Vortex Lines within Low-Level Mesocyclones Obtained from Pseudo-Dual-Doppler Radar Observations

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ABSTRACT

Vortex lines passing through the low-level mesocycle regions of six supercell thunderstorms (three nontornadic, three tornadic) are computed from pseudo-dual-Doppler airborne radar observations obtained during the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX). In every case, at least some of the vortex lines emanating from the low-level mesocycles form arches, that is, they extend vertically from the cyclonic vorticity maximum, then turn horizontally (usually toward the south or southwest) and descend into a broad region of anticyclonic vertical vorticity. This region of anticyclonic vorticity is the same one that has been observed almost invariably to accompany the cyclonic vorticity maximum associated with the low-level mesocycle; the vorticity couplet straddles the hook echo of the supercell thunderstorm. The arching of the vortex lines and the orientation of the vorticity vector along the vortex line arches, compared to the orientation of the ambient (barotropic) vorticity, are strongly suggestive of baroclinic vorticity generation within the hook echo and associated rear-flank downdraft region of the supercells, and subsequent lifting of the baroclinically altered/generated vortex lines by an updraft. Discussion on the generality of these findings, possible implications for tornadogenesis, and the similarity of the observed vortex lines to vortex lines in larger-scale convective systems are included as well.

1. Introduction

Vortex lines (also sometimes called vortex filaments) are lines tangent to the vorticity vector, analogous to the streamline in a velocity vector field (Dutton 1986, p. 364; Pedlosky 1987, p. 25; Kundu 1990, p. 120).1 Vortex lines can aid the visualization of the three-dimensional vorticity field. The three-dimensional perspective provided by vortex lines can expose dynamics that may not be as apparent in inspections of only one vorticity component at a time. For example, the dynamics of midlevel mesocyclogenesis in supercell thunderstorms is easily demonstrated by way of vortex lines (Davies-Jones 1984; Rotunno and Klemp 1985; Fig. 1). Vortex line analyses in phenomena like thunderstorms are complicated by the baroclinic generation of vorticity by the horizontal buoyancy gradients that accompany precipitation regions and vertical drafts. In the presence of significant baroclinic vorticity generation, vortex lines may not even closely approximate material lines (Helmholtz’ theorem). Nonetheless, vortex line analyses can be enlightening in that they can suggest plausible methods of vorticity generation and reorientation (e.g., observations of vortex rings might lead one to surmise that a local buoyancy extremum is present and responsible for the generation of the rings). Although the vertical component of vorticity tends to be emphasized in supercell thunderstorm and tornado studies, there is some merit in systematically inspecting the distribution and orientation of three-dimensional vortex

1 What are referred to as “vortex lines” herein are termed “vorticity lines” by Lugt (1996, p. 90). Lugt defines a vortex line as an isolated vorticity line within a wind field that is otherwise irrotational.

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lines in observed and simulated storms. A lengthier discussion on the benefits of vortex line analysis appears in Straka et al. (2007).

Vortex line analyses appear relatively infrequently within the body of severe local storms literature. In addition to the previously cited theoretical and numerical modeling studies of midlevel mesocyclogenesis by Davies-Jones (1984) and midlevel and low-level mesocyclogenesis by Rotunno and Klemp (1985), respectively, Walko (1993) and Wicker and Wilhelmson (1995) presented vortex lines in their three-dimensional simulations of tornadogenesis. As one would expect, the vortex lines were nearly erect in the tornadoes, turned horizontally at the base of the tornadoes, and then extended horizontally several kilometers from the tornadoes along the surface. Weisman and Davis (1998) presented vortex lines in their investigation of the genesis of line-end vortices in mesoscale convective systems. The counterrotating mesoscale vortices commonly found at opposite ends of quasi-linear convective line segments were joined by “arching” vortex lines that rose out of the cyclonic vortex to the north (in the case of westerly mean vertical shear and a north–south convective line orientation), turned horizontally and extended many tens of kilometers to the south, and then descended into the anticyclonic vortex. More recently, Nolan (2004) showed that three-dimensional Lagrangian vortex methods (Chorin 1996) could be used to simulate mesocyclogenesis as an alternative to the traditional approach of simulating the dynamics with an Eulerian grid. We are unaware of any attempts to construct vortex lines in observed convective storms (using presumably dual-Doppler–derived three-dimensional wind fields) with the exception of the recent supercell thunderstorm studies by Majcen et al. (2006) and Straka et al. (2007).

The origins of midlevel and low-level rotation in supercell thunderstorms have been reviewed by Davies-Jones and Brooks (1993), Rotunno (1993), and Davies-Jones et al. (2001). [Herein, “low level” refers to altitudes nominally ≤1000 m AGL. Davies-Jones et al. (2001) referred to these altitudes as “near ground.” The distinction between low-level and midlevel mesocyclones is discussed further in section 4.] Midlevel vertical vorticity having relatively high correlation with vertical velocity (negative correlation, in the case of a “left-moving” storm)—what most would probably consider the defining characteristic of a supercell thunderstorm (i.e., a rotating updraft)—can be envisioned as arising from the tilting of vortex lines having a significant streamwise component by an “isentropic mountain” (Davies-Jones 1984; Fig. 1). The vortex lines are quasi-horizontal in the ambient environment owing to the presence of large mean vertical wind shear. On the other hand, baroclinic vorticity generation is present in convective storms, at least somewhere, owing to the presence of horizontal buoyancy gradients (if there were no buoyancy gradients there could be no buoyant updraft in the first place). In addition to the updraft, the evaporation of rain, the melting of graupel and hail, and even the direct contribution to negative buoyancy by the mass of hydrometeors themselves unavoidably lead to horizontal buoyancy gradients and baroclinic vorticity generation. Given this addition of baroclinic vorticity (Dutton 1986, p. 390; Davies-Jones 1996; Davies-Jones et al. 2001) to the barotropic vorticity (defined as
the vorticity that has resulted from the amplification and reorientation of the initial ambient vorticity of the vertically sheared environment over the lifetime of the storm), particularly at low levels within the rain-cooled outflow of storms where significant buoyancy gradients would most likely be found [prior modeling and observational evidence that at least some of the air feeding mesocyclones near the ground originate in the rain-cooled outflow (e.g., Klemp and Rotunno 1983)], one probably would not expect the vortex lines passing through low-level mesocyclones necessarily to have the same configuration or orientation as those passing through the midlevel mesocyclone, such as in Fig. 1. Along these lines, Davies-Jones (1982a,b) proposed that a downdraft was actually a prerequisite for the development of low-level rotation in environments in which vertical vorticity was initially negligible near the ground [also see the reviews by Davies-Jones and Brooks (1993) and Davies-Jones et al. (2001)], a notion that has been verified in numerical simulations (e.g., Rotunno and Klemp 1985; Walko 1993) and is consistent with the nearly countless observations of rear-flank downdrafts (RFDs), hook echoes, and “clear slots” in close proximity to tornadoes (Lemon and Doswell 1979; Markowski 2002a).

