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Documentation of a Rare Tornadic Left-Moving Supercell

MATTHEW J. BUNKERS
NOAA/NWS, Weather Forecast Office, Rapid City, SD

JOHN W. STOPPKOTTE
NOAA/NWS, Weather Forecast Office, North Platte, NE

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ABSTRACT

An F1 anticyclonic tornado (i.e., clockwise rotation in the Northern Hemisphere) was produced by an intense left-moving/anticyclonic supercell near Rushville, Nebraska, on 20 June 2006. This is only the fifth formally documented left-moving supercell that produced an anticyclonic tornado. The left-moving supercell exhibited an impressive hook echo, mesoanticyclone, and bounded weak-echo region at the time of tornado occurrence—rivaling those of its right-moving counterparts. Since tornadic left-moving supercells are extremely rare, and thus potentially difficult to recognize, this paper serves to document the radar characteristics and environmental conditions of this event.

1. Introduction

During the late afternoon and early evening of 20 June 2006, a moderate-lived (3 h; Bunkers et al. 2006) left-moving supercell affected northwestern Nebraska with large hail, damaging winds, and an anticyclonic tornado that destroyed one house. Although the tornado was only rated F1 and lasted less than one minute (NCDC 2006), the event is noteworthy because of the rarity of anticyclonic tornadoes, especially those associated with anticyclonic supercells (clockwise rotating in the Northern Hemisphere).

Anticyclonic tornadoes are generally found in, or near, one of three locations of a thunderstorm: (1) the hook echo region of an anticyclonic supercell, as in the present case, (2) an updraft—not necessarily supercellular—that ingests preexisting anticyclonic vorticity associated with wind shears along boundaries, such as gust fronts (e.g., Forbes and Wakimoto 1983; Wakimoto 1983), or (3) the anticyclonic shear side of a hook echo associated with a right-moving supercell (Fig. 1 herein; Fujita 1977; Brown and Knupp 1980; Fujita and Wakimoto 1982).

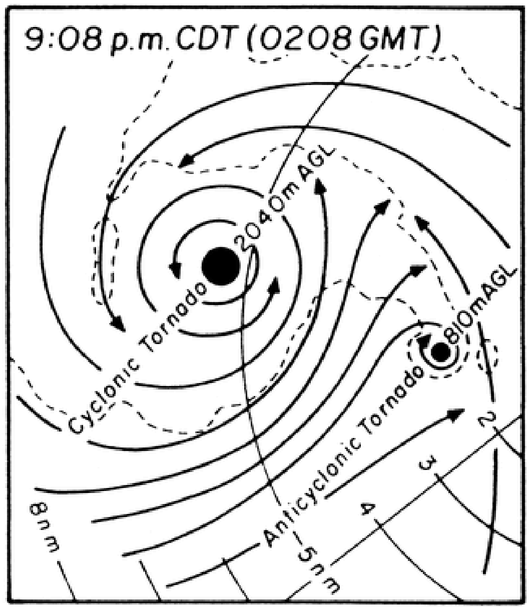

Figure 1: Radar-derived rendering of the Grand Island, NE, anticyclonic tornado of 0208 UTC 4 June 1980. The hook echo is indicated by the dashed line. [Adapted from Fujita (1981).]

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[*] *Corresponding author address:*
Dr. Matthew J. Bunkers, National Weather Service, 300 E. Signal Dr., Rapid City, SD 57701. E-mail: Matthew.Bunkers@noaa.gov

Location (3) may be the most common, and is typically 1–6 km away from the cyclonic tornado (Fig. 1).

Data from Brown and Meitín (1994) suggest 10% of left-moving storms[1] may be tornadic. Moreover, Wakimoto (1983) estimated the ratio of all anticyclonic tornadoes to all cyclonic tornadoes to be 1:700 (or 0.14%). Based on the authors' operational experience, it is estimated there are 1–5 tornadic left-moving supercells for every 100 left-moving supercells (i.e., on the order of 1%).

Only four other anticyclonic tornadoes—that were associated with left-moving supercells—have been formally documented in the literature (Harrold 1966; Hammond 1967; Monteverdi et al. 2001; Dostalek et al. 2004). All cases, except for the one reported by Harrold (1966), are supported in the NOAA publication *Storm Data*. A fifth such case, presented at a training course in Boulder, Colorado, in 2002, documented the 19 April 2002 anticyclonic tornado that occurred south of Lubbock, Texas. The authors reviewed the radar data and storm reports for this case, and concluded that the tornado was produced by a left-moving supercell.

Clearly there is limited information on tornadic left-moving supercells. Because of this, the primary goal of the present study is to add to the knowledge of these storms by documenting the 20 June 2006 tornadic left-moving supercell (hereafter referred to as the "Rushville supercell").

2. Radar characteristics

The Rushville supercell was sampled by the Weather Surveillance Radar-1988 Doppler (WSR-88D) radars at New Underwood, South Dakota (KUDX), and Thedford, Nebraska (KLNX). Furthermore, the Cheyenne, Wyoming (KCYS), radar captured the splitting process during the early stages of the storm west of Alliance, Nebraska. The right-moving member dissipated within 60 min of the split; however, the Rushville supercell persisted (i.e., exhibited clockwise rotation) for 3 h after the split.

The Rushville supercell maintained a "strong" (Stumpf et al. 1998) mesoanticyclone for 80–90% of its 3-h lifetime (based on manual calculations), although the circulation decreased in size during its final hour. From 2223–2341 UTC, the KLNX radar indicated the azimuthal shear (over a horizontal distance of about 10 km or 5.4 n mi) remained near or above 46 m s^{-1} (90 kts). Maximum intensity of the mesoanticyclone was observed at 2312 UTC (Fig. 2), with a peak velocity difference between inbound and outbound values of 67.1 m s^{-1} (130.5 kts).

When the tornado occurred 2.8 km (1.5 n mi) south of Rushville at approximately 2309 UTC, the anticyclonic circulation was about 159 km (86 n mi) from KUDX and 176 km (95 n mi) from KLNX. Owing to the relatively poor viewing aspect of the KLNX radar (i.e., greater distance from the storm and attenuation through the main echo), the tornadic side—and northern flank—of the storm was best sampled by the KUDX radar. Indeed, the most noteworthy feature of the Rushville supercell was its "impressive" hook echo (Fig. 3, upper-left panel), especially since left-moving supercells rarely produce them. The hook echo first appeared 6 min prior to tornado formation (2303 UTC, not shown), and became indistinct 15 min after tornado occurrence (2324 UTC). The hook echo was also discernable from the KLNX radar (2307–2321 UTC; e.g., Fig. 4), but was not as clearly defined as in Fig. 3, consistent with the poorer viewing aspect.

Identification of hook echoes for left-moving supercells can be complicated by the "mirror image" nature of these storms (relative to right-moving supercells). Therefore, the upper-left panels of Figs. 3 and 4 were flipped [i.e., rotated about a horizontal axis; also see Edwards and Hodanish (2006)] so a comparison could be made to the conceptual model for right-moving supercells. Based on this new perspective, the hook echo easily is recognizable on the "southern" flank of the storm (Fig. 5), and is comparable to the classic hook echoes associated with right-moving supercells (Lemon and Doswell 1979). The tornado occurred near the tip of the hook, as would be expected with traditional hook echoes. The challenge the operational forecaster faces is that currently available software does not flip the images in real-time, and thus one has to be quick to recognize (e.g., mentally flip) the anomalous signatures present in Figs. 3 and 4 when left-moving supercells are a concern.

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[1] Brown and Meitín (1994) did not specify whether all of these storms were supercells. Furthermore, their sample was relatively small and not collected in a systematic way.

