P 3.23

THE ASSOCIATION OF CELL MERGERS WITH TORNADO OCCURRENCE

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1. INTRODUCTION

The process of cell merging has long been associated with storm intensification, and is the subject of many studies. Previous studies define cell mergers in terms of radar appearance (Westcott and Kennedy 1989; Lee et al. 2006), referring to the joining of two initially independent radar echoes. Other studies define cell mergers as the joining of two existing updrafts (Westcott 1994; Bluestein and Weisman 2000), or the consolidation of rainfall rate isopleths in numerical simulations (e.g., Kogan and Shapiro 1996). Observational studies have noted the occurrence of cell mergers and the subsequent effect on convective systems (e.g., Malkus 1954; Simpson et al. 1980; Cunning et al. 1982; Westcott 1994; Wurman et al. 2007). Processes related to cell mergers have been shown to affect the precipitation, rotation, longevity, and motion of thunderstorms, as noted in both observational (e.g., Lee et al. 2006; Wurman et al. 2007) and numerical (e.g., Tao and Simpson 1984; Kogan and Shapiro 1996; Bluestein and Weisman 2000; Jewett et al. 2002) studies. Lee et al. (2006) found that 54% of all reported tornadoes during a multi-state outbreak on 19 April, 1996, occurred within +/- 15 minutes of a cell merger. Lee et al. (2006) also found that nearly 60% of all merged cells exhibited an increase in rotation. Many of the storm-scale processes associated with cell mergers, particularly the effects of an ancillary cell merging with a supercell, are not well understood.

Specific pre-existing characteristics of the primary cell and ancillary cell of a merger may be critical to the formation of a tornado. The storm-relative location of the primary cell may also be significant. Much attention has been given to the merging of cells initiating along the flanking line with the parent storm (e.g., Dennis et al. 1970). Lemon (1976) noted intensification of the primary cell updraft following each merger with a flanking line cell. Specifically, updraft buoyancy, low-level convergence, and rotation of the primary updraft were shown to increase. Other types of primary-ancillary cell interactions have been observed to coincide with tornadogenesis. Wurman et al. (2007) observed two cell mergers which both led to a brief intensification period and short-lived tornado, followed by an eventual weakening of the primary cell.

The purpose of this radar-based study is to determine the characteristics and frequency of cell mergers associated with tornado occurrence. To date, no known studies exist examining a tornado-cell merger relationship over a multi-day period. An attempt to identify a favored point of merger position within the primary cell will be made.

2. METHODOLOGY

Ten prolific tornado-producing days, occurring between 1999 and 2006, are selected for this study. The domain is limited to the Texas Panhandle and South Plains region of West Texas. Level II WSR-88D 0.5° elevation base reflectivity and velocity radar data from sites KAMA (Amarillo, Texas) and KLBB (Lubbock, Texas), provided by the National Climatic Data Center (NCDC), are used in this study. Tornado reports are collected from the NCDC Storm Data archive, and include estimated beginning and end times and the location of each event.

Tornado reports are carefully investigated in order to determine whether collocation with a cell

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merger exists. Mergers classified as “tornadic” refer to mergers occurring within +/- 15 minutes of an official tornado report. A total of 91 tornado reports occurred within the domain during the ten days included in this study, with 63 associated with a cell merger. Null cases are included in this study to provide a comparison with tornadic cases. An event classified as “null” represents a merger that involves a primary cell exhibiting rotation (all primary cells in null cases exhibited at least 7.5 ms^{-1} of gate-to-gate shear), with no tornado report logged within +/- 30 minutes of the merger event. Due to the strict criteria applied for selecting a null event, the number of null cases (20) is significantly less than the number of tornadic cases. Additional null cases will be added to the dataset as this study progresses.

3. MERGER CLASSIFICATION AND CHARACTERIZATION

3.1 Merger definition

The definition of a merger in this study is the same as used by Lee et al. (2006): a merger occurs when two previously distinct reflectivity maxima consolidate into one. Determination of the time of merger occurrence is based on information obtained from radar images.