If downdrafts are important for the amplification of low-level vertical vorticity in supercell thunderstorms, the vortex line distribution in the vicinity of low-level mesocyclones should provide insights into the role of the downdrafts. Dual-Doppler wind syntheses and three-dimensional numerical simulations of supercells almost invariably have revealed a region of anticyclonic vorticity on the opposite side of the hook echo as the cyclonic vorticity region associated with the low-level mesocyclone or tornado (Markowski 2002a). These observations may be indications that vorticity tilting in the vicinity of the RFD, which has a close association with the hook echo, is important in the intensification of low-level rotation within supercell storms. A vortex line analysis should shed insight into how this couplet is produced, and in turn, the likely means by which low-level rotation is intensified near the time of tornadoogenesis. The RFD is emphasized in this article, hopefully not unduly, because the horizontal gradient of vertical velocity commonly found in proximity to low-level mesocyclones and tornadoes (Markowski 2002a) is a maximum along the interface separating the RFD and updraft. We do not wish to imply that forward-flank downdrafts (FFDs; Lemon and Doswell 1979) are unimportant to the overall vorticity budget of low-level mesocyclones. In numerical simulations of supercell thunderstorms, the horizontal buoyancy gradient along the forward-flank gust front is an important source of storm-scale horizontal vorticity and is crucial for the development of low-level mesocyclones (Klemp and Rotunno 1983; Rotunno and Klemp 1985) [although recent observations (e.g., Shabbott and Markowski 2006; Beck et al. 2006; Frame et al. 2008) have raised questions about the extensiveness of horizontal vorticity generation within some storms]. We believe, however, that the much stronger downward velocities of the RFD, in contrast to those in the FFD (the forward-flank outflow is more nearly hydrostatic), particularly in the lowest kilometer (e.g., dramatic cloud erosion is commonly observed in conjunction with intensifying RFDs; Markowski 2002a), lend the RFD to be a more likely mechanism for the generation of near-ground cyclonic vertical vorticity. In the absence of preexisting vertical vorticity at the ground, the development of rotation at the ground requires positive vorticity tilting within air parcels that are sinking toward the ground (Davies-Jones 1982a,b; Davies-Jones and Brooks 1993; Davies-Jones et al. 2001).

In this paper we present vortex lines in the low-level mesocyclone regions of supercells using data obtained from airborne Doppler radars during the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX; Rasmussen et al. 1994). This work is intended to provide insight into the likely importance of baroclinic versus barotropic vorticity, particularly in the RFD region, in the amplification of low-level rotation in supercells. The data and wind retrieval method are described in section 2. The observations are presented in section 3. Some discussion and interpretation of the findings are provided in section 4. A summary and some final remarks appear in section 5.

2. Data and methodology

Six supercells were analyzed, all of which were observed during VORTEX-95 (Table 1). Of these, three were nontornadic (29 April, 12 May, 22 May) and three were tornadic (16 May, 31 May, 8 June). All six cases have been documented by a number of investigators using airborne Doppler radar observations (Table 1 provides a complete listing). The analyses of the 12 May, 16 May, 31 May, and 8 June cases utilized data from the Electra Doppler Radar (ELDORA) system on the National Center for Atmospheric Research (NCAR) Electra aircraft (Hildebrand et al. 1994). The analyses of the 29 April and 22 May cases relied on data obtained by the National Oceanic and Atmospheric Administration (NOAA) P-3 tail radar. The relatively small unambiguous velocity of the P-3 tail radar ($\pm 12.9$ m s$^{-1}$; by comparison, the unambiguous velocity of ELDORA was $\pm 78.8$ m s$^{-1}$) resulted in severe speck-
ling of radial velocities in the middle to upper portions of the storms observed by the P-3 tail radar. Dealiasing was not attempted at altitudes above 5.5 km.

In the cases using ELDORA data, the radar data were objectively analyzed to a $30 \times 30 \times 18$ km$^3$ Cartesian grid having horizontal and vertical grid spacings of 400 and 250 m, respectively. In the cases using NOAA P-3 data, the radar data were objectively analyzed to a $30 \times 30 \times 4$ km$^3$ Cartesian grid having the same grid spacings. The objective analyses were performed using the technique described by Barnes (1964). A smoothing parameter of $\kappa = 0.61$ km$^2$ was used, based on the recommendation of Pauley and Wu (1990) to use $\kappa = (1.3\Delta)^2$, where $\Delta$ is the data spacing. Although Pauley and Wu’s recommendation strictly applies to uniformly distributed data, at the range of the storms, the distribution of radar observations tends to be fairly regular. A conservative approach was taken in the determination of $\Delta$, whereby $\Delta$ was specified based on the coarsest data spacing of all of the cases rather than the mean data spacing. For the four ELDORA cases, the along-track data spacing was $\sim 300$ m, and the beamwidth in the mesocyclone regions, which were observed at a range of 10–16 km, was 310–496 m. For the two NOAA P-3 cases, the along-track data spacing was $\sim 600$ m and the beamwidth at 10–16 km ranges was 366–586 m. Using $\Delta = 600$ m (the coarsest data spacing) results in $\kappa = 0.61$ km$^2$ using the Pauley and Wu (1990) recommendation. The ELDORA data were perhaps a bit oversmoothed (i.e., using $\Delta = 496$ m yields a recommended $\kappa$ of 0.42 km$^2$). It was deemed most desirable to use the same degree of smoothing for all of the cases, with the smoothing parameter dictated by the worst resolution of all of the cases. [The reader is referred to Koch et al. (1983) and Trapp and Doswell (2000) for additional discussion on the choice of smoothing parameter.] Data farther than 1.7 km from a grid point [which corresponds to $(5\kappa)^{1/2}$] had their weights set to zero in the interest of computational expediency. No extrapolation of the observations was permitted in the assignment of grid values, as is commonly allowed. The height of the lowest wind data that were not contaminated by ground clutter was generally 300–500 m AGL. Data positions were corrected for storm motion as recommended by Gal-Chen (1982), except here the mean mesocyclone motion averaged over a 30-min period centered on the analysis period was used.