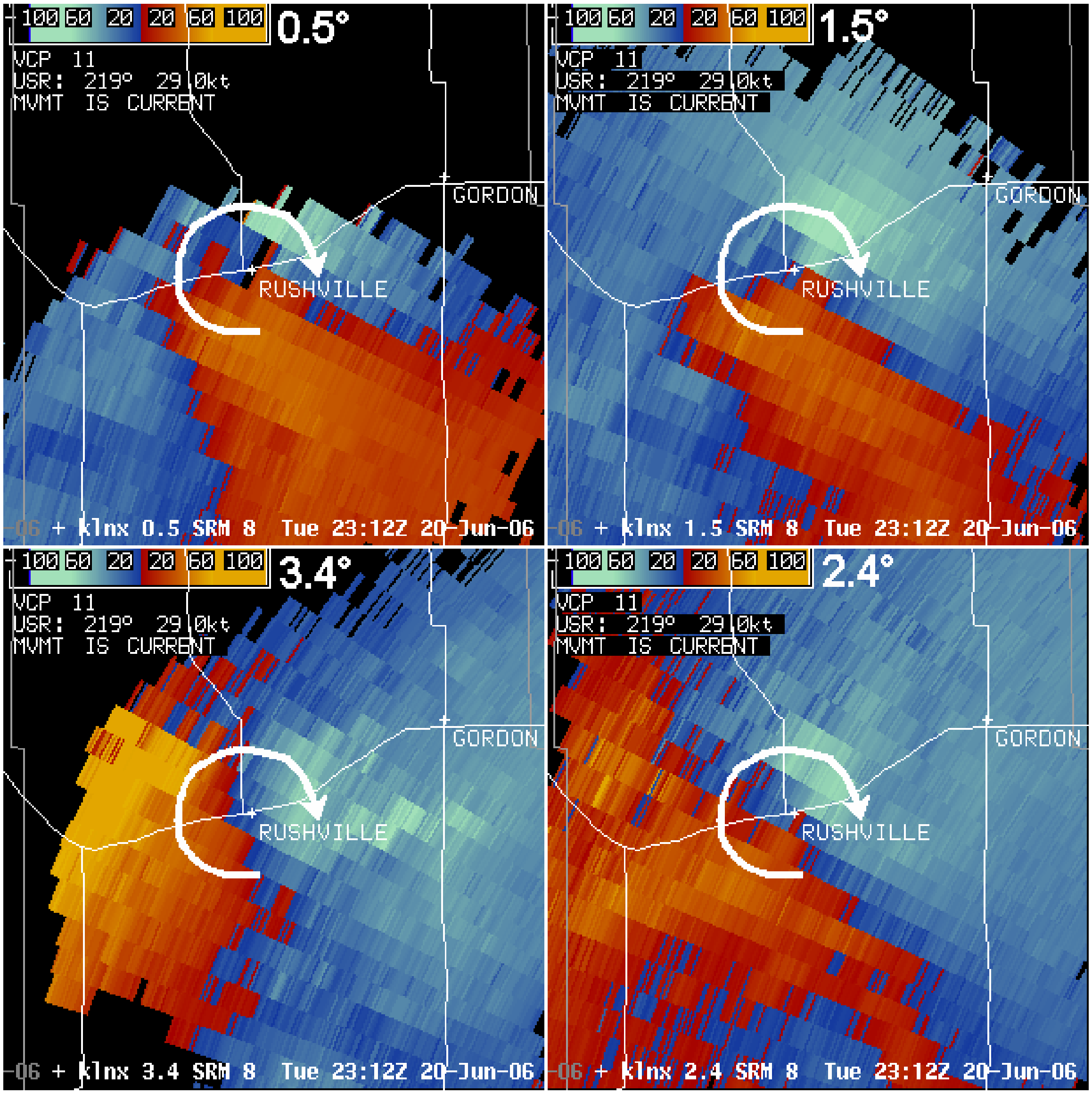


Figure 2: Lowest four storm-relative velocity slices as annotated (clockwise from upper left) from KLNX at 2312 UTC, 20 June 2006 (3 min after the F1 tornado near Rushville, NE). The white circular arrows indicate the sense of rotation; anticyclonic divergence is evident at the 3.4° elevation slice (about 12 km AGL). Town names and US highways are white and county boundaries are gray. KLNX is located 176 km east-southeast of Rushville.

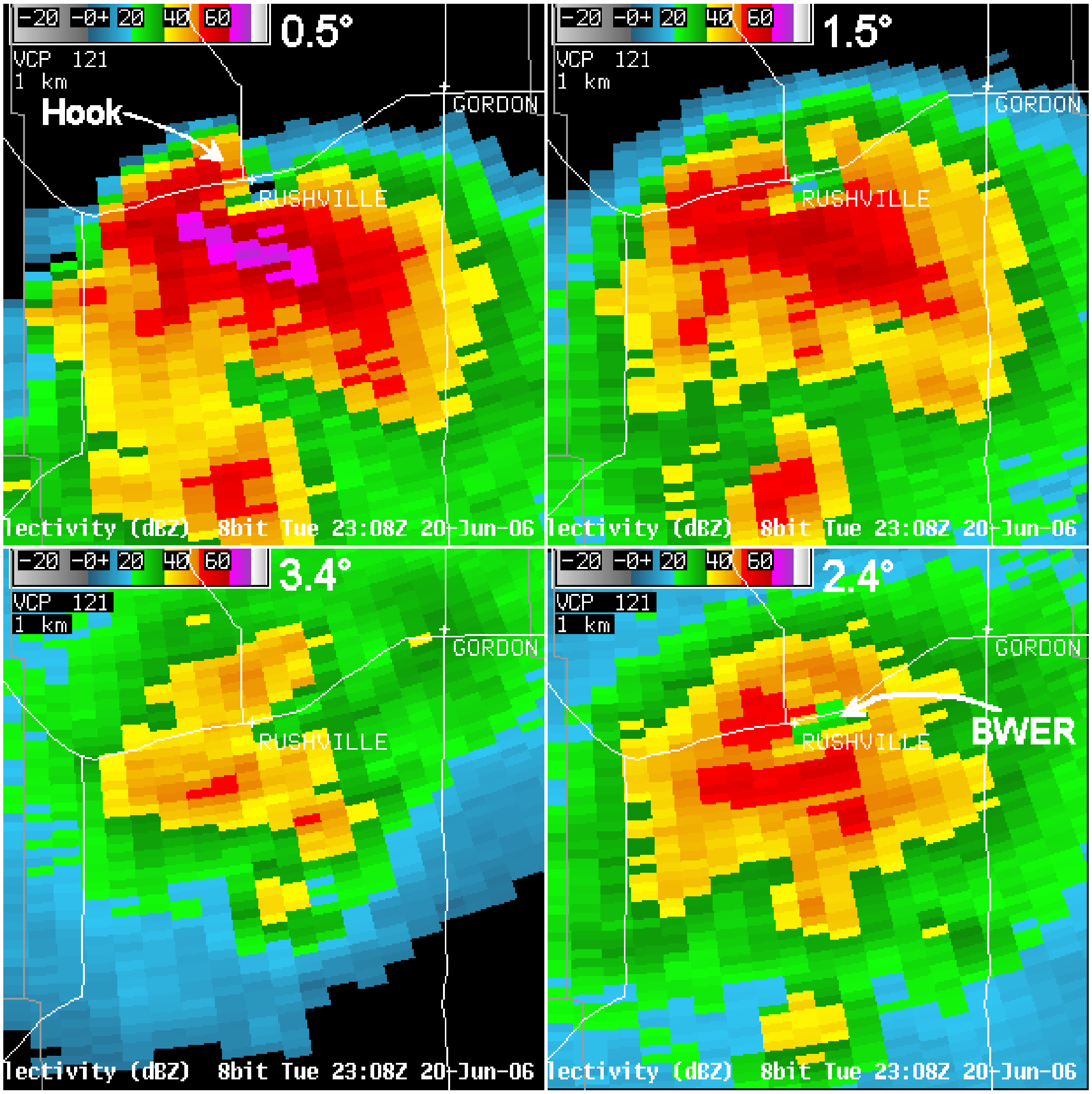


Figure 3: Lowest four reflectivity slices as annotated (clockwise from upper left) from KUDX at 2308 UTC, 20 June 2006 (1 min prior to the F1 tornado near Rushville, NE), mapping as in Fig. 2. The echo at the bottom of the 0.5° image is a secondary storm (and not indicative of a "V-notch"). KUDX is located 159 km north-northwest of Rushville.

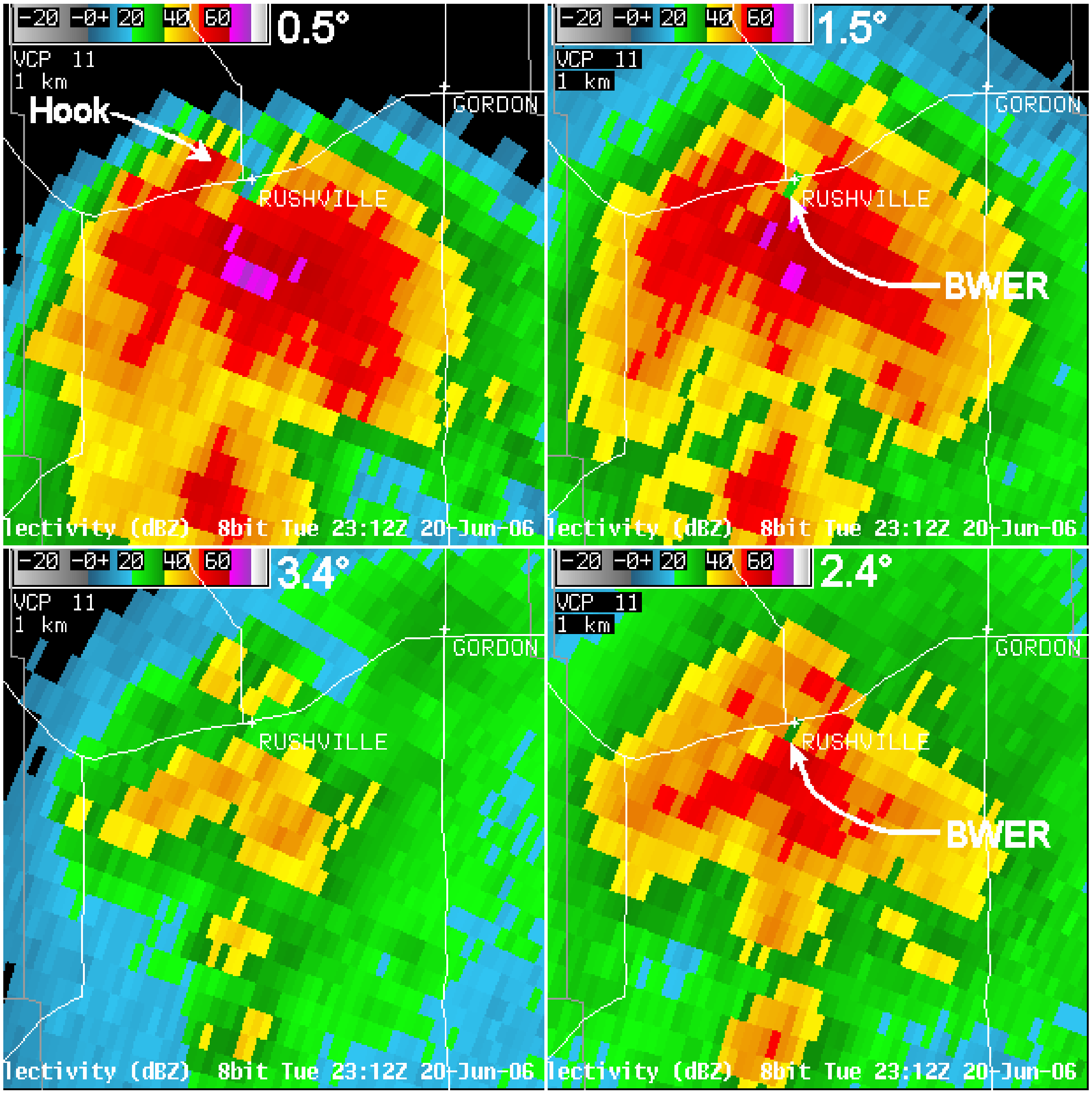


Figure 4: Same as Fig. 3 except for KLNX at 2312 UTC, 20 June 2006 (3 min after the F1 tornado near Rushville, NE). KLNX is located 176 km east-southeast of Rushville.

