

## Comments on "Initiation and Evolution of Updraft Rotation within an Incipient Supercell Thunderstorm"

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Brown (1992) concludes from Doppler radar observations that the origin of midlevel updraft rotation in an "incipient supercell" thunderstorm (the Agawam storm) was not low-level storm-relative streamwise vorticity in the environment, as in the now widely accepted theory espoused by Browning and Landry (1963) and Barnes (1970) from observational evidence, and by Rotunno (1981), Lilly (1982, 1986b), Davies-Jones (1984), and Rotunno and Klemp (1985) from theoretical analyses and numerical modeling results. Brown proposes, instead, that the middle-altitude vertical vorticity couplet was the "source" of vorticity, as first suggested by Fujita and Grandoso (1968). Even though Brown acknowledges us for constructive critiques, we still disagree with his conclusions and present a different interpretation of his results below. Our comments concern theoretical objections to Brown's hypothesis as well as defense of the streamwise vorticity mechanism.

First, we examine the Brown mechanism in the light of vorticity dynamics. The origin of the midlevel vorticity couplet, barely discussed in Brown's paper, must be explained before Brown's theory can be considered complete. It is entirely feasible that the couplet is produced by tilting of low-level horizontal vorticity, in which case the source region of vorticity for midlevel updraft rotation is near the ground, not at midlevels as claimed. Brown says only that the couplet is produced by "interactions between a strong updraft and environmental flow." However, he cites Fujita and Grandoso, who state clearly that the vortices form in the wake of the updraft and imply that the updraft acts as an obstacle to the midlevel environmental flow, and Brown himself (1989) invokes obstacle flow in a conference paper about the Agawam storm.

But there is a considerable body of evidence that the obstacle-flow analogy is not useful. Based on numerical model results, Rotunno and Klemp (1982) showed that

at midlevels the updraft is a rather porous obstacle and that the pressure gradient across the updraft is in the direction of the environmental shear vector rather than in the direction of the storm-relative winds as the obstacle-flow model predicts. Similarly, they found that the vortices were aligned more nearly perpendicular to the shear vector (i.e., parallel to the environmental vorticity vector) than to the storm-relative wind. Using an analytical Beltrami model of a rotating updraft, Davies-Jones (1985) showed that the obstacle analogy predicts the direction of the pressure gradient correctly only near the equilibrium level where the flow resembles a source in a uniform stream.

When there is an obstacle in some sense, one can argue that it is not the updraft itself, but the "mountain" or plume of undiluted air rising out of the boundary layer. At midlevels, plumes of air with high  $\theta_E$  values in their cores, indicative of undiluted ascent from low levels, have been observed in severe storms (e.g., Davies-Jones 1974). The midlevel environmental air must flow around these undiluted cores because they would not exist otherwise. The thermal plume and updraft are not completely coincident because the plume is a manifestation of vertical displacement, the Lagrangian integral of vertical velocity. Owing to upward perturbation pressure gradient forces on the storm-relative upwind side of the plume, the plume generally is displaced downstream from the updraft maximum by perhaps as much as 2–3 km (Sinclair 1973; Davies-Jones 1984; Weisman and Klemp 1984; Brooks and Wilhelmson 1993).

The fact that the approaching midlevel environmental winds divide and go around part of the storm implies the formation of a wake in a real fluid. In the original analog of flow around a solid cylinder, vorticity is generated at and diffuses away from the rigid boundaries. At Reynolds numbers less than 60, a stationary symmetric vortex couplet forms in the lee of the cylinder as a result of boundary-layer separation. In the somewhat more realistic analog of a turbulent jet discharged upward into a crossflow, laboratory experiments and numerical simulations (Sykes et al. 1986