The three-dimensional pseudo-dual-Doppler wind syntheses were performed using the variational technique with weak constraints presented by Gamache (1997) [this method is fairly similar to that described by Gao et al. (1999)]. The three components of the wind field were obtained by minimizing a cost function that considers the radial velocity projections, anelastic mass continuity, upper and lower boundary conditions (in the 29 April and 22 May cases, only a lower boundary condition could be specified due to the fact that radar data were not processed above 5.5 km as stated earlier), and degree of smoothing [see Gamache (1997) for further details]. Precipitation fall speeds were parameterized in terms of radar reflectivity factor using the parameterization used by Dowell and Bluestein (2002a).

The theoretical response of the objective analyses is $<0.01, 0.22, 0.51, 0.69, 0.79, \text{and} 0.94$ for wavelengths of 1, 2, 3, 4, 5, and 10 km, respectively. Given that the objective analyses employed a fairly large (conservative) degree of smoothing prior to the wind synthesis, the additional smoothing applied in synthesizing the three-dimensional wind fields [i.e., the smoothing that is included in the Gamache (1997) cost function] is relatively minor. Features having scales larger than approximately 3 km probably can be viewed as being reasonably well-resolved.

The reader is referred to Jorgensen et al. (1983), Hildebrand and Mueller (1985), Ray and Stephenson (1990), and Wakimoto et al. (1998) for general discussions of the errors in airborne pseudo-dual-Doppler wind retrievals. It is worth stating that the wind syntheses constructed herein are qualitatively very similar to those that have been derived by previous investigators (Table 1) using slightly different techniques. Although it certainly would have been possible to compute vortex lines from the wind syntheses produced by the previous

<table>
<thead>
<tr>
<th>Case</th>
<th>Tornadic/nontornadic</th>
<th>Airborne radar system</th>
<th>Prior documentation</th>
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</thead>
<tbody>
<tr>
<td>29 Apr 1995</td>
<td>Nontornadic</td>
<td>NOAA P-3</td>
<td>Trapp (1999)</td>
</tr>
<tr>
<td>16 May 1995</td>
<td>Tornadic</td>
<td>ELDORA</td>
<td>Wakimoto and Liu (1998); Wakimoto et al. (1998); Trapp (1999); Cai and Wakimoto (2001)</td>
</tr>
<tr>
<td>22 May 1995</td>
<td>Nontornadic</td>
<td>NOAA P-3</td>
<td>Trapp (1999); Bluestein and Gaddy (2001)</td>
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<tr>
<td>8 Jun 1995</td>
<td>Tornadic</td>
<td>ELDORA</td>
<td>Dowell and Bluestein (2002a,b); Wakimoto et al. (2003)</td>
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investigators, it was deemed desirable to use identical objective analysis and wind synthesis methods and parameters for all of the vortex line analyses presented herein, given the sensitivity of vorticity (and even greater sensitivity of vortex lines) to small-scale details in the wind field.

The three-dimensional vorticity components were computed at each grid point using second-order, centered differences, except along data boundaries where one-sided differences were used. The vorticity components were lightly smoothed with a one-step Leise filter (Leise 1982), after which vortex lines were computed using a fourth-order Runge–Kutta integration. The finescale structure of the vortex lines is, as one would surmise, fairly sensitive to the degree to which the vorticity components are smoothed; however, the qualitative characteristics of the vortex lines (e.g., whether vortex lines form loops, arches, or erupt vertically from near the ground to mid- to upper levels) are fairly robust for reasonable degrees of smoothing (see appendix).

The vortex lines presented in section 3 pass through and near to the center of the vertical vorticity maximum at 1 km AGL, which we also occasionally refer to as the low-level mesocyclone; one vortex line passes through the vertical vorticity maximum, and four additional vortex lines pass through points surrounding the vertical vorticity maximum (these points form a 1 km × 1 km square centered on the vorticity maximum, with the exception of the 22 May case, for which a 2 km × 2 km square was used owing to the mesocyclone core being nearly twice as large as in the other cases). When possible, an additional, sixth vortex line originating in the ambient environment ahead of the storm gust fronts also is shown for each case. In the nontornadic cases, vortex lines are shown at the time of maximum low-level vertical vorticity (tornadogenesis “failure”) identified by prior investigators [Wakimoto and Cai (2000) for the 12 May case (0034:39–0041:15 UTC 13 May); Trapp (1999) in the 29 April (0026:22–0030:59 UTC 30 April) and 22 May (2355:11–0000:58 UTC) cases]. For the tornadic cases, vortex lines are shown prior to tornadogenesis (generally 10–20 min before tornadogenesis) as well as at the time of tornadogenesis. It also is worth mentioning that the location of the tornado is not necessarily coincident with the vertical vorticity maximum retrieved in the three-dimensional wind synthenses (e.g., Wakimoto et al. 2004), which only retain mesocyclone-scale kinematic features. Only the vortex lines clustered around the mesocyclone center were computed; no attempt to construct vortex lines through the center of the tornado was undertaken since the tornadoes were not resolved by the airborne radars.

3. Observations

a. Nontornadic supercell cases: 12 May, 29 April, 22 May

Figures 2–5 depict the radar reflectivity, storm-relative wind vectors, and vertical vorticity at 1 km AGL, in addition to vortex lines passing through and near to the low-level vertical vorticity maximum, for the 12 May, 29 April, and 22 May nontornadic supercell cases, respectively. A vortex line originating in the ambient boundary layer south of the gust front also is shown for the 12 May and 29 April cases (lack of dual-Doppler observations in the ambient environment precluded the calculation of an environmental vortex line in the 22 May case). The environmental hodographs for each case are presented in Fig. 6.

In all three nontornadic supercell cases, the low-level mesocyclones are associated with vertical vorticity maxima well in excess of 1 \( \times 10^{-2} \) s\(^{-1} \). The strongest low-level mesocyclone is analyzed in the 12 May storm, with a peak vertical vorticity of approximately 5 \( \times 10^{-2} \) s\(^{-1} \) at 1 km AGL (Fig. 2a). 3 The weakest low-level mesocyclone at the time of tornadogenesis failure is analyzed in the 22 May case, with a peak vertical vorticity of approximately 2 \( \times 10^{-2} \) s\(^{-1} \) at 1 km AGL (Fig. 5a), although it is worth noting that the core radius of the low-level mesocyclone of the 22 May storm is almost twice as wide as that analyzed in the 12 May storm at the times analyzed herein; thus, the 12 May and 22 May mesocyclones have more similar circulations.