The point of merger is determined from the position of the reflectivity maximum of the ancillary cell with respect to the primary cell, and is assigned when the ancillary cell is no longer distinguishable as a separate and distinct echo. It is likely that other properties of the ancillary cell interact with the primary cell (e.g., ancillary cell outflow) prior to merger, but these are often undetectable in reflectivity imagery, and were therefore not used in this study.

3.2 Radar analysis

Past studies suggest that an increase in reflectivity and/or rotation are indicative of an intensifying updraft following a merger (e.g., Kogan and Shapiro 1996; Finley et al. 2001). Reflectivity and velocity values are recorded for three scans prior to and after each merger (approximately +/- 15 minutes) to determine changes in intensity. Reflectivity is classified to trend upward (downward) if the maximum reflectivity of the primary cell increases (decreases) by at least 5 dBZ. The 5 dBZ threshold is valid at the time of merger, or up to two scans following the merger. In order to measure updraft rotation, the maximum gate-to-gate shear (hereafter, MGGS) across the mesocyclone is recorded and used. An increase (decrease) of 5 ms^{-1} of MGGS, either at the time of merger or up to two scans after the merger, indicates an upward (downward) trend in rotation.

It is hypothesized that the size of the ancillary cell may affect the outcome of a merger. Smaller cells contain less areal coverage of precipitation, which may limit negative effects (e.g., seeding of primary updraft) associated with a merger. Precipitation ingested into an updraft leads to a decrease in buoyancy due to evaporative cooling. In addition, drag from precipitation may decrease upward vertical velocity within the updraft (Das 1964). However, larger cells may also be favorable for a constructive merger event as increased buoyancy in larger updrafts may interact with neighboring updrafts. The estimated size and reflectivity of the ancillary cell is compared with intensity trends to determine if there is a relationship.

3.3 Demonstration Case

A representative case from 10 June 2005 is selected to demonstrate the classification of a merger event. In this case, several ancillary cells interacted with a dominant, primary cell. Reports obtained from Storm Data indicate a tornado occurred at 0130 UTC near Clarendon, TX. At 0108 UTC, numerous ancillary cells are evident in the vicinity of a large supercell (Fig. 1a, 2a). A total of three cell mergers were observed between the period of 0112 UTC and 0134 UTC. An ancillary cell (1B) merged to the south of the primary updraft at 0112 UTC (Fig. 1b). An area of rotation, defined by the base velocity couplet, within 1A is clearly evident in the base velocity image (Fig. 2b). An increase in MGGS is occurring near the location of merger 1B. Continued interaction occurs with additional ancillary cells through several volume scans (Fig. 1c-e, 2c-e). At 0130 UTC, cell 1C has merged with the updraft of 1A, as there is no longer a distinct reflectivity maximum associated with 1C (Fig. 1f). A significant increase in MGGS is noted, with a value of 37.8 ms^{-1} observed (Fig. 2f). At 0134 UTC, cell 1D merges with the forward flank of 1A (Fig. 1g), which is coincident with a significant weakening of cell 1A. It is noted that the merger of cell 1C with 1A occurred simultaneously with the reported tornado (Fig. 2g).