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and references therein) reveal a similar vortex pair at low levels where the jet is still quasi-erect and an effective obstacle to the crossflow. Sykes et al. attribute these vortices to the shedding and subsequent vertical stretching of vertical vorticity associated with the lateral shear between the jet and free stream as the flow "separates" behind the jet. However, this does not explain how vertical vorticity is actually produced because the crossflow-obstacle interface is no longer a solid boundary. Moreover, Coelho and Hunt (1989) found that "the external flow around a strong jet is, to a first approximation, potential flow around a circular cylinder with suction, caused by the entrainment into the jet; the diffusion of vorticity into the wake is weak and therefore the jet does not act on the external flow like a solid bluff body." By deduction, the vertical vorticity must stem ultimately from tilting of horizontal vortex rings that are emitted continuously from the jet source (as concluded also by Coelho and Hunt 1989; and Higuera and Martinez 1993). The vorticity cannot originate elsewhere because the crossflow is irrotational and the lower boundary is stress free in the simulations. In thunderstorms, there are of course no jet sources, but there are instead buoyancy forces that generate positive azimuthal vorticity around warm plumes. Initially irrotational air streaming by a plume on its right (left) side would acquire streamwise (antistreamwise) vorticity baroclinically, and cyclonic (anticyclonic) vorticity through tilting if it subsequently rose in secondary updrafts on the downwind flanks of the plume. Thus, the vortices could form as a result of *tilting* of midlevel baroclinically generated vorticity, but they would not precede the downwind updrafts as in part of Brown's theory. However, we believe for reasons discussed below that the vortex couplet originates mostly from the tilting of low-level environmental vorticity.

We continue evaluating Brown's theory by examining entrainment effects in more detail. Since the vortices form in a mixture of ambient low- $\theta_E$  air that is flowing around the obstacle and of air shed from the edge of the updraft, they must consist of fairly low- $\theta_E$  air. For a new updraft to acquire rotation by growing through one of these vortices, it must entrain this air, a turbulent mixing process that dilutes both the updraft's buoyancy and the vortex's vertical vorticity. The midlevel vertical vorticity is unlikely to be amplified much subsequent to entrainment unless the process occurs at 3–4 km because (i) vertical vorticity is being advected rapidly upward, (ii) vertical stretching of vortex tubes occurs only below the updraft's level of nondivergence, which is at 5–6 km, and (iii) the "obstacle effect" is naturally absent in the storm's inflow layer (roughly the lowest 2–3 km). Moreover, updraft rotation by the entrainment mechanism cannot be sustained because as soon as the new updraft grows through a lee vortex, it becomes part of the overall obstacle and the vortex must migrate to its flanks. Thus, the updraft's supply of vertical vorticity is shut off

quickly, and the entrained vorticity-rich air rises rapidly to high levels in the head of the updraft.

Furthermore, the same entrainment mechanism cannot apply to the left-flank, anticyclonic updrafts. Owing to the rightward propagation of the overall storm, the rotation of these updrafts changes from cyclonic to anticyclonic as they progress from the right to the left side of the storm. Since the left-flank updraft is the oldest of the three coexisting updrafts, it does not grow through the anticyclonic vortex shed from the central updraft/obstacle. Instead, it must acquire its anticyclonic rotation by entraining through its sides anticyclonic vorticity shed from the left flank of the central updraft. Unlike the central updraft, the left-flank updraft cannot obstruct the flow much; otherwise, the anticyclonic vortex would form in the lee of the compound obstacle composed of the central and left-flank updrafts. Thus, the mechanism for left-flank anticyclonic rotation depends on the nonporosity of the central updraft and the porosity of the left one. One might argue that the anticyclonic updrafts should be more porous than the other ones because they are generally weaker. However, updraft U0 during most of its anticyclonic phase is as strong as updraft U2 ever gets in its entire life (see Brown's Fig. 9). Clearly, Brown's theory is incomplete without some consistent explanation of why and when updrafts stop behaving to the environmental flow as obstacles and start behaving quite differently as entraining jets.

We raise two other issues that cast further doubt on Brown's model. First, to explain the supposed lack of cyclonic rotation in updraft U1 even when it was the right-flank updraft, Brown surmises that, prior to data collection, the location of new updraft formation was on the right-rear flank of the previous updraft instead of on the right-forward flank as observed later. This places U0 in the U1 anticyclonic lee vortex instead of U1 in the U0 cyclonic lee vortex. However, there is no data to confirm that the location of new updraft formation shifted or even that U0 formed before U1 (the storm had not commenced its propagation to the right of the mean wind) or that U1 did not rotate early in its life. Second, flow around a cylinder depends on rotation (if any) of the cylinder. Thus, there should be some right-left asymmetry in the positions of the wake vortices when the central (blocking) updraft is itself rotating significantly (as is the case with U4 after 1538 when the midlevel storm-relative winds and mesocyclonic winds are comparable). No such asymmetry is evident in Brown's Figs. 8 and 12.