Almost all of the vortex lines passing through the low-level mesocyclone in the 12 May storm extend a few kilometers upward from the cyclonic vorticity maximum, but then turn southwestward and descend into a broad region of low-level anticyclonic vertical vorticity found in the trailing portion of the hook echo (Figs. 2b,c). In other words, the couplet of oppositely signed vertical vorticity (reviewed in section 1) that seems to be a ubiquitous characteristic of supercell hook echo regions is joined by vortex line “arches.” These vortex lines bear a striking resemblance to the vortex lines originating in the cold pools of mesoscale

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2 Trapp (1999) analyzed the 12 May 1995 case at earlier times (2252 and 2256 UTC analysis times were presented) using NOAA P-3 data (the 0034–0041 UTC period is analyzed herein using ELDORA data).

3 The maximum low-level (0–1 km AGL) vertical vorticity analyzed by Trapp (1999) in his 2252 and 2256 UTC analyses of the 12 May case was approximately 2.5 \( \times 10^{-2} \) s\(^{-1} \).
convective systems simulated by Weisman and Davis (1998), which are subsequently drawn upward by updrafts, leading to the formation of counterrotating line-end vortices. This similarity will be revisited in section 4.

The vortex lines that originate in the boundary layer of the ambient environment south of the gust front in the 12 May case point generally toward the north (Figs. 2b,c), consistent with the environmental hodograph obtained from inflow soundings (Fig. 6a; excluding a shallow layer within ~200 m of the ground, in which the environmental horizontal vorticity points toward the southwest). The environmental vortex line displayed in Fig. 2c ascends abruptly from south to north, entering the midlevel updraft and mesocyclone region several kilometers above the ground. The differences in the configurations of the environmental vortex line and the vortex lines passing through the low-level vorticity maximum (e.g., the horizontal component of the environmental vorticity points in roughly the opposite direction to the horizontal component of the vorticity that defines the vortex line arches emanating from the low-level vertical vorticity maximum) might imply that different dynamical processes were important to the production of vertical vorticity at different altitudes. This issue also is reserved for section 4.

Additional vortex lines also are constructed at select locations northwest (upstream) of the aforementioned vortex lines (Fig. 3). These vortex lines also form arches, but the apexes of the arches extend to progressively lower altitudes the farther northwest one looks. The vortex line farthest northwest in Fig. 3 is inclined very little with respect to the horizontal, and the view from above (Fig. 3a) indicates that this vortex line nearly forms a closed loop (the endpoints of this vortex line extend below the data horizon), with the orientation of the vorticity along this vortex line suggestive of a local maximum of downdraft and/or negative buoyancy being nearly encircled by this vortex line. Indeed,

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**Fig. 2.** (a) Equivalent radar reflectivity factor (dBZ; shaded) at 1.0 km AGL at 0034:39–0041:15 UTC 13 May 1995. Storm-relative wind vectors and vertical vorticity \( \zeta \) contours (\( 10^{-2} \) s\(^{-1} \) contour interval; the zero contour is suppressed and negative contours are dashed) at the same altitude also are overlaid. The region enclosed by the square in (a) is enlarged. The direction of the vorticity vector is indicated by the arrow heads. Five of the vortex lines pass through points centered on and surrounding the vertical vorticity maximum at 1.0 km. A sixth vortex line originates in the environment ahead of the gust front. (c) As in (b), but a three-dimensional perspective is shown.
a local downdraft maximum was observed in this location (Fig. 3a).

In the 29 April and 22 May nontornadic cases, similar evidence of vortex line arches is present, although per-
haps to a lesser degree. In the 29 April case (Figs. 4b,c), only the vortex line passing through the southeastern part of the low-level mesocyclone forms an arch in a manner similar to the majority of vortex lines constructed for the 12 May case. In the 22 May case (Figs. 5b,c), only the vortex lines passing through the western part of the low-level mesocyclone form such arches (because of overlapping vortex lines, it might be somewhat difficult to see that the vortex line arches enter the western part of the low-level mesocyclone in Figs. 5b,c).

The differences in the exact number of vortex lines that form arches should not be overinterpreted (the number of vortex lines passing through even a tiny area is infinite unless a convention is applied that relates the spacing of lines to the strength of the field), as it is somewhat arbitrary in that more vortex line arches could have been drawn if the points surrounding the low-level vertical vorticity maximum through which the vortex lines passed were adjusted from case to case, depending on the size and horizontal structure of the low-level mesocyclone. Instead, vortex lines were drawn through the exact same arrangement of points surrounding the low-level mesocyclones in each case (one point centered on the vertical vorticity maximum, with four additional points surrounding the vertical vorticity maximum, as discussed in section 2). Furthermore, and perhaps more importantly, recall that the top of the data region in the 29 April and 22 May cases was 4 km, compared to 18 km in the 12 May case. One cannot know where the vortex lines that exit the relatively shallow domains in the 29 April and 22 May cases would go after reaching an altitude of 4 km.

Similar to the 12 May case, the horizontal component of the environmental vorticity in the 29 April case (which points toward the northeast; Fig. 6b) points in roughly the opposite direction as the horizontal component of the vorticity that defines the vortex line arch emanating from the low-level vertical vorticity maximum (Fig. 4b). In the 22 May case, although no ambient vortex line in the near-storm environment could be computed from the dual-Doppler observations, hodographs obtained from soundings launched in the storm inflow showed a horizontal vorticity orientation that veered significantly with height, from southwestward pointing in the lowest few hundred meters to north-northeastward pointing at 1 km (Fig. 6c); the orientation of the horizontal vorticity in the vortex line arches evident in Fig. 5c was approximately parallel to the horizontal vorticity at ~500 m but differed substantially from the orientation of the environmental horizontal vorticity in the 0–300-m layer and above 800 m (Fig. 6c).

**FIG. 5.** As in Fig. 2, but for 2355:11–0000:58 UTC 22–23 May 1995. A vortex line originating in the environment ahead of the gust front could not be drawn owing to limited observations.
b. Tornadic supercell cases: 16 May, 31 May, 8 June

Figures 7–12 depict vortex lines and low-level radar reflectivity, storm-relative wind vectors, and vertical vorticity for the 16 May, 31 May, and 8 June tornadic supercell cases. The supercells produced F3, F0, and F2 tornadoes, respectively.\(^4\)

For each case, analyses are presented both at the time of tornadogenesis as well as at an earlier time (the exact lead time varies from case to case). The reader may find it interesting that the vertical vorticity maxima at 1 km AGL are not systematically larger in the tornadic cases, even at the time of tornadogenesis (Figs. 8a, 10a, 12a), compared to the nontornadic cases (Figs. 2a, 4a, 5a). In fact, this might be considered one of the most important findings of VORTEX: tornadic and nontornadic supercells have surprising kinematic similarities at scales larger than the tornado (e.g., the mesocyclone scale) (Trapp 1999; Wakimoto and Cai 2000).