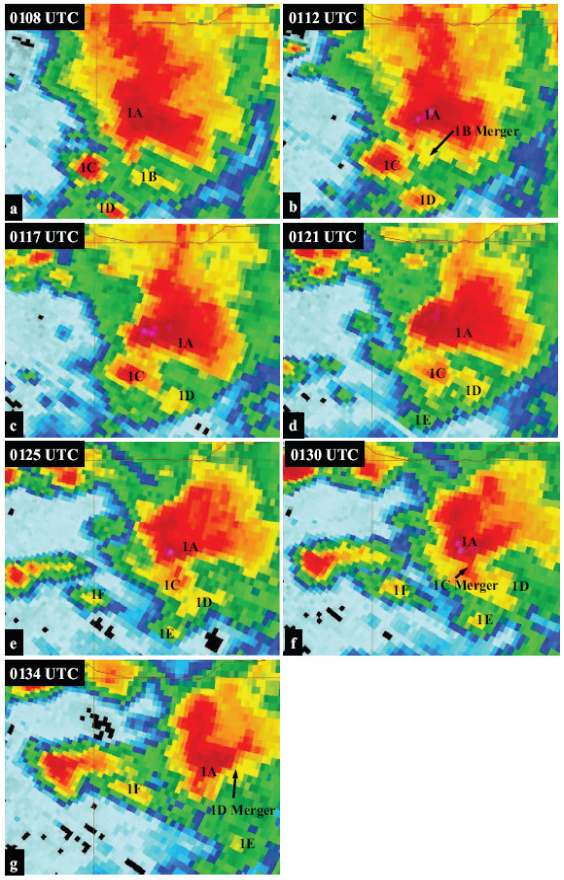

Figure 1. *KAMA radar reflectivity imagery (0.5º elevation) from 10 June 2005. Panel times are (a) 0108, (b) 0112, (c) 0117, (d) 0121, (e) 0125, (f) 0130, and (g) 0134 UTC. Individual cells and the location of mergers are labeled in black.*

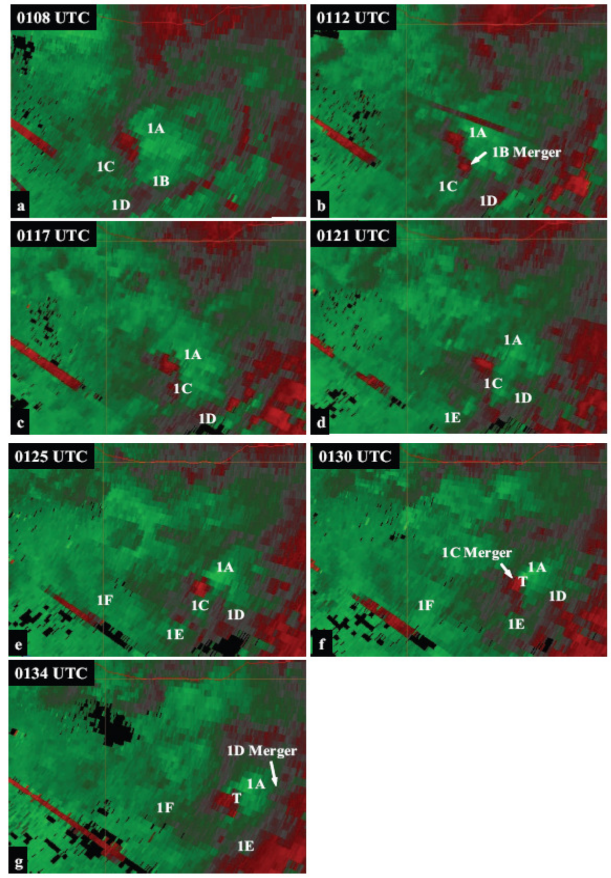

Figure 2. *KAMA radar radial velocity imagery (0.5º elevation) from 10 June 2005. Panel times are (a) 0108, (b) 0112, (c) 0117, (d) 0121, (e) 0125, (f) 0130, and (g) 0134 UTC. "T" represents the approximate position of reported tornadoes. Individual cells and the location of mergers are labeled in white.*

4. ANALYSIS

A total of 53 out of the 98 (54.1%) tornadoes considered in this study are associated with a cell merger that occurred within +/- 15 minutes of the tornado report (Table 1). It is found that 56.6% of tornadic mergers occurred within five minutes of a tornado report (Fig. 3). A clear plurality of these mergers occurred 0 to 5 minutes after the reported tornado, suggesting that a tornado-relevant interaction between the ancillary cell and primary cell may occur immediately prior to the cell merger.