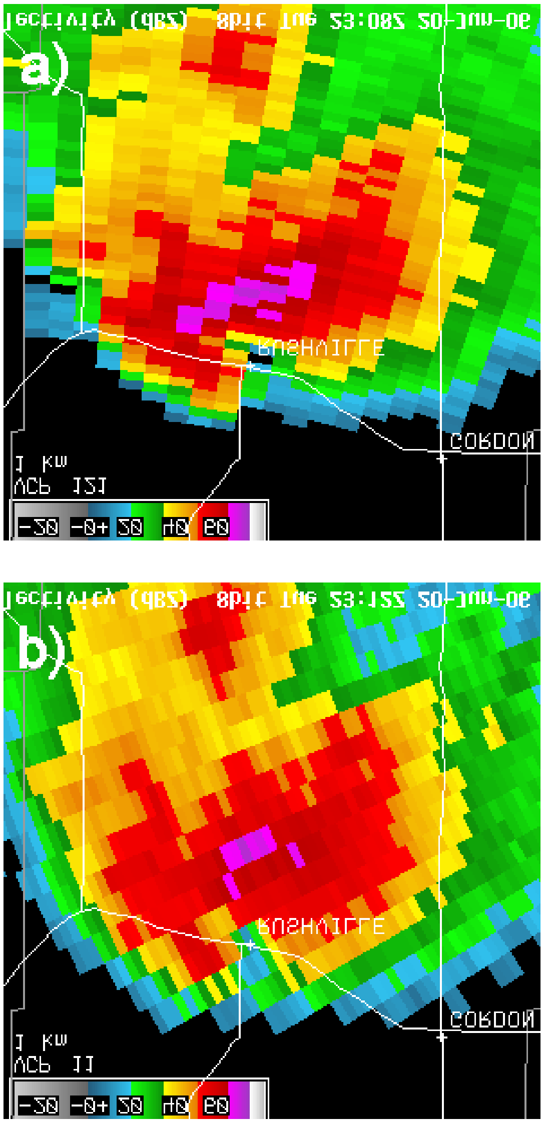


Figure 5: Flipped 0.5° reflectivity images from (a) KUDX at 2308 UTC, 20 June 2006 (1 min prior to the F1 tornado near Rushville) and (b) KLNX at 2312 UTC, 20 June 2006 (3 min after the F1 tornado near Rushville).

The height of the 0.5° KUDX radar beam over Rushville is 2.68 km AGL (8800 feet)—assuming standard atmospheric conditions. The 0.5° KLNX radar beam height is even higher (3.14 km or 10300 ft). Even though a hook echo was discernable by the two radars at this distance, the low-level circulation cannot be observed at this range (i.e., approximately the lowest 3 km of the Rushville supercell was not sampled). Nevertheless, the maximum 0.5° "gate-to-gate" velocity difference was still 56 m s^{-1} (109 kts) from the KLNX radar 2 min prior to tornado occurrence, and was 48 m s^{-1} (93 kts) 3 min after tornado time (Fig. 2, upper-left panel).

A well-defined bounded weak-echo region (BWER) also was clearly identifiable from the KUDX radar for approximately the same duration as the hook echo, with a maximum areal extent of ~8.5 km occurring just prior to the tornado (Fig. 3, lower-right panel). In addition, the midlevel 35-dBZ echo overhang extended 11 km (6 n mi) north of the low-level reflectivity gradient. The BWER was also evident from the KLNX radar for a similar duration, although its extent was not as broad as that seen by the KUDX radar (cf. Figs. 3 and 4).

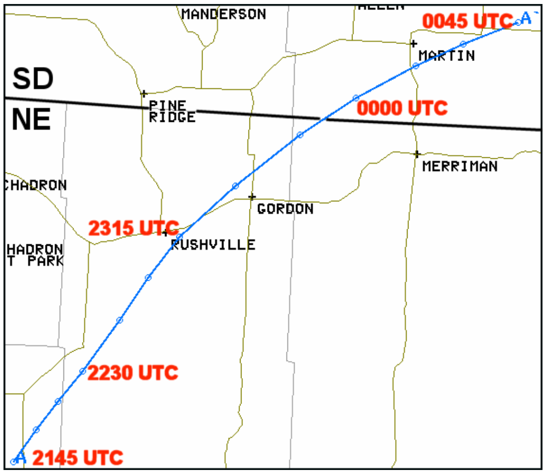


Figure 6: Track (blue) of the Rushville supercell from its incipient *rotation* to its demise (2145–0045 UTC). Small circles are located at 45-min intervals and are based on the echo centroid.

The Rushville supercell displayed four different stages of motion (Fig. 6), somewhat analogous to the nontornadic left-moving supercell studied by Edwards and Hodanish (2006). During the organizing stage (2145–2230 UTC), the Rushville supercell's echo centroid moved from 214° at 11.3 m s^{-1} (22 kts), well to the left of the vertical wind shear (as shown later in Fig. 10 and discussed in section 3e). During the second stage (2230–2315 UTC)—when the anticyclonic rotation was the most intense—the motion was from 213° at 14.9 m s^{-1} (29 kts). The third stage (2315–0000 UTC) corresponded with further storm acceleration (225° at 21.1 m s^{-1} or 41 kts), as well as BWER collapse shortly after the Rushville tornado. This stage also coincided with the most damaging straight-line winds and the largest hail, which likely were associated with a downburst after BWER collapse (based on a damage survey). The acceleration of the storm's gust front just before 2315 UTC may have disrupted the lifetime of the tornado, or perhaps precluded the formation of additional tornadoes. During the final stage of storm motion (0000–0045 UTC), the supercell tracked more eastward (243° at 16.5 m s^{-1} or 32 kts) and showed the smallest deviation from the shear vector (although still significant).

The Rushville supercell differs from other documented nontornadic left-moving supercells (e.g., Brown and Meitín 1994; Nielsen-Gammon and Read 1995; Grasso and Hilgendorf 2001; Lindsey and Bunkers 2005; Edwards and Hodanish 2006) most noticeably by way of its hook echo and BWER. Many of the nontornadic left-moving supercells noted in previous studies produced large hail (as in the present case), but hook echoes and/or BWERs were not identified. Sometimes "false hooks" have been observed with left-moving storms [i.e., cyclonic hook echoes that are on the "wrong" flank of the left-moving storm; Houze et al. (1993)], but this was not the case with the Rushville supercell. In addition, many of the documented left-moving supercells [e.g., see the references in Bunkers (2002)] generally have been smaller, less intense, and shorter lived than the Rushville supercell.

Documented studies of tornadic left-moving supercells show both similarities and differences from the present study. The tornadic left-moving supercell presented in Monteverdi et al. (2001) was relatively small, but it did have a pendant echo that suggested tornadic potential. Conversely, Dostalek et al. (2004) studied a tornadic left-moving supercell that was of moderate size and strength, but it did not possess a hook echo; instead, tornadogenesis appeared to be more strongly associated with local boundary interactions than in the present case. Lastly, the tornadic left-moving supercell from Sills et al. (2004) closely resembles the Rushville supercell; however, this occurred in Australia where left-movers are equivalent to right-movers in the Northern Hemisphere (i.e., both are cyclonic).

Synthesizing these results, the Rushville supercell was especially intense in terms of the rotational velocities and reflectivity signatures (e.g., BWER and peak reflectivity of 73 dBZ). The tornado developed in a fashion analogous to what commonly occurs with right-moving tornadic supercells, and occurred in association with a "classic" hook echo that arguably was best viewed by flipping the reflectivity images. Interestingly, the most damaging weather was the hail and straight-line winds (which occurred shortly after the BWER collapsed), and not the tornado.