We now leave the hypothesis of obstacle flow and midlevel source regions of vorticity, and look to tilting of low-level vorticity for the origins of updraft rotation. The hodographs for Brown's case indicate that significant environmental vorticity is confined either to the lowest 2–3 km or to above 7 km. (The latter is obviously too high to be a source region for midlevel updraft rotation.) The presence of strong low-level shear and near absence of environmental vorticity in the 3–

7-km layer strongly suggests that the middle-altitude vorticity couplet originates from the thermal plume drawing up loops of initially horizontal vortex tubes from low levels. In fact, the formation of a midlevel vortex pair by this mechanism is inevitable whenever an updraft grows up through a significant low-level shear layer. At midlevels, the axis of the thermal plume is slightly downstream (perhaps as much as 2–3 km) from that of the updraft. Thus, the vortices, which straddle the thermal plume, could form up to 3 km downstream of the updraft, as also predicted for different reasons by the obstacle model and observed in the Agawam storm. Note that our mechanism places the vortices in buoyant air, which should be subject to considerable vertical stretching as it accelerates upwards to midlevels. When the vortex pair is transverse to the midlevel storm-relative flow as in the Agawam storm, it acts like an obstacle by translating slower than the ambient wind (owing to the velocity each vortex induces on the other) and diverting the ambient flow around the plume (Eagleman and Lin 1977). Therefore, the vortex pair may cause the “obstacle,” instead of vice versa.

When the low-level environmental vorticity has a significant streamwise component (i.e., one in the direction of the storm-relative winds), linear and semi-linear theories (Davies-Jones 1984; Rotunno and Klemp 1985) predict that an isolated updraft will have net cyclonic rotation (i.e., a positive correlation between vertical velocity and vertical vorticity). In the idealized limits of purely streamwise vorticity at every level and no buoyancy, an exact Beltrami solution of the Euler equations demonstrates that vertical vorticity and vertical velocity become perfectly correlated (Lilly 1982; Davies-Jones 1984, 1985). Thus, tilting of environmental streamwise vorticity causes an updraft to rotate strongly at midlevels, but only weakly at low levels. On the other hand, if the vorticity is purely crosswise, then the updraft should have anticyclonic vorticity on its left side (looking downshear) and cyclonic vorticity on its right side with no net rotation overall. In comparing theoretical predictions with observations, it should be recalled that the theories treat an isolated updraft, whereas the Agawam storm at any one time had three closely spaced updrafts, which at low levels probably overlapped to form one large updraft region with embedded maxima. Consequently, the updrafts have to be regarded as a group, rather than in isolation, because the midlevel rotational characteristics of the storm are determined mainly by the deformed configuration of initially horizontal vortex tubes that originate from low levels, where the updrafts tend to overlap. The updrafts are not isolated from one another because there are no large gaps between updrafts where the low-level vortex lines are unperturbed. Thus, the theories are relevant to the rotations of three adjacent updrafts only if the left-flank, central, and right-flank updrafts are thought of as the left, middle, and right side of a single large updraft. Proceeding on

this assumption and letting  $A$ ,  $N$ , and  $C$  denote anticyclonic, no, and cyclonic rotation, respectively, then the rotation of an updraft triad should be, from left to right,  $ANC$ , for purely crosswise environmental vorticity, and  $ACC$  when crosswise and streamwise components are roughly equal. Note that individual updrafts change from cyclonic to anticyclonic rotation as the overall updraft propagates to the right and they move across the overall updraft from right to left during their lives.

Based on “the observation that a strong updraft (U1) was in existence for tens of minutes in the presence of low-altitude streamwise vorticity and the updraft did not rotate,” Brown concludes “that the conventional hypothesis—that updraft rotation is due to the vertical tilting of low-altitude streamwise horizontal vorticity by the updraft—was not operative in the Agawam storm.” Brown’s Fig. 8 reveals that during the time that it was not rotating, U1 was in the center of a triad (not on the right flank as stated on p. 1999) with anticyclonic updraft U0 on its left and an unlabeled cyclonic updraft on its right (so presumably the overall updraft also had little net rotation). Prior to data collection, U1 may have rotated cyclonically when presumably it was on the right flank of the storm, and later it rotated anticyclonically after it became the left-flank updraft. As discussed above,  $ANC$ -type rotation suggests that the low-level environmental vorticity was mainly crosswise at this time, and that the hodographs used by Brown may not represent well the shear in the storm’s inflow (see below). Even with these hodographs, this case is still an extremely weak one to choose as a counterexample to refute the streamwise vorticity theory, since Brown admits that “conditions are borderline for the formation of a rotating updraft (mesocyclone) within the storm,” because of the marginal directional shear, mean storm-relative wind and storm-relative helicity (the integral over height of streamwise vorticity times the storm-relative wind) over the lowest 2.5 km. According to our calculations, the bulk Richardson numbers at Fort Sill and Norman are also marginal for supercell formation (37 and 39, respectively, using Brown’s CAPE values, in contrast to the 14 and 18 listed by Brown). Even though observed vorticity values did exceed the threshold value for mesocyclones from time to time, Brown’s Fig. 10 indicates that only updraft U4 rotated with enough intensity (vorticity greater than  $10^{-2} \text{ s}^{-1}$ ) over a large enough time (half a period of revolution) and depth (3 km) to be considered a borderline mesocyclone (Burgess 1976), and this occurred at 1542, just before the end of data collection at 1550. It is only at this late time that the Agawam storm conceivably could be regarded as an “incipient” supercell storm. The fact that “all of the subsequent (to U1) right-flank updrafts rotated cyclonically at middle altitudes” is not by itself “indicative of incipient supercell development” because this should occur also in organized multicell storms in westerly shear. The rotational characteristic that marks a su-

