewhat greater similarity to the 2 June 1995 DRCs. However, in general the storm had much larger reflectivity concentrated around the rear flank compared to downshear as in the 2 June storms. The DRC that commenced shortly after 0105 UTC clearly descended (Fig. 11). This DRC minimally met the criteria by having only 4-dB isolation from the storm core. While the DRC was aloft, there was no mesocyclone in the 0.5° velocity scan. Immediately after the DRC reached the base scan, mesocyclone and gate-to-gate differential velocities abruptly increased to \(\simeq 30\) m s\(^{-1}\). In this case, as with the Rush Center supercell.
Center storm, it appears that the descent of the DRC and rear-to-front flow initiated a velocity couplet and low-level mesocyclone.

The second DRC in the Hoisington storm, associated with the killer F4 tornado, was more reminiscent of the Rush Center HP supercell than the Dimmitt or Olton–Hart–Tulia events. Like the Rush Center storm, this DRC arched upward and northward toward the storm core (Fig. 9d), instead of descending almost vertically from a large echo overhang. In both storms, the reflectivity maximum of the DRC at the base scan occurred just south of a weaker reflectivity notch associated with the storm inflow and updraft. Also as at Rush Center, this DRC was associated with a very prominent and intense velocity signature of locally intense rear-to-front flow. The values of low-level differential velocity became large during the first DRC event (Fig. 11), but then increased abruptly after the development of the second DRC, followed by the development of the F4 tornado. This second DRC had somewhat greater isolation (4–8 dB) from the storm core than the first event, but it was pendant from a very low echo overhang. Events such as this, in which the DRC is embedded in generally large reflectivities, are more easily recognized by first noting the locally intense rear-to-front flow and counterrotating shear signature in the single-Doppler velocity data, and then observing whether there is a reflectivity maximum between the vortices.

f. 16 May 1995 Kansas tornadoes: Garden City and Hanston

VORTEX field teams observed two significant tornadoes in Kansas on 16 May 1995. The first, near Garden City, has been extensively documented by Wakimoto and Liu (1998) and Wakimoto et al. (1998). In our analysis of the Garden City supercell, we find
that it follows a progression of DRC development, followed by intensification of low-level shear. The morphology of this supercell (Fig. 12a) was similar to several of the tornadic supercells discussed earlier, with a large, prominent echo overhang along the south side, and a DRC that tapered toward the ground at the rear flank. It should be noted that this DRC only marginally met the criterion, with 4-dB isolation. The prominent velocity signature (enhanced rear-to-front flow associated with a Doppler shear signature of counterrotating vortices) is displaced somewhat to the east of the DRC. However, it is plausible that the velocity signature associated with a DRC is very dependent on the radar viewing angle. The time series of the evolution of this echo (Fig. 13) is similar to some of the other tornadic storms. Low-level rotation intensified abruptly upon descent of the DRC. As with the Rush Center and first Hoisington DRCs, it was the local increase in rear-to-front flow that produced the increase in differential velocity at the 0.5° level (Fig. 13). We note that this kinematic feature, found in single-Doppler WSR-88D data, apparently is the outflow intensification shown by Wakimoto et al. (1998, their Fig. 5) utilizing airborne dual-Doppler analyses.

A second significant tornado formed near Hanston, Kansas (Fig. 12b), later in the evening. This supercell evolved very rapidly. First echo was noted in the base scan around 0124 UTC, and the storm had a mature supercell morphology including a strong mesocyclone and BWER by 0135 UTC. The DRC was first noted aloft at 0129 and 0135 UTC, and descended to the surface by 0141 UTC. The significant tornado formed at about this same time and was observed by VORTEX teams to persist for at least 45 min.

4. Discussion

This study is a first step toward a broader understanding of the occurrence of DRCs in supercells, and the relationship of those echoes with tornado formation. The sample reported here is much too small for any general conclusions to be drawn. We leave it to future research to establish a climatological quantification of the occurrence of DRCs and their association with tornadoes, as well as any possible refinements of the definition of a DRC. However, from the data reported herein, we can certainly pose some speculative questions for further investigation.

In the limited sample, DRCs were always associated with a velocity signature in the base scan in which the Doppler velocity within a few kilometers of the DRC appeared to be quite different than that in the nearby region. When viewing angles permitted, this velocity

**Fig. 12.** As in Fig. 6. Radar data are from the Dodge City WSR-88D.
signature could be described as consisting of locally intense rear-to-front flow straddled by counterrotating vortices. It was the development of this kinematic signature that gave rise to increasing differential velocity that we quantified in these analyses. Additional research is ongoing to determine how frequently, in a large sample, DRCs are associated with this kinematic pattern and tornado formation, and how often supercell tornadoes develop without evidence of prior DRC formation. Our preliminary subjective impression is that the DRC is fairly common in tornadic storms; when available, these findings will be reported upon in order to give the operational community a sense of the significance of the DRC. At the present time, we simply suggest that the presence of a DRC and/or a small-scale disturbance in the velocity field below supercell echo overhangs should be sufficient justification for heightened concern over tornado potential. We would caution forecasters that our work in no way implies that all supercell tornadoes are preceded by DRCs.

We have noted that not all DRCs seem to be associated with the same overall reflectivity morphology. This leads to additional questions concerning how DRCs form. As of this writing, we have not found definitive evidence to aid in answering this question. Some leading hypotheses might include 1) flow stagnation at the rear of the updraft creates a narrow zone where precipitation develops and descends without being swept around the updraft and deposited toward the forward flank; 2) hydrometeors capable of seeding the updraft are deposited in a confined region toward its rear by divergent flow near the updraft summit; these seeds cause rapid precipitation growth as they descend into the periphery of the main updraft; or 3) a growing cumulus tower merges with the storm and seeds the updraft in a confined region.

In our cursory look at 3 May 1999 data (not included herein), we have noted that tornado formation seemed to be associated with the counterrotating vortex signatures (i.e., locally intense rear to front) in many cases, if not most. However, this signature was itself associated with a variety of reflectivity features, including DRCs resembling those shown herein, hooks without embedded reflectivity maxima, and very innocuous-looking showers pendant from echo overhang well removed from the main precipitation core. These latter shower echoes sometimes met the DRC criteria, and occurred at reflectivity values as low as 15 dBZ. Thus, we believe additional research is necessary to identify the physical role of various rear-flank reflectivity features in producing the relevant kinematic structures.

5. Conclusions

This paper has defined a phenomenon dubbed a DRC. This is a reflectivity maximum pendant from the echo overhang above a supercell weak-echo region. Examples of supercells with and without DRCs have been presented from two days during the VORTEX experiment, as well as one day with tornadic HP supercell storms in central Kansas. It was found that in all cases, tornado formation was preceded by the descent of a DRC. However, the sample reported herein is much too small to allow conclusions regarding the overall frequency of DRC occurrence in supercells, or the frequency with which DRCs precede tornado formation.

This preliminary analysis does answer some research questions, as posed in the introduction. First, DRCs occur in some tornadic supercells prior to tornado formation. Second, this work establishes that DRCs can occur without tornado formation, or apparent increases in low-level differential Doppler velocity (two occurrences in the Olton–Hart–Tulia supercell). Finally, it establishes that some supercells do not produce DRCs. In the cases examined here, these supercells also did not produce tornadoes.

Several avenues for further research are suggested by this preliminary work, including climatological analyses, review of historical dual-Doppler literature, and case studies utilizing dual-polarization Doppler data.
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