3. Environmental conditions

The main focus of the environmental analysis is on the mesoscale and storm-scale conditions pertaining to the Rushville supercell. However, a composite chart and brief description of the synoptic scale around the time of the tornado is given below. More details can be gleaned, for example, from the Storm Prediction Center (SPC) upper-air archive of mandatory charts at: http://www.spc.noaa.gov/obswx/maps/

a. Synoptic scale

Flow over Nebraska at 250–300 hPa was zonal around 23 m s^{-1} (45 kts); a jet maximum was located across Montana and North Dakota (Fig. 7). At 500 hPa, a shortwave trough was identified upstream of the Rushville area over central Wyoming. At the surface, a nearly stationary front was located over far southeastern Wyoming and eastern Colorado, and a secondary cold front had moved south through most of

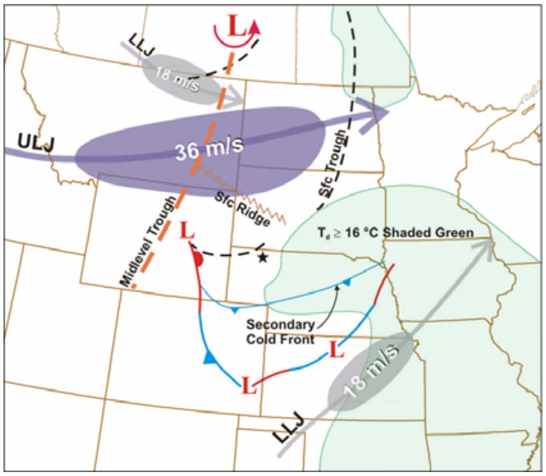


Figure 7: Composite synoptic chart valid around the time of the Rushville tornado. Rushville is indicated by the black star. "ULJ" refers to the upper-level jet axis, "LLJ" refers to the low-level jet axes, and the upper low is denoted with a semicircular arrow.

western Nebraska (Fig. 7). This setup was resulting in cold advection in the low levels across western Nebraska—similar to the case in Edwards and Hodanish (2006). This pattern was also producing upslope flow across western and central Nebraska, which was consequently advecting larger amounts of moisture into the area. The combination of steep 700–500-hPa lapse rates (~8 °C km^{-1}) and surface dewpoints of 12–16°C (53–63°F) resulted in surface-based CAPE of 1500–2000 J kg^{-1} in the vicinity of Rushville (not shown), around the time of the tornado.

b. Mesoscale to storm scale

Previous research has suggested that tornadic left-moving supercells have interacted with, or at least been associated with, mesoscale boundaries (Monteverdi et al. 2001; Dostalek et al. 2004). The importance of boundaries relative to tornadic *right-moving* supercells has already been well established (Markowski et al. 1998). A mesoscale boundary was also present near the Rushville supercell (Fig. 8; also see Fig. 7), and this *may* have played an important role in storm intensity and tornado occurrence.

Subjective analyses indicated that a weak trough was located in extreme northwestern Nebraska at 2200 UTC (Fig. 8), extending just north of Rushville. A relatively drier air mass was along the western extent of this trough (and across the western Nebraska panhandle). A thunderstorm outflow boundary had spread northeastward just southwest of the Rushville area by 2200 UTC (Fig. 8), placing that region in a zone of confluence between the trough to the north and this approaching outflow feature.

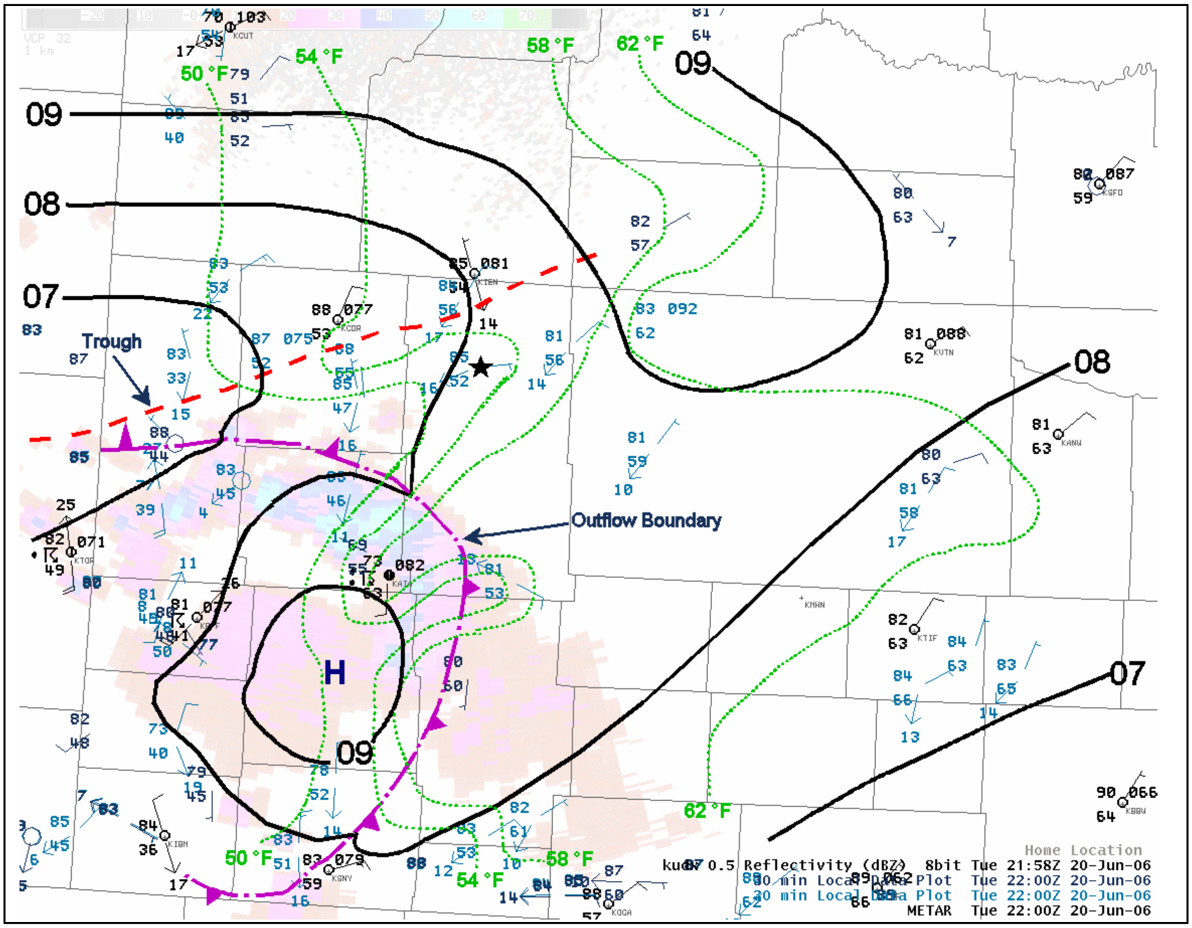


Figure 8: Subjective subsynoptic surface analysis at 2200 UTC, 20 June 2006. Conventional station plots have been used with temperatures and dewpoints in °F, and full wind barbs (half wind barbs) representing 10 kts (5 kts). A faded reflectivity image (in the background) was used to help identify the thunderstorm outflow boundary. Rushville is indicated by the black star.

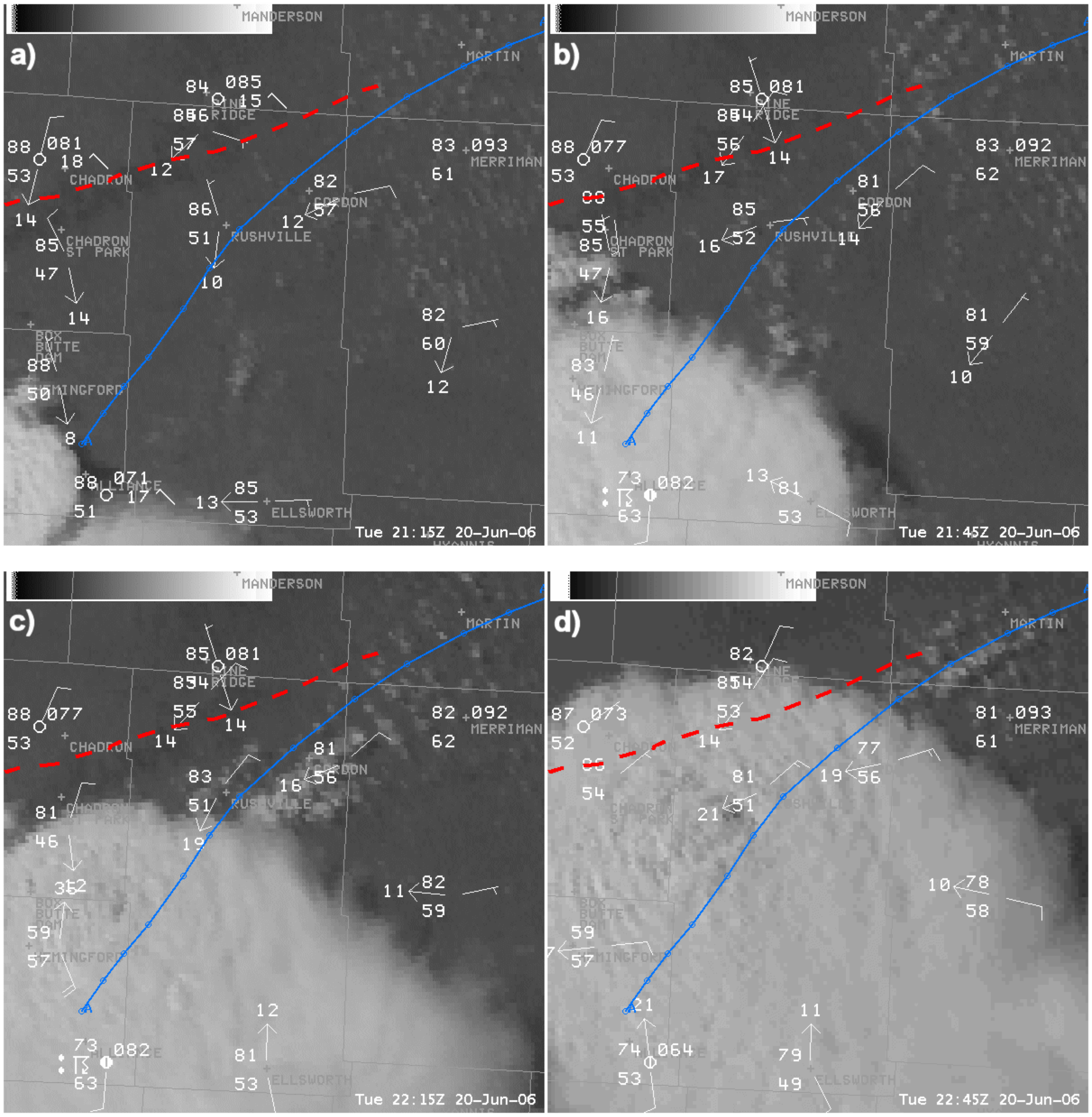


Figure 9: Visible satellite images from 20 June 2006 at (a) 2115 UTC, (b) 2145 UTC, (c) 2215 UTC, and (d) 2245 UTC. The 30-min mesonetwork observations (white) from NE are valid 15-min after the satellite valid times. Conventional station plots have been used with temperatures and dewpoints in °F, and full wind barbs (half wind barbs) representing 10 kts (5 kts). The red dashed line represents the trough shown in Fig. 8, and the blue line represents the track of the echo centroid shown in Fig. 6.