parcel is sustained strong correlation between vertical vorticity and vertical velocity over a significant depth of the overall updraft (Droegemeier et al. 1993).

Brown's argument depends critically on his composite hodograph accurately portraying the low-level ambient wind shear on the inflow side of the storm, despite uncertainties arising from the facts that neither sounding actually sampled the inflow and that the low-level winds in this case vary significantly over short distances and time intervals. The two hodographs used for the composite resemble each other superficially, but have some important differences at low levels. The Norman hodograph (ahead of the storm) does not deviate far from a straight line, with the initial storm motion vector lying only slightly to the right side. A basically straight hodograph explains why the two adjacent, but separate, initial echoes "behaved like a typical pair of splitting thunderstorms." The Fort Sill hodograph (behind the storm) is far more curved in the lowest 2 km and is more favorable for mesocyclone development based on greater storm-relative winds, streamwise vorticity, and helicity at low levels. Although not shown by Brown, there is a simultaneous hodograph at Elmore City (the southeastern station in Brown's Fig. 1) on the inflow (right) side of the storm at about the same distance (50 km) from the storm as

the other ones. This hodograph (Fig. 1) is significantly different from the others at low levels. It is even straighter than the Norman one, and shows practically zero storm-relative helicity for the Agawam storm and slightly negative helicity for the left-moving storm. However, the surface wind is stronger than observed at 1446 in the inflow closer to the storm (Fig. 1, Brown's Fig. 14). After modifying the Elmore City hodograph by replacing the surface wind with the mesonet network measurement, the 0–3-km storm-relative helicity is positive but still fairly small ( $80 \text{ m}^2 \text{ s}^{-2}$  before and  $100 \text{ m}^2 \text{ s}^{-2}$  after the storm moved to the right). This is consistent with Brown's Fig. 14, which shows storm-relative winds veering with height (i.e., positive streamwise vorticity) in the lowest 500 m of the inflow as it enters the storm. It might be argued that the 1500 Elmore City sounding does not represent the storm's inflow because it has a convective available potential energy (CAPE) of only  $1290 \text{ J kg}^{-1}$ . However, this CAPE is sufficient for a maximum vertical velocity of  $40 \text{ m s}^{-1}$ , which is only slightly less than U1's peak updraft speed (Brown's Fig. 9). This estimate is based on Brooks and Wilhelmson's (1993) finding that in numerically simulated storms the maximum vertical velocity is up to 80% of the parcel theory value, a result that is consistent with observational data (Davies-Jones