Vortex line arches are observed in all of the tornadic cases, just as they are for the nontornadic cases. In all three tornadic cases, as is found for the nontornadic cases, the orientation of the horizontal vorticity associated with the vortex line arches. The environmental vorticity tends to point northward, whereas the vortex lines that form arches tend to turn southward or westward after emanating from the low-level vertical vorticity maxima (Figs. 7–12b,c).

Some tendency exists for the arches to be more common prior to tornadogenesis. In the 16 May case, an analysis derived approximately 29 min prior to tornadogenesis (2301:40–2307:00 UTC) reveals that the vortex lines passing through the center and to the south of the low-level vertical vorticity maximum abruptly turn southwestward below 3 km AGL, where they then descend and exit the bottom of the data domain 3–7 km from the vertical vorticity maximum (Figs. 7b,c). Dur-

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\(^4\) The 8 June 1995 supercell produced a number of significant tornadoes (the most intense was rated F5 by R. Wakimoto) in cyclic fashion. The analyses presented herein were obtained during and just prior to the development of the first tornado. See Dowell and Bluestein (2002a) for further details.
FIG. 7. As in Fig. 2, but for 2301:40–2307:00 UTC 16 May 1995.

FIG. 8. As in Fig. 2, but for 2331:00–2336:00 UTC 16 May 1995.
Fig. 9. As in Fig. 2, but for 2218:00–2222:00 UTC 31 May 1995.

Fig. 10. As in Fig. 2, but for 2236:40–2244:32 UTC 31 May 1995.
FIG. 11. As in Fig. 2, but for 2239:42–2245:18 UTC 8 Jun 1995.

FIG. 12. As in Fig. 2, but for 2246:47–2250:33 UTC 8 Jun 1995.
ing the analysis period in which tornadogenesis occurred (2331:00–2336:00 UTC), the vortex lines on the eastern flank of the low-level mesocyclone form arches, whereas the vortex line passing through the center of the low-level vertical vorticity maximum is fairly upright and extends all the way to the storm summit (Figs. 8b,c).

In the 31 May case, almost all of the vortex lines passing through the low-level vertical vorticity maximum 19 min before tornadogenesis (2218:00–2222:00 UTC) form short arches, with the vertical planes containing the arches being oriented from east-southeast to west-northwest, or approximately normal to the major axis of the echo appendage on the rear flank of the storm (Figs. 9b,c). During the analysis period containing tornadogenesis (2236:40–2244:32 UTC), almost all of the vortex lines reach the storm summit (Figs. 10b,c). The lone vortex line arch originates in the northwestern flank of the low-level mesocyclone and extends above 8 km before turning back toward the ground, where it enters a broad region of anticyclonic vertical vorticity to the rear of the hook echo. The environmental vortex line displayed during this analysis period enters the midlevel updraft and mesocyclone (Fig. 10c) in a manner similar to that observed in the 12 May case (Fig. 2c).

Relatively limited vortex line arching appears in the 8 June pretornadic analysis period (2239:42–2245:18 UTC; Figs. 11b,c), which is only 7 min prior to the analysis period (analyses are not available at earlier times) during which tornadogenesis occurred (2246:47–2250:33 UTC; Fig. 12). The vortex line originating in the southwestern portion of the low-level vertical vorticity maximum rises to an altitude of nearly 4.5 km, then turns toward the west and descends into a region of anticyclonic vertical vorticity to the rear of the storm (Figs. 11b,c). Another vortex line during the pretornadic analysis period, originating in the southeastern portion of the low-level mesocyclone, turns toward the north-northwest and descends within the main precipitation core, exiting the domain approximately 3 km AGL. During the analysis period in which tornadogenesis occurs, almost all of the vortex lines reach the storm summit (although these vortex lines tilt north-eastward with height), with the lone exception being the vortex line that originates in the southwestern portion of the low-level mesocyclone (Figs. 12b,c). This vortex line erupts vertically out of the low-level vertical vorticity maximum, then abruptly turns horizontally and makes one and a half counterclockwise loops having a radius of roughly 1.5 km before descending to the bottom of the data domain and entering a region of anticyclonic vertical vorticity immediately west of the cyclonic vertical vorticity maximum. The vortex line encircled a relative maximum in the midlevel vertical velocity field (not shown) that apparently was associated with a flanking updraft. The orientation of the horizontal vorticity along the “looping” portion of the vortex line is consistent with the presence of a relative maximum of buoyancy and updraft at the center of the loop. This vortex line serves as a nice example of how complex vortex line distributions and configurations can be.

Regarding the tendency for arches to be more common prior to tornadogenesis, as the low-level vorticity intensifies, the vortex lines passing through the vorticity maximum ought to become more vertical, with the summits of the arches extending to higher altitudes. [Straka et al. (2007) also found that arches give way to vortex lines extending deeply and vertically as their vortices intensified, with the prominence of the arch structures being a function of time in their simulation.] Two possible reasons for why arching vortex lines are less commonly observed as tornadogenesis nears might be that the apexes of the arches are simply too high for us to observe, or that by the time the arches are lifted to such high altitudes, their configurations have been significantly modified by additional baroclinic effects or turbulence, the latter of which can cause vortex lines to be severed and reattached to other lines instantaneously as long as there are no loose ends at any time (additional discussion is provided in section 4e). Both effects prevent the vortex lines from behaving as material lines. Furthermore, in each case, vortex lines have been drawn through the same 1 km × 1 km lattice of grid points centered on the vorticity maximum at 1 km. If this region is extended to the periphery of the vortex, where vertical vorticity is not as large, additional arching vortex lines are observed, even at the time of tornadogenesis (e.g., Fig. 13).