A region of relatively high dew points can be seen east of this outflow, and also along the eastern extent of the trough discussed above. Clearly, storms that developed in the Rushville area would have interacted with these two boundaries, and also would have had access to the richer moisture between the outflow feature and the trough.

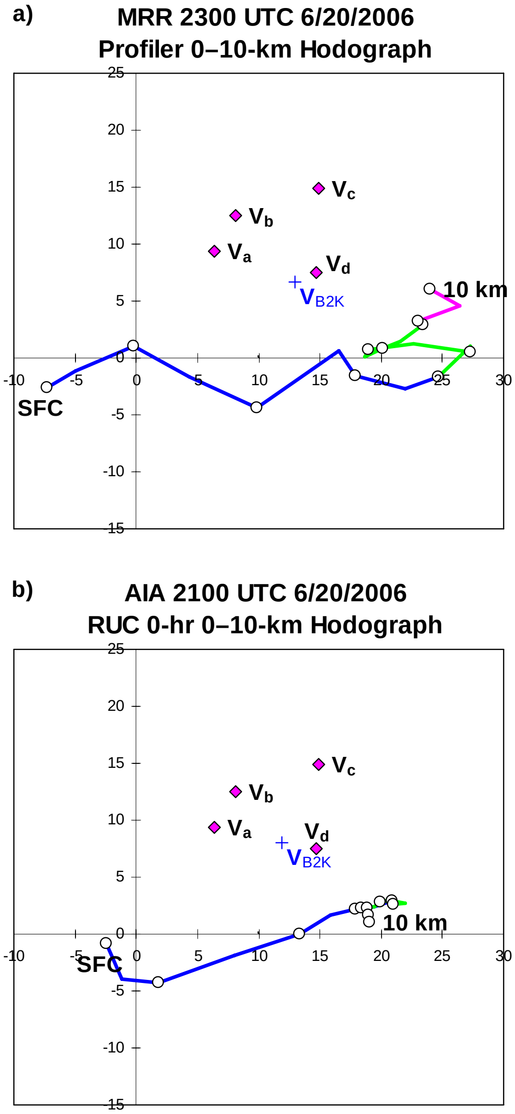
The satellite images (Fig. 9) show the evolution and intensification of the Rushville supercell as it moved across northwestern Nebraska between 2115–2245 UTC. To the east of the echo centroid track (Fig. 9a), surface winds were from the east-northeast and dewpoints were 12–16°C (53–61°F). However, to the west of the storm track, the winds were from the north and dewpoints were 8–14°C (47–57°F). Moreover, surface temperatures were 1.6–2.2°C (3–4°F) cooler on the east side of the storm track, consistent with the cold advection noted above. This pattern resulted in moisture advection and mass convergence in advance of the Rushville supercell.

Conditions were similar 30 min later at 2145 UTC, although the winds had veered to the east at the Rushville mesonet site (Fig. 9b). A subtle line of cumulus was also becoming apparent from just northeast of the thunderstorm anvil to the east of Rushville (cf. Figs. 9a and 9b). These likely were manifestations of the moisture advection, mass convergence, and increasing low-level storm-relative inflow.

By 2215 UTC (Fig. 9c) the line of cumulus had become well established, with congestus noted from Rushville through Gordon. The flow from the northeast ahead of the Rushville supercell increased to 5–10 m s^{-1}, and was generally confluent in the Rushville area. The same general pattern continued at 2245 UTC (Fig. 9d) as the line of cumulus congestus remained visible ahead of the Rushville supercell in the vicinity of the surface trough. Note that this area of cumulus congestus was not apparent from either of the KUDX or KLNX radars. The above processes appeared to help set the stage for tornadogenesis; the tornado occurred 24 min after the time of the satellite image in Fig. 9d.

c. Proximity hodographs

A proximity hodograph was constructed for Rushville using the Merriman, Nebraska (MRR), profiler data at 2300 UTC (Fig. 10a); the profiler is located 63 km (34 n mi) to the east-northeast of Rushville (note the location of Merriman in Fig. 9). A surface wind from 70° at 8 ms^{-1} (15 kts) was used, based on the 2300 UTC winds at mesonet sites in the inflow region of the


a) MRR 2300 UTC 6/20/2006
Profiler 0–10-km Hodograph

b) AIA 2100 UTC 6/20/2006
RUC 0-hr 0–10-km Hodograph

Figure 10: Proximity 0–10-km AGL hodographs for (a) Merriman, NE, at 2300 UTC, 20 June 2006 and (b) Alliance, NE, at 2100 UTC. The lowest 4 km is blue, the next 4–8 km is green, and the upper 8–10 km is magenta. Data are plotted every 500 m, and open circles are plotted every 1 km. The observed storm motions are given by the filled magenta diamonds, and subscripts a–d correspond to the four stages of motion discussed at the end of section 2 and shown in Fig. 6. The forecast motion for a left-moving supercell as described in Bunkers et al. (2000) is given as $\mathbf{V}_{\mathrm{B2K}}$ (blue).

Rushville supercell. In addition, a hodograph was developed for Alliance, Nebraska (AIA), using the Rapid Update Cycle (RUC) analysis at 2100 UTC (Fig. 10b). AIA is 80 km (43 n mi) south-southwest of Rushville, and at 2100 UTC was in advance of the thunderstorm that was beginning to split into the Rushville supercell (recall the beginning of section 2). The RUC 0-h analysis soundings indicated good (subjective) agreement with both Fig. 10a and the 0000 UTC, 21 June 2006 radiosonde observation from North Platte, Nebraska. The RUC profile therefore is believed to be reasonably representative of the near-storm environment at AIA.

The AIA hodograph at 2100 UTC turned counterclockwise (cyclonically) with height in the lowest 2 km AGL (Fig. 10b). The backing ground-relative winds indicate the weak cold advection that was present. This profile is consistent with the enhancement of the left-moving (Rushville) supercell and the diminution of the right-mover within 60 min (Weisman and Klemp 1986). Conversely, the MRR hodograph displayed a quasi-linear shear profile in the lowest 5–6 km (Fig. 10a), which, based on modeling studies, is inconsistent with the dominant nature of the Rushville supercell. Irrespective of the hodograph differences, the storm-relative helicity (SRH) was substantially negative throughout the lowest 1–3 km for both profiles (Table 1), with absolute values larger than those for nearly all cases in Bunkers (2002).

Table 1: SRH (m^2 s^{-2}) for varying layers (km) using the hodographs in Fig. 10 and the storm motion ($\mathbf{V_b}$) prior to the Rushville tornado. The "AIAmod" column accounts for a surface wind of 70° at 8 m s^{-1} (15 kts) at AIA in Fig. 10b.

Layer	MRR	AIA	AIAmod
0–1	-48	-101	-164
0–2	-213	-267	-330
0–3	-331	-333	-396
1–3	-283	-232	-232

The *veering* of the surface winds along and to the east of the storm track (Fig. 9) likely contributed to enhanced *negative* SRH just ahead of the supercell, especially in the near-ground inflow layer (Table 1). Recall that backing surface winds typically lead to enhanced positive SRH in the traditional setting for tornadic right-moving supercells. Indeed, the direction of the surface wind is critical to the MRR hodograph with respect to the sign of the 0–1-km SRH. For example, if a surface wind from the northeast (45°) is used in Fig. 10a, the 0–1-km SRH is slightly positive (13 m^2 s^{-2}), whereas with a wind from the north (360°) the SRH indicates tornadic right-moving supercells (117 $m^2 s^{-2}$). Alternatively, if the surface wind is modified to 70° at 8 m s^{-1} (15 kts) for the AIA hodograph (consistent with Fig. 10a), the low-level SRH becomes even more negative (Table 1). In summary, the proximity hodograph analysis suggests the veering and strengthening of the near-surface winds was important for increasing the low-level shear/SRH prior to tornadogenesis.

d. Supercell/tornado forecasting parameters

Thompson et al. (2004) described two multivariate parameters that can be used to anticipate right-moving supercells and their associated significant tornadoes—the supercell composite parameter (SCP) and the significant tornado parameter (STP)[2]. Edwards et al. (2004) modified the SCP to account for left-moving supercells (i.e., the LSCP); the SRH is based on the motion of a left-moving supercell (versus the motion of a right mover). The STP can also be modified for a left-moving supercell in an analogous way, yielding a left-moving STP (LSTP).

The SPC routinely produces hourly plots of various parameters, including the LSCP. The 2-h evolution of the LSCP from just after the initiation of the Rushville supercell shows high values of this parameter nosing into the Rushville area (Fig. 11); the highest values occurred where the supercell initiated. Note that values of -1 slightly support left-moving supercells, but values of -5 to -10 are relatively large and thus strongly supportive (Thompson et al. 2004). Based on manual calculations using the MRR/AIA proximity hodographs for the kinematic data, and the RUC 0-h analysis valid at 2300 UTC for the thermodynamic data, LSCP values ranged from -3 to -14 (depending upon which "proximity" value of CAPE or SRH was used). Although the SPC does not produce plots of LSTP, manually computed values for MRR ranged from -0.3 to -1.5. These are in the middle of the weakly tornadic distribution of Thompson et al. (2004).