4.1 Flanking line mergers

An attempt is made to separate events where the ancillary cell initiates along the flanking line of the primary cell. Convection along the flanking line is forced by the rear-flank gust front, which is typically more prominent in stronger supercells (Markowski 2002). Cells along the flanking line that do merge with the primary updraft may enhance buoyancy and create a more favorable environment for tornadogenesis (Lemon 1976). In the current study, it is found that flanking line mergers are more common in tornadic cases (23.8%) than null cases (5%).

4.2 Reflectivity and velocity trends

Nearly one-third of tornadic mergers experienced an increase in MGGS and/or reflectivity, 50.8% of tornadic cases exhibited no change in intensity, and only 14.3% experienced a decrease in intensity. Many cells exhibited a response in MGGS or reflectivity following a merger, but did not meet the defined thresholds. For null cases, 45% exhibited an increase in intensity, 45% remained unchanged, and 10% decreased in intensity.

Date	Mergers (Assoc. / Total)	%	Tornadoes (Assoc. / Total)	%
05/20/99	1 / 5	20.0	1 / 6	16.7
06/11/99	0 / 50	0.0	0 / 3	0.0
05/29/01	2 / 18	11.1	2 / 10	20.0
05/05/02	9 / 20	45.0	12 / 22	54.5
05/13/03	9 / 64	14.1	6 / 16	37.5
05/24/03	6 / 60	10.0	5 / 6	83.3
05/12/05	13 / 62	21.0	9 / 9	100.0
06/09/05	9 / 44	20.5	6 / 7	85.7
06/11/05	3 / 26	11.5	3 / 9	33.3
06/12/05	11 / 29	37.9	9 / 10	90.0

Table 1. *A list of days included in this study. Cell mergers of all types within the domain are counted from one hour before the first tornado report until one hour after the last tornado report. "Assoc. Mergers" are the number of mergers occurring within +/- 15 min of a tornado report. "Assoc. Tornadoes" are the number of tornadoes occurring within +/- 15 min of a merger.*

Many of the tornadic cases exhibited an increase in the calculated MGGS value. For tornadic mergers, a mean MGGS velocity of 26.3 ms^{-1} is calculated prior to a merger, and a value of 28.4 ms^{-1} is calculated immediately following a merger. Many of the null cases exhibited significantly less MGGS than tornadic cases. An increase in mean shear velocity is still noted for these null cases, however. The mean MGGS velocity five minutes prior to merger is 12.4 ms^{-1}, and five minutes after merger is 13.0 ms^{-1}. There is a clear discrepancy between tornadic and null cases in mean MGGS magnitudes (Fig. 4).

Only 4 of 63 tornadic cases displayed an increase in reflectivity following a merger, and only one case displayed a decrease in reflectivity. The calculated mean values of reflectivity immediately prior to (62.7 dBZ) and after (62.8 dBZ) the time of merger support these results as well. The difference in mean reflectivity values between null and tornadic cases is less significant than the observed differences in rotation. Null cases exhibited slightly higher reflectivity values than tornadic cases; both displayed very small increases in reflectivity between fifteen minutes prior to and after merger (not shown).

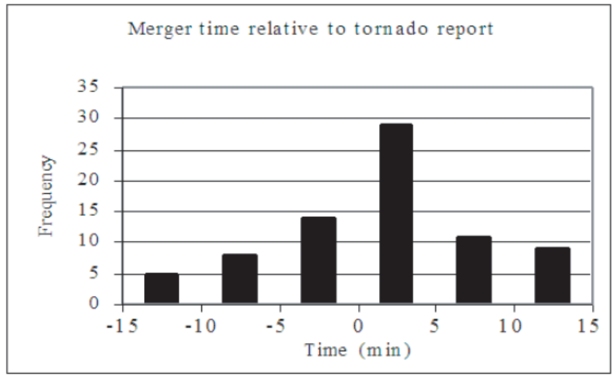

Figure 3. *A histogram of merger time relative to the tornado report in five minute intervals. Time period begins 15 minutes prior to merger and ends 15 minutes after merger.*