4. Discussion

a. Vortex line arches observed in prior supercell studies

These are not the first observations of vortex line arches. Similar vortex line configurations have been found in the Dimmitt, Texas, tornadic supercell intercepted during VORTEX on 2 June 1995 (Straka et al. 2007), in a non-tornadic supercell observed by a pair of Doppler On Wheels (Wurman et al. 1997) radars on 12 June 2004 (Majcen et al. 2006), and even in the simulations of the 20 May 1977 Del City, Oklahoma, supercell by Rotunno and Klemp (1985), as evidenced by the vortex line shown in their Fig. 9 (Fig. 14). [Presumably other investigators who have simulated supercells using
the 20 May 1977 proximity sounding (e.g., Klemp et al. 1981; Klemp and Rotunno 1983; Grasso and Cotton 1995; Adlerman et al. 1999; Adlerman and Droegemeier 2002) would find a similar vortex line configuration in the low-level mesocyclone region. This vortex line originates in the ambient environment, is “deflected” from the south toward the west upon encountering outflow having a relatively low equivalent potential temperature ($\theta_e$; the vortex line cannot pass through a $\theta_e$ surface if Ertel’s potential vorticity is conserved and is zero), enters the low-level vertical vorticity maximum, and then rises and descends toward the southwest to form an arch like those observed in section 3. In the present study, we cannot determine where the vortex lines go after passing below approximately 300–500 m AGL owing to the limitations of the data (see section 2). Thus, we cannot say whether the observed vortex line arches, if extended, would reach into the forward-flank baroclinic zone near the ground, and ultimately even into the ambient environment, as in the analysis of Rotunno and Klemp (Fig. 14). It is possible that the horizontal extension of the vortex line from the low-level vertical vorticity maximum into the forward-flank region and ambient environment in the analysis of Rotunno and Klemp should not be interpreted too “literally”; the lowest model grid level was 250 m AGL, the same level at which the vertical vorticity maximum was identified through which the vortex line was drawn. Not only would the configuration of the vortex line at the lowest grid level depend on the (unrealistic) free-slip lower boundary condition, but the vortex line passing through the vertical vorticity maximum at the lowest grid level should have passed below the lowest model grid level. Its horizontal extension into the forward-flank region and ambient environment is therefore extrapolated.

Although the sample of observed and simulated supercells displaying arching vortex lines is very small, vortex line calculations, when done, have never failed to reveal arches that connect the counterrotating vortices that straddle the hook echo. The fact that such vorticity couplets have been observed in essentially every dual-Doppler and numerical modeling study of supercells (Markowski 2002a; also refer to section 1) might lead one to wonder whether vortex line arches are as common to supercell RFD regions as are these vorticity couplets (i.e., it is tempting to wonder whether
vortex line arches are a ubiquitous trait of supercell thunderstorms).

b. Inferences about baroclinic vorticity generation

The vortex line arches evident in all six supercells bear a striking resemblance to the vortex lines computed by Weisman and Davis (1998) in their numerical modeling study of the formation of line-end vortices in mesoscale convective systems (Fig. 15). Weisman and Davis found that counterrotating vortices arise on opposite ends of a finite-length convective line owing to the lifting of vortex lines that are baroclinically generated within the horizontal buoyancy gradient of the cold pool.5 It is tempting to draw the same conclusion in the present study: baroclinic vorticity generation almost certainly led to the development of the vortex line arches observed in the supercell low-level mesocyclone and RFD region. This conclusion is supported by a number of observations: (i) the environmental vorticity points in markedly different directions (often in the exact opposite direction) compared to the orientation of the horizontal vorticity component that defines the vortex line arches emanating from the low-level vertical vorticity maxima; (ii) the horizontal vorticity component at the apexes of the arches tends to point in the same direction as vorticity that would be baroclinically generated by buoyancy gradients in the RFD region, assuming the buoyancy isopleths in the RFD region are approximately parallel to the rear-flank gust front; (iii) if only the tilting of barotropic vorticity by a downdraft were involved in the production of the observed low-level mesocyclones, vortex lines should form U shapes rather than arches. Let us expand a bit on this last point below.

If the ambient, barotropic vorticity is dominated by the horizontal component (in the limit of a horizontally homogeneous environment, ambient vertical vorticity is absent and vortex lines are horizontal), the tilting of vortex lines by an updraft produces midlevel vertical vorticity (the degree to which the cyclonic vertical vorticity maximum is in phase with the midlevel vertical velocity maximum depends on the degree to which the ambient horizontal vorticity is streamwise, as shown in Fig. 1) but no significant vertical vorticity near the ground (Fig. 16a). Tilting of the ambient vorticity by the horizontal vertical velocity gradients associated with an updraft alone is not effective at producing vertical vorticity near the ground because air is rising away from the surface as horizontal vorticity is tilted into the vertical. But if a downdraft is involved in the tilting process, then vertical vorticity can be advected toward the surface as it is produced via tilting (Davies-Jones and Brooks 1993; Grasso and Cotton 1995; Adlerman et al. 1999), yielding significant vertical vorticity next to the ground (Fig. 16b). Tilting of surface-layer horizontal vorticity by the extreme vertical velocity gradient associated with the tornado updraft itself probably contributes to the near-ground vertical vorticity in a significant way. However, such abrupt upward turning of streamlines, strong pressure gradients, and large vertical velocities are not present next to the ground prior to tornadogenesis; thus, such tilting in the absence of a downdraft cannot be invoked to explain the amplification of near-ground vertical vorticity that results in tornadogenesis. (This conclusion depends on eddies being too weak to transport vertical vorticity downward against the flow. Furthermore, once a tornado is established, the tilting of surface-layer horizontal vorticity by the extreme vertical velocity gradient associated with the tornado updraft itself probably contributes to the near-ground vertical vorticity in a significant way. However, such abrupt upward turning of streamlines, strong pressure gradients, and large vertical velocities are not present next to the ground prior to tornadogenesis; thus, such tilting in the absence of a downdraft cannot be invoked to explain the amplification of near-ground vertical vorticity that results in tornadogenesis.) If only ambient, barotropic vorticity is involved in the aforementioned process, then the vortex lines that pass through the low-level mesocyclone and connect the counterrotating vorticity extrema that are routinely observed to straddle the hook echo and RFD would form U shapes, not arches [Fig. 16b; also see Fig. 5 of Weisman and Davis (1998)]. Thus, although it is dynamically

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5 Weisman and Davis (1998) also found that when environmental horizontal vorticity is large, tilting of environmental vortex lines also can produce significant vertical vortices in the same way that supercell thunderstorm updrafts acquire vertical vorticity.
possible to develop strong near-ground rotation and even a tornado from the tilting of ambient, barotropic vorticity, as has been shown by Davies-Jones (2000a, 2007) and Markowski et al. (2003). The observations of vortex lines arches, if they apply generally, would indicate that baroclinic vorticity generation in the RFD region is important in the amplification of low-level vertical vorticity in observed supercells.