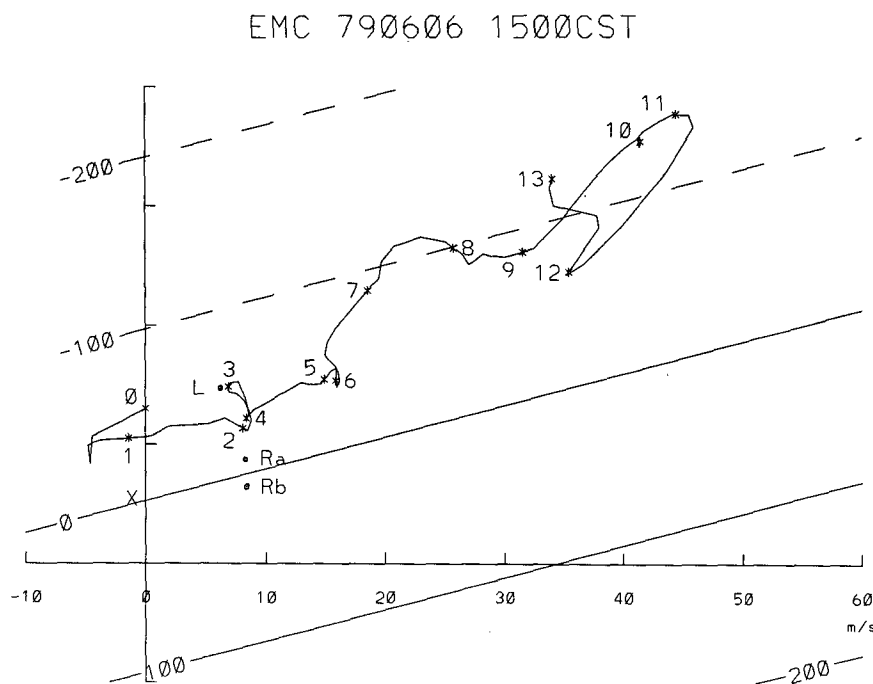


FIG. 1. Elmore City hodograph at 1500 CST. Tick marks along the  $u$  and  $v$  axes are spaced  $10 \text{ m s}^{-1}$  apart. Asterisks and accompanying numbers along curve mark height above ground level at 1-km intervals from 0 to 13 km. Dots represent the tips of storm motion vectors for the Agawam storm before (Ra) and after (Rb) it turned to the right and for the left-moving storm (L), as given in Brown (1992). The surface wind observation from a mesonet station in the storm inflow at 1446 is denoted by X. The straight lines are contours of storm-relative helicity as a function of storm motion (Davies-Jones et al. 1990). Contour lines are solid and dashed for nonnegative and negative helicity values, respectively, and the contour interval is  $100 \text{ m}^2 \text{ s}^{-2}$ .

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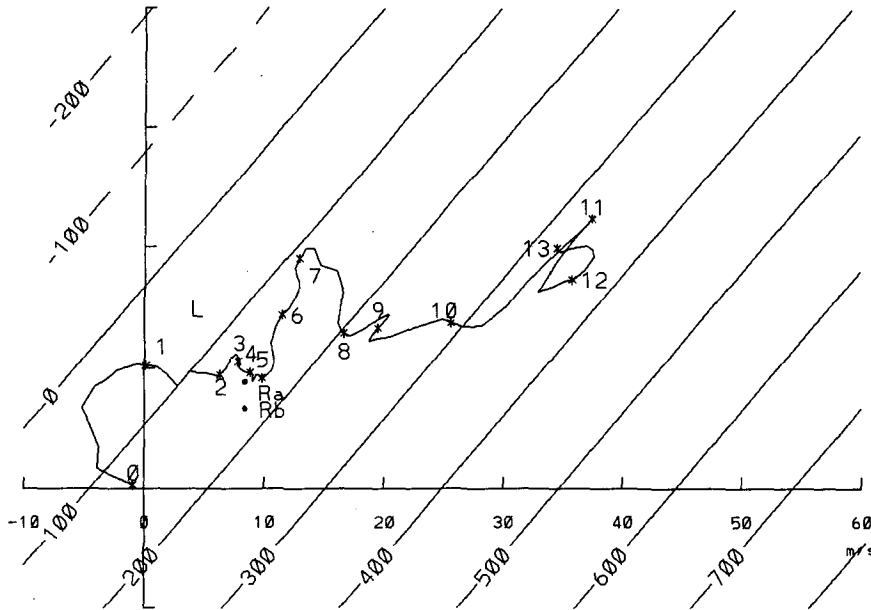


FIG. 2. Stroud hodograph at 1630 CST. Details as in Fig. 1.

1974). In summary, the available data do not support Brown's rejection, based on U1's lack of rotation, of the streamwise vorticity hypothesis because, of the three hodographs, only the one behind the storm is even marginally favorable for mesocyclone formation.