4.3 Merger location relative to the primary updraft

The radial distance and azimuth is calculated relative to the primary updraft for each merger, where the center point of the updraft is assumed to be collocated with the radar-identified mesocyclone. If no identifiable area of rotation is present, then the updraft center is assumed to be slightly upshear of the reflectivity maximum. It is found that mergers associated with null cases occurred closer to the updraft center (4.0 km mean absolute separation) than for tornadic cases (8.1 km mean absolute separation). Many tornadic mergers are clustered immediately behind and to the left of the updraft relative to the 850 hPa to 300 hPa shear vector (Fig. 5a). The mean tornadic merger position is approximately 0.7 km behind and 1.7 km to the left of the updraft center, though considerable variability exists. Non-tornadic mergers generally exhibit a different pattern (Fig. 5b). Null merger locations are spread ahead and to the right of the updraft center, and are centered closer to the updraft, with a mean position located 0.6 km ahead of the primary updraft. A dearth of null mergers behind and to the left of the updraft center is apparent.

4.4 Ancillary cell characteristics

Characteristics of the ancillary cell are similar for tornadic and null cases. The mean reflectivity of the ancillary cell in null cases five minutes prior to merger is 50.8 dBZ, which is 2.4 dBZ higher than ancillary cells in tornadic cases.

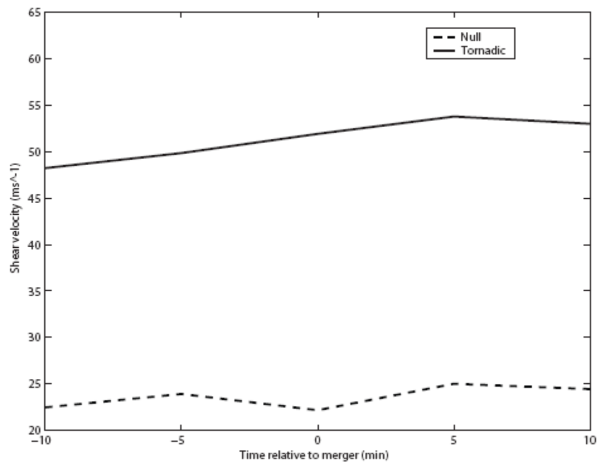

Figure 4. *Composite maximum GGS velocity (ms^{-1}) of the primary cell versus time relative to merger (min). The solid line indicates tornadic cases. The dashed line indicates null cases. Time is in five minute intervals, from ten minutes prior to merger to ten minutes after merger.*

Although the discrepancy is small, it is suggested that higher precipitation loading from the ancillary cell (as indicated by reflectivity) may deter tornadogenesis during cell mergers. The area covered by ancillary cells is also found to be slightly lower for tornadic mergers (not shown).

5. SUMMARY AND DISCUSSION

A strong relationship between cell mergers and tornado occurrence was found. A total of 98 tornado reports occurred over the ten days included in this study. Fifty-three of these tornadoes, or 54%, were associated with a cell merger.

In general, tornadic mergers occur farther away from the primary updraft than null mergers. The mean absolute distance from the updraft, as well as the mean position relative to the primary updraft center, both support this claim. The mean position of tornadic mergers was behind and to the left the primary updraft center (e.g., to the west and north of the updraft center in mean westerly shear). We suggest possible explanations for this relationship here. In null cases, precipitation from the ancillary cell -a maximum at the position of merger- may seed the primary updraft, reducing buoyancy and the stretching of vertical vorticity in lower levels (Fig. 6).