Three-dimensional numerical simulations have shown that baroclinic vorticity generation within the forward-flank outflow also is important in the generation of low-level rotation (Klemp and Rotunno 1983; Rotunno and Klemp 1985), as reviewed in section 1; however, the orientation of the vortex line arches observed in the present sample of supercells, while certainly not excluding the possibility of significant horizontal vorticity generation in the forward-flank outflow, strongly suggest baroclinic generation in the RFD region [refer to (ii) in the third paragraph of this section]. Forward-flank baroclinity alone cannot produce an arch that straddles the hook echo unless the trajectory of an air parcel coming out of the forward-flank outflow follows an arch itself [i.e., this trajectory would have to exit the updraft to the rear (typically west or southwest) after rising a short distance]. In our consideration, this would require a rather exotic three-dimensional wind field. Forward-flank baroclinity certainly could extend the “foot” of the cycloptic “leg” of a vortex line arch into the forward-flank baroclinic zone along the ground, but we cannot envision how a vortex line arch that straddles the hook echo could result from anything other than the lifting of baroclinic vortex lines that originate in the RFD outflow. The reader also is referred back to Fig. 3, for example, which shows vortex lines upstream of the arches. The vortex lines, one of which nearly forms a closed loop around a relative downdraft maximum, are suggestive of baroclinic vorticity generation in the RFD/hook echo region.

The idea that baroclinic vorticity generation in the RFD/hook echo region is important to the development of near-ground rotation in supercells has been advanced by Davies-Jones and Brooks (1993), Davies-Jones (1996, 2000b), Adlerman et al. (1999), and Davies-Jones et al. (2001). More recently, Davies-Jones (2006), in agreement with numerical simulations by Straka et al. (2007), demonstrated how a relative minimum in the buoyancy field, like that observed within

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6 Baroclinic vorticity was present in the Davies-Jones (2000a, 2007) and Markowski et al. (2003) simulations, but only barotropic vorticity contributed to the tornadoes in these simulations. The baroclinic vorticity could not be converted to vertical vorticity via tilting owing to the axisymmetry used in these idealized simulations.
the RFD/hook echo region of a supercell, produces baroclinic vortex rings that descend to the ground (Figs. 17a,b) and, if they interact with a nearby updraft, the leading edges of the rings subsequently can be lifted such that the vortex lines form arches (Fig. 17c). The vortex line arches that arise from this baroclinic process are similar to those found in the supercells we have observed, which lends much credence to the aforementioned hypothesis for the role of RFD/hook echo baroclinity in the generation of near-ground rotation in supercells. In some ways, these ideas are similar to one of Fujita’s (1985) microburst conceptual models (Fig. 18), but in Fujita’s model, the vortex rings spread out at the ground and do not interact with a localized updraft such that the leading edges of the vortex rings are lifted to produce a vorticity couplet.

**c. Relationship between midlevel mesocyclones and low-level mesocyclones**

A generalized depiction of vortex lines in the vicinity of a low-level mesocyclone is shown in Fig. 19. The portrayal has been inferred from the sample of supercells surveyed herein (Figs. 2–12, particularly Fig. 3, which displays vortex lines upstream of the vortex line arches that emanate from the low-level vertical vorticity maximum), and is superimposed on a photograph of a generic supercell thunderstorm in order to facilitate visualization. The portrayal also conforms to the observational and numerical modeling findings of Straka et al. (2007). Although the descending, baroclinically generated vortex lines shown in Fig. 19 are drawn as closed loops, as if encircling a local buoyancy minimum in the RFD (e.g., Fig. 17), the arching process does not depend on the vortex lines forming closed loops. The results would be qualitatively similar in the case of a buoyancy minimum in the hook echo/RFD that was conterminous with the negative buoyancy and downdraft in the forward reaches of the storm, such that the vortex lines that ultimately formed arches were not closed loops on their rear sides, but rather extended far into the precipitation region and out of the photograph.

We take the opportunity here to discuss what occasionally has been, in our experience, a confusing or misunderstood relationship between the low-level and midlevel mesocyclone. We prefer to avoid rigid distinctions between the two if at all possible. We believe the
more meaningful distinction in the generation of vertical vorticity is between the tilting of horizontal vorticity that involves only an updraft versus tilting that involves both an updraft and a downdraft. When only an updraft is involved in the tilting of horizontal vorticity (whether it be environmental horizontal vorticity or storm-generated horizontal vorticity, e.g., that which might be generated in the forward-flank region), air is rising as tilting produces vertical vorticity (the vertical advection of vertical vorticity has the opposite sign of the tilting), as discussed in section 4b. Significant vertical vorticity can be generated above the ground, but not at the ground. Even a low-level mesocyclone, if one defines “low-level” nominally as 500–1000 m AGL, could arise from the tilting of environmental horizontal vorticity if the horizontal vorticity is very large and the updraft very strong. On the other hand, if a downdraft is involved in the tilting process, air can be sinking toward the ground while tilting is producing vertical vorticity (section 4b). Thus, significant vertical vorticity can be achieved at the ground.

Summarizing, in the early stages of a supercell’s life, vertical vorticity in the mesocyclone comes from the tilting of environmental horizontal vorticity (the “midlevel” versus “low-level” distinction is somewhat arbitrary—the altitude at which “significant” vertical vorticity appears decreases as the environmental horizontal vorticity increases and is subjective anyway). In
later stages, once storm-scale buoyancy gradients arise at low levels but before significant vertical vorticity is present at the ground, the vertical vorticity in the midlevel mesocyclone as well as low-level mesocyclone likely comes from tilting of the ambient environmental horizontal vorticity as well as additional horizontal vorticity that might be generated baroclinically by way of storm-scale buoyancy gradients. Once a mature supercell is established, with significant rotation extending all the way to the surface (and downdrafts necessarily having played a critical role in arriving at this state), the vertical vorticity in the midlevel mesocyclone as well as low-level mesocyclone comes from both the ambient environment as well as from near the ground via vertical advection. Some of the vortex lines traced backward from the midlevel vertical vorticity maximum extend horizontally into the ambient environment and others extend vertically through the vertical vorticity maximum at the lowest data level. Some of the vortex lines traced forward from the midlevel vertical vorticity maximum extend to the storm summit and others form arches that bend back toward the trailing part of the hook echo where anticyclonic vertical vorticity is present. Notice that the illustration in Fig. 19 depicts a midlevel mesocyclone that contains a vortex line that extends into the ambient environment as well as one that forms an arch.