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[2] Refer to Doswell and Schultz (2006) for a discussion of severe storm forecast parameters.

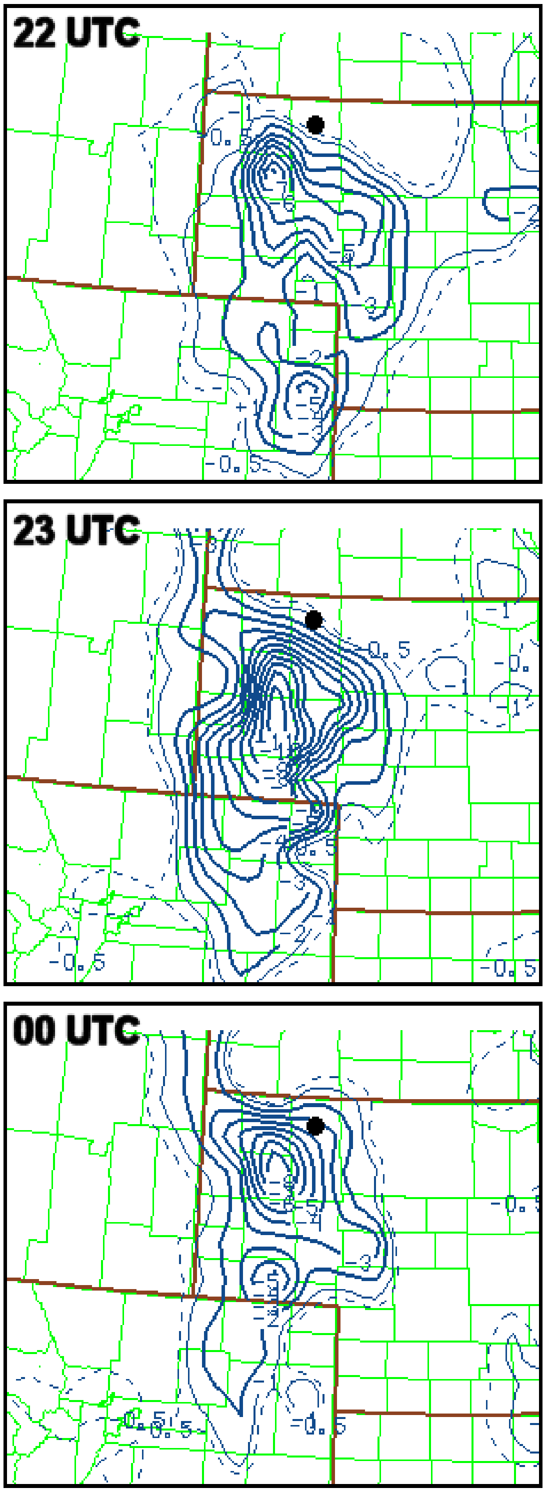

Figure 11: The left-moving supercell composite parameter (LSCP) from the Storm Prediction Center (SPC) valid 2200 and 2300 UTC (20 June 2006) and 0000 UTC (21 June 2006). Rushville is indicated by the black dot.

e. Storm motion

The motion of the Rushville supercell with respect to the environment deserves some attention. Focusing on the hodographs in Fig. 10, storm motions deviated by 7–15 m s^{-1} to the left of the vertical wind shear vector. Note the speed increased between stages one and two as the mesoanticyclone intensified. The third stage of supercell motion ($\mathbf{V}_c$) corresponded with BWER collapse and an associated downburst that likely caused the storm to accelerate along its gust front [reflectivity animations (not shown) support this assertion]. Finally, as the Rushville supercell went through a cyclic process, it entered a fourth stage ($\mathbf{V}_d$), when the storm was not as large or intense as before. Despite these variations, the overall motion of the Rushville supercell remained to the left of the vertical wind shear throughout its lifetime, as would be expected with a clockwise-rotating supercell (anticyclonic in the Northern Hemisphere). Therefore, if forecasters remain cognizant of the vertical wind shear profile *and* the forecast supercell motions (Bunkers et al. 2000; Zeitler and Bunkers 2005), anticipation of left-moving supercells should be fairly straightforward.

4. Summary and conclusions

The Rushville supercell possessed a very strong mesoanticyclone for most of its lifetime, and produced a brief tornado (Fig. 12) in a manner similar to the traditional right-moving supercell tornadogenesis process. Its classic-looking hook echo and BWER developed shortly before the anticyclonic F1 tornado touched down just south of Rushville, Nebraska, although the most significant damage from this storm was associated with the nontornadic severe weather. The post-tornadic increase of severe weather was associated with BWER collapse and storm acceleration, which may have prevented additional tornadoes from forming—owing to the overwhelming effects of the surface cold pool. The structure and evolution of the Rushville supercell were notably different from many previously documented left-moving supercells.

The Rushville supercell moved northeast in the vicinity of a mesoscale surface trough that may have been important in modulating supercell intensity and aiding tornadogenesis. Indeed, the surface, satellite, and proximity hodograph analyses imply the near-ground layer was modified such that the moisture and wind stratifications became more favorable as the Rushville supercell approached the surface trough. Horizontal vorticity, derived from the vertical wind shear that possessed some low-level counterclockwise curvature (aided by weak low-level cold advection), appeared favorable for tornadic left-moving supercells, especially in advance of the Rushville supercell. Furthermore, guidance from supercell forecasting parameters portended the left-moving supercell event [comments from Doswell and Schultz (2006) notwithstanding].

Figure 12: Photograph of cloud feature/possible F1 anticyclonic tornado associated with the left-moving/anticyclonic supercell near Rushville, NE, on 20 June 2006 (tornado time ~2309 UTC). The view is toward the southeast. Image courtesy of Jacque Trumbull. [This is the only known photographic documentation of the storm, and verbal accounts were not available.]

Aspects of this unique case that can help forecasters during warning situations are summarized below.

- Forecasters must maintain the highest situational awareness when dealing with left-moving supercells because current operational radar algorithms in the United States are not designed to detect anticyclonic signatures.
- The real-time detection of tornadic signatures (e.g., hook echoes) associated with left-moving supercells can be aided by a proper conceptual model as well as mentally flipping reflectivity images.
- Even weak mesoscale boundaries, as in this case, apparently can play a nontrivial role in supercell evolution and tornadogenesis. Thus, the near-storm environment needs to be closely monitored for clues that may portend tornadic evolution.

Although this study presents just a single case, it reinforces the notion from previous studies that boundaries and the near-surface layer appear to be rather important for tornadogenesis (e.g., Markowski et al. 1998, 2003). Furthermore, regions of weak low-level cold advection may be conducive to the occurrence of left-moving supercells [based on the present study and that of Edwards and Hodanish (2006)]. This is certainly something that demands further investigation, perhaps through a climatological analysis of low-level patterns attending left-moving supercell events. Future work also should be directed toward a better understanding of the differences in the structure and evolution of the Rushville supercell with respect to other "more typical" left-moving supercell events. Finally, we echo the sentiments of Monteverdi et al. (2001) and Bunkers (2002), namely, an algorithm to *detect and quantify* anticyclonic circulations in thunderstorms would be of great value to operational forecasters across the United States.

Acknowledgments. The authors would like to thank Deb Blondin (Warning Coordination Meteorologist at North Platte, NE) for performing a storm survey to examine the extent of the storm damage (both tornadic and nontornadic). Roger Edwards from the SPC provided valuable information on historical data for tornadic left-moving supercells, and Dr. Paul Smith provided helpful guidance on creating the color scale for Fig. 2. Lastly, we appreciate the thorough reviews provided by Brian Curran and Drs. Chuck Doswell and John Monteverdi.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Charles A. Doswell III):

Initial Review:

Recommendation: Accept with Major Revisions

General Reply

Thank you for your careful review. We have made substantial revisions to the environmental analysis section, and nearly all of your comments have been integrated into the revised manuscript. The annotated version was reviewed first, and that dictated the order in which the responses appear below. Most minor comments were accepted, and therefore, are not elaborated on below (unless they were not accepted, in which case a reply is given below). Also, please note that the tornado time was changed by 3 minutes based on further investigation by the WCM at North Platte. Lastly, in order to reduce the length of the paper, we are open to removing the subsections on tornado parameters and baroclinic vorticity. We'll leave this to the consensus of the reviewers and Editor.

[Minor comments omitted...]

Is there a better photo available? Frankly, from this photo, it's unclear it's even a tornado – could be a "scud bomb." I see no debris swirl, for example.

Regarding the photograph, this is the only one we have available to us (no others exist to our knowledge). If it weren't for the supporting storm damage survey, we also would have to question the validity of this photo representing a tornado.

Such a brief, relatively weak tornado is, of course, not particularly noteworthy. You're talking about one minute out of a 3 h lifetime for the storm.

Your point about the short duration of the tornado not being noteworthy is well taken. However, it is unclear to us if you want any modifications here (e.g., a footnote?).

I disagree with this use of the term "satellite" tornado. To my knowledge, no consensus exists to use this term to describe the third type of anticyclonic tornado.

We have replaced "is often" with "some have loosely" to indicate the lack of consensus regarding the "satellite tornado" terminology. If you have a better term, we are "all ears."

[Re: Data from Brown and Meitín (1994) suggest 10% of left-moving storms may be tornadic.]

The sample in the Brown and Meitín paper is pretty small and was not really collected in any systematic way [Re: Wakimoto (1983) ratio]… Saying this at the end of this discussion seems to leave the reader hanging. This comment should go before you comment about your own estimation of the relative frequency. Further, the 1 in 700 figure might be off in the other direction from that produced by Brown and Meitín – the DAPPL tape data used by Wakimoto more than 20 years ago could easily be seriously underreporting the occurrence of anticyclonic tornadoes.