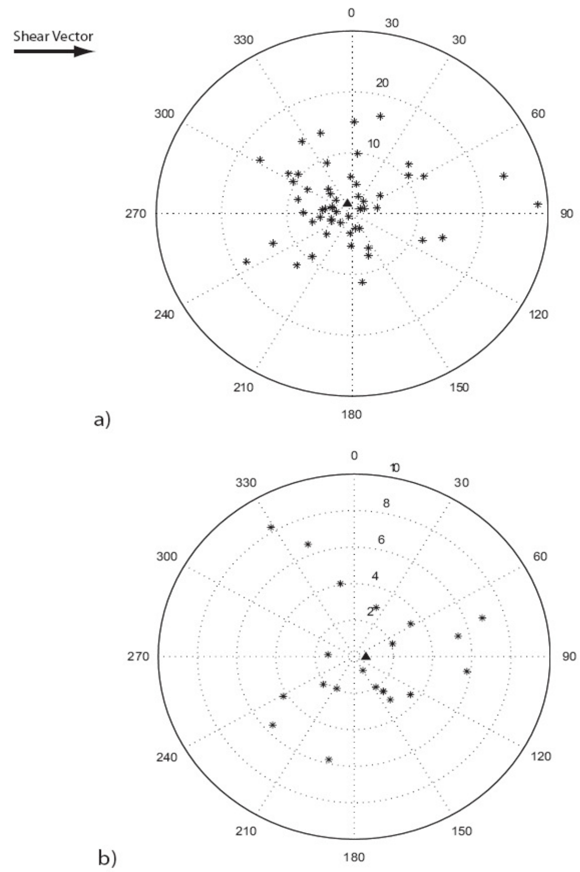

Figure 5. *Location of a) tornadic and b) null mergers relative to the primary updraft center. Radial position (km) and azimuth (º) is displayed for each merger. Positions are adjusted for the mean 850 hPa - 300 hPa shear vector, which is oriented at 90º. The triangle represents the mean merger position. Note the difference in the distance scale between a) and b).*

With tornadic cases, precipitation is less likely to directly affect the primary updraft (Fig. 7). Further, enhanced convergence may occur briefly as ancillary cell outflow interacts with the rear flank gust front of the primary storm. As air from within the RFD surrounds the mesocyclone, an area of convergence is produced on the back side of a (developing) tornado (Fujita 1975). It is posed here that the outflow of the ancillary cell further enhances the area of convergence, though storm-scale observations were unavailable to confirm this hypothesis. Outflow from the ancillary cell may also increase the baroclinic generation of horizontal vorticity within the rear-flank region of the primary storm.

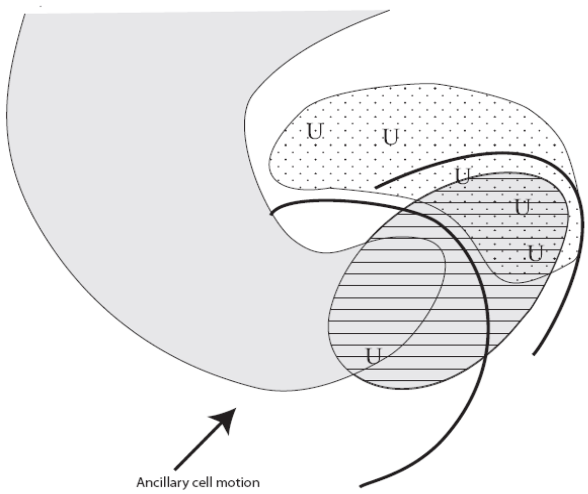

Figure 6. *A schematic diagram of the typical ancillary cell position for null cases within the hook echo region of the primary cell. The solid black lines represent gust fronts. The shaded grey areas represent radar echoes. The striped black region represents the precipitation from the ancillary cell. The dotted region represents the updraft of the primary cell. "U" represents the general area of the updraft in the ancillary and primary cells.*