d. Paradoxical observations of weak cold pools in tornadic supercells

What we believe to be one of the outstanding mysteries is why, if baroclinic generation of vorticity in the RFD region is as important as the vortex line analyses seem to suggest, there is so much growing evidence from field observations that strong cold pools and excessive negative buoyancy at the surface are detrimental to tornadogenesis (Markowski 2002b; Markowski et al. 2002; Shabbott and Markowski 2006; Grzych et al. 2007). For example, the 8 June 1995 tornadic supercell studied herein has been shown to have possessed only very small (<2 K) temperature deficits at the surface (Dowell and Bluestein 2002a; Markowski et al. 2002). Moreover, climatological studies (Rasmussen and Blanchard 1998; Thompson et al. 2003) show that tornadic supercells are favored in environments having a large boundary layer relative humidity, which would tend to limit the production of exceptionally cold outflow and associated baroclinity. [Of course, cold outflow can be produced by the entrainment of potentially cold midlevel environmental air, independent of the boundary layer relative humidity. Moreover, the melting of ice is enhanced in humid conditions. However, these effects do not appear to completely mask the contribution to outflow strength from the evaporation of rain within the boundary layer, as evidenced by significant correlations between observed cold pool strength and environmental boundary layer relative humidity (Markowski et al. 2002; Shabbott and Markowski 2006).] We are not in a position to answer this question at this point, but perhaps supercell baroclinity is another “Goldilocks” problem whereby at least some baroclinity is crucial (all thunderstorms have at least some baroclinicity, as discussed in section 1), but too much, especially near the ground, is detrimental in that large near-ground baroclinity would imply very cold air near the ground and thus rapid gust front motion relative to the main updraft, which might undercut it (Brooks et al. 1993) or inhibit the vorticity stretching required by tornadogenesis (Leslie and Smith 1978; Markowski et al. 2003). In terms of Fig. 17, if the downdraft air containing the vortex rings is too negatively buoyant, then perhaps the end result is something resembling Fujita’s microburst model (Fig. 18) rather than significant lifting of the leading edge of the vortex rings to produce vertical vorticity (Fig. 17c). It goes without saying that thermodynamic observations above the ground would be invaluable in trying to assess the overall importance of baroclinic vorticity generation within supercell thunderstorms. We currently lack a three-dimensional, let alone four-dimensional, conceptual model of the range of thermodynamic characteristics in supercell thunderstorms and how these would impact vorticity generation and reorientation in ways that might be important for tornadogenesis.

e. Effects of turbulence on the vortex lines

Finally, a few comments regarding the effects of turbulence on the vortex lines are warranted. Although the effects of subgrid-scale turbulence on supercell dynamics are of secondary importance (if they were not, numerical simulations would be very sensitive to the turbulence parameterization), turbulence can have an important effect on the vortex lines. As described by Morton (1984), cross-diffusion of vorticity allows “surgery” of vortex lines (see his Figs. 10i, iii). Lines can be severed and reattached to other lines instantaneously as long as there are no loose ends at any time (∇ · ω = 0). Although Morton is dealing with viscous diffusion, a similar process can occur with subgrid-scale turbulence. We cannot observe what is happening locally with the vortex lines at the unresolved scales, thus when two oppositely directed lines come very close together, the surgery may be performed on our “smooth lines.” The likelihood of cross-diffusion of vortex lines altering our simple concept of their configuration increases with time after the rings of baroclinic vorticity are gener-
ated; as time increases, there is a greater likelihood for having a lifted arching vortex line find itself in close proximity to midlevel vortex lines that might have a different orientation. This effect might partly contribute to the greater tendency to observe prominent arches early in the tornadogenesis process.

5. Summary and conclusions

Pseudo-dual-Doppler radar observations were used to construct vortex lines within the low-level mesocyclone regions of six supercells (three nontornadic, three tornadic) near the time of maximum low-level rotation. The main findings and conclusions are summarized as follows:

1) Some vortex lines originating in the low-level vertical vorticity maximum extended to the storm summit, whereas others formed arches that connected the vertical vorticity maximum to the commonly observed region of anticyclonic vertical vorticity on the opposite flank of the hook echo of the supercell.

2) At least some vortex line arches emanate from the low-level mesocyclone in every case at every analysis time; vortex line arches are a robust trait of the sample of supercells studied herein.

3) The arching of the vortex lines and the orientation of the vorticity vector along the vortex line arches, compared to the orientation of the ambient (barotropic) vorticity, are strongly suggestive of baroclinic vorticity generation within the hook echo and associated rear-flank downdraft region of the supercells, and subsequent lifting of the baroclinically altered vortex lines by an updraft, rather than ambient vortex lines alone being tilted by either an updraft or downdraft to produce a low-level vertical vorticity maximum.7

Although the tornadogenesis problem is horribly nonlinear and is complicated by the presence of both barotropic and baroclinic vorticity, each likely varying significantly from case to case in terms of orientation, magnitude, distribution, etc., we believe that vortex line analysis can provide a beneficial perspective. We eagerly await future analyses in order to evaluate whether the findings of the present study extend to a larger sample of supercells. We also believe that a priority of future field experiments should be the collection of thermodynamic observations above the ground (perhaps even extending several kilometers above the surface) to better characterize the three-dimensional buoyancy field, given the apparent importance of baroclinic processes despite the general lack of strong cold pools beneath the most prolific tornadic storms. Finally, it also is interesting to ponder whether the dynamics shown by Davies-Jones (1996) and Weisman and Davis (1998) to lead to mesoscale vortices in larger-scale convective systems operate on a wide range of scales; that is, is it possible that the same fundamental dynamical process (baroclinic vortex lines generated in a cool downdraft and subsequently lifted by an updraft) can produce vortices that range in size and intensity from bookend vortices to near-ground mesocyclones to tornadoes?

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APPENDIX

Sensitivity of Vortex Lines to Smoothing and Grid Parameters

The sensitivity of the vortex line configurations to the smoothing and grid parameters was explored extensively. Figure A1 presents some examples, whereby the Barnes smoothing parameter $\kappa$ was doubled (to 1.22 km²), the horizontal grid spacing was doubled (to 800 m), and vorticity components were left unsmoothed prior to vortex line calculations (i.e., a one-step Leise filter was not applied to the vorticity components after deriving them from the three-dimensional wind retrieval). Not surprisingly, the finescale structure of the vortex lines is fairly sensitive to the smoothing and grid spacing; however, the qualitative characteristics of the vortex lines (e.g., whether vortex lines form loops or arches) are fairly robust.
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Fig. A1. Three-dimensional perspective of vortex lines at 0034:39–0041:15 UTC 13 May 1995 for a variety of smoothing and grid parameters. Equivalent radar reflectivity factor (dBZ; shaded) and vertical vorticity (contours 10−2 s−1 contour interval; the zero contour is suppressed and negative contours are dashed) at 1.0 km AGL also are plotted: (a) κ = 0.61 km², 400-m horizontal grid spacing, vorticity components smoothed with one-step Leise filter (as in Fig. 2c); (b) κ = 0.61 km², 400-m horizontal grid spacing, vorticity components received no additional smoothing prior to vortex line calculations; (c) κ = 0.61 km², 800-m horizontal grid spacing, vorticity components smoothed with one-step Leise filter; (d) κ = 1.22 km², 400-m horizontal grid spacing, vorticity components smoothed with one-step Leise filter.
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