Another sentence was added to footnote #2 to describe the limitations of the Brown and Meitín (1994) study. In addition, the rest of this paragraph was revised in accordance with your recommendations.

Perhaps I'm just being argumentative, but if a forecaster needs to flip the radar images over to find an anticyclonic hook echo, this is a major training shortfall, not a substantial basis for complaining about the software.

It can be very difficult to get forecasters to look at things in a different way. For example, I (MJB) have experienced this with hodograph training (e.g., vertical wind shear and supercell motion). For whatever reason, it is hard for some forecasters to look at an "atypical" hodograph and anticipate off-hodograph motion to the right of the shear vector. But after you translate that hodograph to the upper-right quadrant, the light bulbs go off. And despite substantial training efforts, certain "human factors" still make it difficult for some to discern atypical configurations that are obvious to others. We agree that this isn't a basis for complaining about software; however, it is still worthy to point out the potential benefit(s) of mentally flipping the reflectivity images.

Is there some point to be made regarding the acceleration? If so, what is it? This discussion has failed to compare and contrast the evolution of this echo with that of other persistent left-movers. It would be very useful to make such a comparison, I believe, since most left-movers have a very different structure and evolution from this example.

Apparently you don't like our sentence about the supercell acceleration at the end of section 2; we have therefore removed it. However, we have included a sentence in the previous paragraph speculating on the potential relationship of the storm acceleration to tornado production. If you think this is not needed, or if you think there is some point we need to make about the supercell evolution, please explicitly state it. It is not our intention to go through an extensive radar examination of left-moving supercells just to compare them to the Rushville case.

Sorry, but I don't necessarily see that both of these [hodographs] are "linear" in their lowest 5-6 km! This sounds to me as if the authors are seeing what they want to see, not what is there.

The discussion of the hodographs was improved. It is agreed that the LBF hodograph was not unidirectional (a sloppy claim that we overlooked). Instead of the LBF hodograph, we decided to show the RUC hodograph for AIA at 2100 UTC (as storm splitting was commencing). This clearly shows counterclockwise curvature of the low-level shear vectors, which is consistent with the dominant left-moving supercell. Lastly, we reconsidered the mesonet plot and decided 70° was more appropriate than 90° for the surface wind direction in advance of the Rushville supercell.

Presumably, the nature of the hodograph doesn't matter to this bulk shear magnitude – by the way, the units of shear are not m s^{-1} but only s^{-1}. I realize it's conventional to use the magnitude of the shear vector, but I want to discourage such an error.

Regarding the 0-1-km bulk shear versus SRH claim, we have removed this sentence because it didn't flow well with the rest of the paragraph. At any rate, to answer your question, please refer to the figures in Markowski et al. (2003) and Thompson et al. (2003). The statistical separation is better for the shear versus the SRH. ...we agree that, technically speaking, shear is in units of s^{-1}. However, in the operational *world, it is customary to refer to the shear as a given magnitude (e.g., 10 m* s^{-1}*) over a given depth (e.g., 1 km). This implies the units are in* s^{-1}*, but avoids the "ugliness" of saying the shear is 0.01* s^{-1}*.*

***[Editor's Note:* In a formal journal such as EJSSM, metric units *must* be prioritized in text; however English equivalents in parentheses are optional for work that is operationally (US) oriented.]**

To what extent does the length of this "estimated vorticity vector" correspond to a calculation, or is it simply schematic? There are some interesting issues tied to this. If we use CAPE to estimate the buoyancy gradient, it's hardly very large across this boundary. This does not preclude the possibility for baroclinic vorticity generation, depending on precisely how it is actually calculated. The authors have not provided any information about how this was calculated, or even if it was calculated, as opposed to simply "estimated." This is a serious oversight in this chain of reasoning.

The length of the estimated vorticity vector is simply schematic, and this was clearly noted in the revised manuscript. We also "toned down" this discussion, and furthermore, we are willing to delete it altogether if the consensus of the reviewers dictates.

Second Review:

As suggested by the editor, the photograph of the "tornado" is sufficiently unconvincing as a tornado that I don't think it should be the centerpiece of this presentation. If the authors use the radar imagery as the focus, then I'm satisfied with including this photograph, provided that some brief discussion of its credibility is added.

The image of the supposed tornado has been moved to the end of the paper, and a disclaimer has been added to the caption.

"Location #3 may be the most common, producing what some have loosely referred to as a "satellite" tornado, …" I continue to have problems with this statement. I don't think what I consider to be a "satellite tornado" forms on the anticyclonic shear side of the RFD. A satellite tornado is, according to chaser jargon, one that rotates (cyclonically) around a cyclonic tornado. It is that rotation around the main tornado that is responsible for the choice of terminology. Indeed, some might choose to call an anticyclonic tornado on the anticyclonic shear side of the RFD a satellite tornado, but it would be incorrect to do so.

We agree, especially after looking at images of the 3 May 1999 tornadoes and noting a smaller "satellite" tornado rotating around a much larger one. Thus, this phrase has been removed.

The authors simply are unable to reconcile the apparent conflict between the implications of the two different reconstructed "proximity" hodographs. To argue that one is more representative than the other is a logical fallacy. The use of the hodograph curvature argument is based on a hypothesis that hodograph curvature determines the dominance of left- or right-moving supercells. The fact that the observations for one hodograph are consistent with the hypothesis and that the other hodograph is inconsistent with that hypothesis does not entitle us to say that one hodograph is more "representative" than the other. Unless you have a compelling argument in favor of one hodograph compared to the other based on some other information, you cannot infer that one hodograph is correct simply because it matches your preconceived conceptual model.

It is agreed that this sentence was speculative; therefore, it has been removed.

Re: "During the first two stages of supercell motion ($\mathbf{V_a}$ and $\mathbf{V_b}$, Fig. 11), the Rushville supercell had a strong mesoanticyclone, which is consistent with these larger deviations." I'm unaware of any demonstration that the degree of deviation of storm motion from the shear vector is proportional to the strength of the storm-scale vortex. Can the authors provide any evidence for this?

First, this section has been "toned down" so that it doesn't appear self-serving; however, we have maintained the last sentence because it is our belief that a forecaster can benefit from the knowledge of forecast supercell motions during severe weather operations. Second, we are not aware of any formal documentation *relating the strength of the storm-scale vortex to the off-hodograph propagation, so we have removed this phrase.*

REVIEWER B (John P. Monteverdi):

Initial Review:

Recommendation: Accept with Minor Revisions

General Comments and Recommendation to the Editor

The authors are documenting a rare tornadic left-moving supercell. The tornado developed in the traditional supercell cascade; in short, it was a mesoanticyclone-induced. This is the first study (of which I am aware) in which the entire "cascade" process is documented. In Monteverdi et al. (2001) (in the authors' references), for example, although there was clear evidence of a descending circulation from the mid level mesoanticyclone, the development of the low level circulation was inferred, rather than directly monitored by Doppler radar.

The manuscript is also well-written, generally, and very interesting. I commend the authors for it.

As such, this study represents a contribution and would be of great interest to readers of the Electronic Journal of Severe Storms Meteorology (EJSSM). I am recommending to the Editor that the paper may be (is) acceptable with minor revisions, but am requesting that the revised manuscript be sent back to me for further review.

General Reply

Thank you for your careful review and kind words. Nearly all of your comments have been accepted, and we have included a composite synoptic chart and a subjective subsynoptic surface analysis in the revised manuscript. Moreover, the title has been changed along the lines suggested. Please note that parts of section 3 were substantially modified based on all of the reviews. We leave it to the Editor to determine if the paper is more suitable as an "Images of Note" or an Article. Also, please note that the tornado time was changed by 3 minutes based on further investigation by the WCM at North Platte. Lastly, in order to reduce the length of the paper, we are open to removing the subsections on tornado parameters and baroclinic vorticity. We'll leave this to the consensus of the reviewers and Editor.

Comments on Scientific Content and Quality of the Presentation

The study is an excellent contribution and the manuscript is generally well written. The figures are good. But I think that there are some important omissions. I discuss these in general and specifically in 1(b) below.

I also believe that the way the authors have chosen to discuss things can be cleaned up a bit. As it stands, although the manuscript displays the authors' competence, and illustrates a proper use of the scientific method, there are some omissions in logic. I outline these below

Specific Major Comments

There are several areas of the manuscript that I feel should be shored up.

[Obsolete page, figure and section numbering omitted...]

I was struck by the lack of an analyzed subsynoptic plot. This would be key in establishing the location of the boundary that the authors claim played a role in the Rushville storm's evolution. This could fit either in Section 3.a, or 3.b, the latter section being the one in which the authors allude to the boundary. Since the authors feel that this boundary was significant, its role should be more carefully documented.

The authors' allude to this boundary, stress its importance, and discuss it in the text many times. Yet, there is no conventionally-analyzed plot to illustrate this, beyond the plot of the observations on the satellite figures.

As a sidelight to this, one of the small problems I see with the manuscript is that although it is targeted for the "Images of Note" section of EJSSM, that it's quite long. There is much discussion, for example, of the radar echo structure and evolution; and none of it is superfluous. In fact, perhaps the Editor should consider placing this as an Article or a Note. In any case, even as a short contribution to "Images of Note", I feel that an analyzed subsynoptic analysis should be included.

The subjective subsynoptic surface analysis was placed in section 3b where the subtle boundary is discussed. Interestingly, the isobars do not lend support for the position of our previously asserted mesoscale boundary; however, it does suggest a subtle pressure trough was located just to the northwest of the path of the Rushville echo centroid. The location of this surface trough has been included as an overlay on the satellite images.