The following scenario offers one possible explanation, based on the tilting of low-level vorticity, for the behavior of the Agawam storm. Prior to 1500, the rotation of the Agawam storm is *ANC* in our notation, indicating that the overall updraft has little net rotation, perhaps due to mainly crosswise environmental vorticity entering the storm. This would be the case if the hodograph on the inflow side were nearly straight with storm motion almost on the hodograph, as at Elmora City. After 1500, the right edge of the storm begins propagating to the right as the cold pool expanded, and the rotation pattern changes to *ACC* with probable net cyclonic rotation of the overall updraft. The change in the motion of the right flank (about  $15^\circ$  to the right according to Brown's Fig. 8) increased the storm-relative winds and helicity slightly, but probably not enough to explain the borderline mesocyclone associated with U4 at 1542. The initial rotation of U4 is associated with its location on the right side of the overall updraft where vortex tubes are being tilted up to produce cyclonic vorticity. Why it continued to rotate cyclonically after it shifted to the center of the updraft troika is a matter of conjecture because of the paucity of data in the storm inflow. Perhaps the local hodograph became more curved at low levels. The low-level winds are quite variable in this case and do not have to change much to produce marginal conditions

for mesocyclone formation. This point is illustrated by the 1630 sounding at Stroud, which is about 100 km to the northeast of the storm. The hodograph (Fig. 2) has low-level curvature due to near-easterly winds close to the ground, streamwise vorticity in the lowest few hundred meters and a storm-relative helicity of  $180 \text{ m}^2 \text{ s}^{-2}$ , slightly above the  $150 \text{ m}^2 \text{ s}^{-2}$  threshold for mesocyclone formation suggested by Davies-Jones et al. (1990). Admittedly, the CAPE of this sounding is only  $630 \text{ J kg}^{-1}$ , but this can account for a maximum vertical velocity up to  $28 \text{ m s}^{-1}$ , which is only slightly lower than U4's peak updraft speed (see Brown's Fig. 9). Increasing hodograph curvature might also explain the storm's rightward propagation after 1500 (Rotunno and Klemp 1982). Since none of the data presented by Brown contradicts the above hypothetical version of events, his elimination of the streamwise vorticity mechanism is unjustified. Disproving the streamwise vorticity theory requires a far more definitive case, measurements of streamwise and crosswise vorticity in the air that actually enters the updraft, analysis of how the parcels that pass through the vortices acquire high values of vertical vorticity, and better quantification of updraft rotation by computing the correlation between vertical velocity and vertical vorticity.

Last, Brown is confused about the role of propagation in the streamwise vorticity theory. The steady-state Beltrami flow model of a rotating nonbuoyant updraft in a veering environmental wind field (Davies-Jones 1985) illustrates by example that "continuous [or any] propagation" is not essential for "the continuous flow of streamwise vorticity into the updraft."

We should note, however, that this special case is exceptional; in general, updraft propagation and rotation are closely linked (Rotunno and Klemp 1982). Brown states that "The continuous-propagation version [of the vertical vorticity hypothesis] assumes either that the nonrotating updraft migrates toward the cyclonic member of the couplet, or vice-versa, until they become collocated. The updraft then starts to rotate cyclonically as it entrains the ambient vertical vorticity (Heymtsfield 1978; Rotunno 1981; Weisman and Klemp 1982; Davies-Jones 1984; Rotunno and Klemp 1985; Lilly 1986a)." However, the updraft must be rotating already by the time that it becomes collocated with a vortex, and all the references cited invoke vertical vorticity production by the tilting term: that is, the horizontal vorticity hypothesis! "The concept of lateral migration of the updraft relative to the vertical-vorticity couplet" is admittedly complicated, but has been superseded by a more illuminating conceptual model involving uplifted isentropic surfaces and drawn-up loops of vortex tubes (Davies-Jones 1984). In this new conceptual model, it is evident that a new updraft on the right flank will rotate cyclonically on the whole. This is true regardless of whether the vorticity is streamwise or crosswise, provided that the new updraft is not completely detached from the existing region of uplift in the purely crosswise case. Therefore, tilting of horizontal vorticity still takes place, regardless of whether the propagation (if any) is discrete or continuous. This is reassuring since it is now well recognized that pure supercell storms in the classic sense (i.e., steady state, unicellular, continuously propagating) do not exist in nature and that the concept of continuous propagation is an idealization. Even storms that appear to be classic supercells on reflectivity displays are found, under closer scrutiny of fine-resolution Doppler velocity displays, to be evolving and propagating discretely through the periodic birth of a new and simultaneous decay of an old mesocyclone core (NOAA 1990, pp. 8–31).

While we remain open-minded concerning new theories of updraft rotation, we believe that any such theories should explain clearly the ultimate origins of the vorticity and should be defensible from a vorticity dynamics standpoint. Furthermore, the established paradigm for the origin of updraft rotation in *supercell* storms should not be discarded on the basis of *inconclusive* evidence from *one* storm that is at best an "incipient supercell."

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