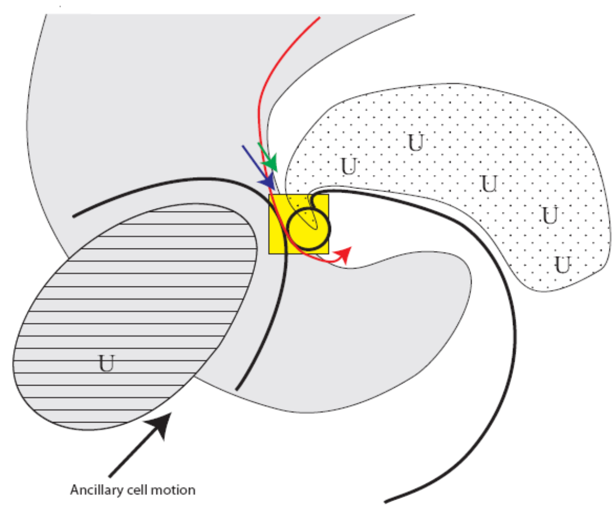

Figure 7. *A schematic diagram of the typical ancillary cell position for tornadic cases within the hook echo region of the primary cell. The solid black lines represent gust fronts. The shaded grey areas represent radar echoes. The striped black region represents the precipitation from the ancillary cell. The dotted region represents the updraft of the primary cell. "U" represents general areas of updraft. The red line represents the typical trajectory of air parcels entering the low-level mesocyclone. The black circle represents possible tornado location. Approximate vorticity vectors prior to (green arrow) and after (blue arrow) baroclinic enhancement of horizontal vorticity are displayed. The shaded yellow region is an area of enhanced convergence.*

Studies have shown that many air parcels enter the low-level mesocyclone after passing through the RFD first (e.g., Lemon and Doswell 1979; Wicker and Wilhelmson 1995; Klemp and Rotunno 1983). Baroclinic vorticity generation in this descending region can be a mechanism for producing strong vertical vorticity near the earth's surface when tilted by the primary storm updraft (Davies-Jones and Brooks 1993). A higher proportion of null cases merge in the immediate vicinity of the updraft center. Though outflow can enhance convergence under the primary updraft regardless of merger position, it is suggested that null merger positions near the primary updraft leave the updraft more vulnerable to ingesting precipitation from the ancillary cell, which would limit the potential for vertical vorticity stretching by the primary updraft. Even if the updraft is not directly affected by the ancillary cell precipitation and outflow in these cases, then the inflow environment may be disrupted.

In most supercells, the inflow is located ahead and to the right of the updraft, which is also the same location where many null mergers occur. Any modulation of the buoyancy in the inflow region would be expected to affect the primary cell.

As outflows contributing to primary and ancillary cell mergers may play a role in promoting tornadogenesis, it would be beneficial to include surface thermodynamic data to determine favorable deficits in θ_e and θ_v for tornadoes and identify precisely when these thermodynamic perturbations interact with the primary updraft. An attempt was made in this study to use the West Texas Mesonet (Schroeder et al. 2005) to retrieve surface thermodynamic data. However, the outflow from ancillary cells in these cases was generally too small scale of a feature to be captured even by the dense network. It is anticipated that rapidly-deployable high-density surface observation networks, such as the newly-developed StickNet (Weiss and Schroeder 2008), will be successful in capturing the thermodynamics and kinematics of cell mergers.

Higher resolution radar data may reveal more subtle differences between tornadic and non-tornadic cell mergers. Many storm-scale features (e.g., Lee et al. 2006) were likely not captured due to the large bin spacing of the WSR-88D. In addition, research-grade mobile radars would provide more accurate measurements of the magnitude and dimension of rotation (i.e., vorticity). Dual-Doppler radar analysis would reveal the three-dimensional wind fields within the primary and ancillary cells during a merger, and would allow for an accurate estimation of convergence near the primary storm updraft.

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