Note that in section 3.b, the authors describe the boundary and the characteristics of the air mass on either side in words. That's not a good way to approach the characterization of the surface conditions.

Regarding the last part of your comment, we are not sure what you are looking for in terms of the boundary and air mass description. Please clarify if our revisions have not satisfied your concerns. Were you talking about an objective analysis of virtual temperature, for example?

Section 3a, Lack of Supporting Graphics

As a corollary to my previous comments, I notice that in section 3.a that authors do not include a single mid or upper tropospheric chart to provide the readers with the "big picture" they are describing in this section. I'd suggest a composite chart of some sort, rather than specific constant pressure charts. The authors could then schematically show the location of features both at the surface and aloft that were major players in setting up the synoptic-scale environment.

A composite synoptic chart was added as Fig. 8. Thanks for the suggestion!

Discussion of Proximity Hodographs

First, I wonder if this section, which is very important, shouldn't be in a newly headed subsection. There is a logical disconnection between the stream-of-consciousness in the discussion of the satellite evolution and the subsynoptic environment supporting the authors' contention of the importance of the boundary.

A newly headed subsection (3c) was created for the discussion of proximity hodographs.

Second, isn't this a logical location for a discussion, even if brief, about the thermodynamic setup. The sounding comes much later, I realize, but it might be more logical to the reader to have a discussion of the buoyancy as it relates to the discussion of the synoptic-scale environment. I note that the authors relate the sounding (which is RUC-generated) to that pesky boundary again. That's why it's so important for the authors to show that boundary more clearly.

A brief mention of CAPE is given at the beginning of the environmental section, and the thermodynamic setup has been somewhat expanded based on the subsynoptic surface map. If we have not sufficiently satisfied your concerns please let us know.

Third, I'll have to disagree a bit about the authors' interpretation of Figs. 10a-b. The authors state that both hodographs display a linear shear profile in the lowest 5 to 6 km. Since the authors also showed in other sections of the manuscript that the Rushville storm presented a left split that had become enhanced, one would have expected the hodograph to show a counterclockwise curvature (cyclonic loop) in the lowest 5 km or so. And, actually, that's what I see in Fig. 10b. The fact that in Section 2, the authors describe the right split as dissipating quickly suggests that Fig. 10b would be the more representative of the two hodographs.

The discussion of the hodographs was improved. It is agreed that the LBF hodograph was not unidirectional (a sloppy claim that we overlooked). Instead of the LBF hodograph, we decided to show the RUC hodograph for AIA at 2100 UTC (around the time of storm splitting). This clearly shows counterclockwise curvature of the low-level shear vectors, which is consistent with the dominant left-

moving supercell. RUC hodographs for points from AIA to Rushville (not shown in the paper) maintain this low-level curvature through 2200 UTC, but to a lesser degree than at AIA at 2100 UTC. Lastly, we reconsidered the mesonet plot and decided 70° was more appropriate than 90° for the surface wind direction in advance of the Rushville supercell.

The authors also allude to the RUC 0-h analysis soundings. It would be interesting to see those, or at least the one that corresponds best to the location of the Rushville storm's location. Please note that I am not arguing that the model data is superior to the subjectively obtained proximity hodographs. I just think it would be a "capper" on the argument if the RUC hodographs looked like Fig. 10b.

By the way, Fig. 10a does indeed look like a case in which storm's would be splitting into mirror image supercells. However, such supercells would liable NOT to be tornadic.

Second Review:

General Comments and Recommendation to the Editor

I think that the manuscript is improved. I only have minor comments to make at this point, but I am still suggesting some changes. I do not need to see another draft, and leave it up to the authors and the Editor to decide whether or not to make the changes. It's almost ready to go.

Specific Major Comments

There are several areas of the manuscript that I feel should be shored up.

[Photo of possible tornado] and Title

I see that the authors have shortened the title. This is a good change. However, now that the manuscript has been cleaned up, I do see a small problem emerging in this draft.

First, as I already have passed along to the authors (and the Editor and, also, one of the other reviewers), I am unconvinced that [the photograph] shows a tornado. Yes, it may be the tornado, but the center point of the manuscript shouldn't be this picture, but the documentation of a relatively rare tornadic event.

Thus, the "Image of Note" aspect of this manuscript should focus on the radar documentation, and not the purported tornado image. So, I am suggesting (not "requiring") two changes. First, I think that the tornado image should be deemphasized, possibly, by placing it towards the rear of the manuscript. Frankly, it looks like an outflow feature to me, but it certainly still could be a tornado.

The image of the supposed tornado has been moved to the end of the paper, and a disclaimer has been added to the caption.

Second, hopefully the authors won't be too flabbergasted if I suggest another title change, to highlight what images are the images of "note" in this manuscript. I suggest "Radar Documentation of a Tornadic Left-Moving Supercell." On the other hand, if the purpose of the manuscript is just to document all aspects of this event, then the title can remain as it is, although then, of course, it wouldn't be an "Image of Note" contribution.

We decided not to change the title.

[Editor's Note: **In aggregate, all the images were "of note," per se, in that they presented several crucial visual illustrations of the most outstanding and conceptually educational aspects of this storm. As such, this manuscript could be categorized appropriately in the EJSSM "Images of Note" bin, whatever the order of appearance of the various imagery in the final draft.]**

Figure 9

I am gratified to see the subsynoptic plot included as Fig. 9. However, I note that the authors have not used conventional symbols to indicate the dry line and the outflow boundary. They should redraft the figure, using conventional symbols.

Also, I think that a little more imagination could be used to draw the isobars. I made an attempt (and I will try to attach it somehow), although I couldn't read the data very well...so I could be way off. But, in general, if you have an outflow boundary where you have it, there should be some reflection in the isobars, perhaps a "bubble" high, and some kinking indicating troughing along the boundary. Also, conventionally, you'd "break" the dry line (or front, etc.) where you have an outflow crossing it. I "inferred" that a 1009 isobar would be inside the outflow feature because of the station with a 10 knot south wind...and a pressure of 1008.2. There has to be a pressure gradient to support that wind, so there probably is a 1009 south of it.

We have updated the subsynoptic plot to use the symbology you suggested. In addition, we no longer have a dryline analyzed based on reanalysis and the extent of the outflow boundary.

REVIEWER C (Brian Curran):

Initial Review:

Recommendation: Accept with Minor Revisions

It is my recommendation that this paper is acceptable with minor revisions, but I ask the authors to send the revised manuscript back for further review.

In my opinion this paper is a well written documentation of a rare left-moving supercell and associated anticyclonic tornado. I commend the authors' operational perspective and recommendations for both future research and using visualization techniques for severe storm interrogation and evaluation. Several of the figures are hard for me to read, however, and I ask that the authors consider simplifying some of the images, use color schemes friendly to those with red-green colorblindness, and make annotations on images that are supportive of arguments within the text.

General Reply

Thank you for your careful review. We have strived to improve the figure quality, and nearly all of your comments have been integrated into the revised manuscript. Please note that parts of section 3 were substantially modified based on all of the reviews. Also, please note that the tornado time was changed by 3 minutes based on further investigation by the WCM at North Platte. Lastly, in order to reduce the length of the paper, we are open to removing the subsections on tornado parameters and baroclinic vorticity. We'll leave this to the consensus of the reviewers and Editor.

Scientific content

[Minor comments omitted...]

Radar characteristics: Was a deep convergence zone (Lemon, L. R., and D. W. Burgess, 1992: Supercell associated deep convergence zone revealed by a WSR-88D. Preprints, *26th Conf. on Radar Meteorology*, Norman, OK, Amer. Meteor. Soc., 206-208) noted within the Rushville storm? Evidence of such a zone may strengthen your observation of a very strong updraft.

There appeared to be a deep convergence zone (DCZ) up to about 30,000 feet AGL prior to the Rushville tornado. The precise depth/strength is uncertain based on radar sampling issues, but the DCZ did not appear to be as deep or intense as that presented in Lemon and Burgess (1993). Since Lemon and Burgess didn't explicitly relate the DCZ to updraft strength (only updraft position), we have not mentioned it in the present paper. Moreover, this last sentence on the BWER relationship to updraft strength has been removed per reviewer A's comments.

Environmental conditions (c. Baroclinic vorticity generation): Have you considered what effects, if any, low level baroclinic vorticity generation along the anvil shadow (Markowski et al. 1998: Observations of low-level baroclinity generated by anvil shadows. Mon. Wea. Rev., 126, 2942-2958)? Would the orientation of the baroclinically-generated horizontal vorticity vector along the northern anvil shadow of the Rushville storm also contribute some clockwise rotation?

We had not previously considered the potential role of low-level baroclinic vorticity generation along the anvil shadow. However, after looking at Markowski et al. (1998) and the visible satellite images for this case, we believe it would have played a trivial role, so we have not mentioned it in the paper. In effect, the storm-relative inflow would not have allowed sufficient residence time of parcels in the anvil-generated baroclinity.

Second Review:

I thank the authors for considering and implementing most of the suggestions offered during the first review. Revision of many of the figures, while difficult, is appreciated.

The rewrite of section 3 looks good. There is a lot of useful information here regarding the near-storm environment prior to supercell development. The paper is somewhat lengthy, but considering that there are very few reviews of anticyclonic tornadic supercells in the literature, this length may be justified. Deletion of subsections d. and e. in section 3 might shorten the paper by a page; however, removal of these subsections may eliminate useful information for forecasters faced with similar events. I recommend that these subsections remain within the paper but will defer this decision to the authors and to the Editor.

The points I brought up during the first review have been addressed by the authors to my satisfaction. I therefore recommend to the Editor that this paper be accepted for publication.