The Bowdle, South Dakota, Cyclic Tornadic Supercell of 22 May 2010: 
Surface Analysis of Rear-Flank Downdraft Evolution and 
Multiple Internal Surges

BRUCE D. LEE AND CATHERINE A. FINLEY
WindLogics Inc., Grand Rapids, Minnesota

CHRISTOPHER D. KARSTENS
Iowa State University, Ames, Iowa

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ABSTRACT

Mobile mesonet sampling in the hook echo/rear-flank downdraft (RFD) region of a tornadic supercell near Bowdle, South Dakota, provided the opportunity to examine RFD thermodynamic and kinematic attributes and evolution. Focused analysis of the fifth low-level mesocyclone cycle that produced two significant tornadoes including a violent tornado, revealed four RFD internal surge (RFDIS) events. RFDISs appeared to influence tornado development, intensity, and demise by altering the thermodynamic and kinematic character of the RFD region bounding the pretornadic and tornadic circulations. Significant tornadoes developed and matured when the RFD, modulated by internal surges, was kinematically strong, only weakly negatively buoyant, and very potentially buoyant. In contrast, the demise of the Bowdle tornado was concurrent with a much cooler RFDIS that replaced more buoyant and far more potentially buoyant RFD air near the tornado. This surge also likely contributed to a displacement of the tornado from the storm updraft. Development of the first tornado and rapid intensification of the Bowdle tornado occurred when an RFDIS boundary convergence zone interacted with the pretornadic and tornadic circulations, respectively. In the latter case, a strong vertical vortex sheet along an RFDIS boundary appeared to be a near-surface cyclonic vorticity source for the tornado. A downdraft closely bounding the right flank of the developing first tornado and intensifying Bowdle tornado provided some of the inflow to these circulations. For the Bowdle tornado, parcels were also streaming toward the tornado from its immediate east and northeast. A cyclonic–anticyclonic vortex couplet was observed during a portion of each significant tornado cycle.

1. Introduction

High-resolution time and space observations in and adjacent to the supercell hook echo/rear-flank downdraft (RFD) region (Markowski 2002) are crucial for understanding the processes involved in tornado development, maintenance, and decay. To understand why some tornadoes are very intense, quite large, and/or long lived, kinematic and thermodynamic observations must be obtained over a wide spectrum of tornadoes. With the rapid evolution of mobile Doppler radar (Wurman et al. 1997; Bluestein and Pazmany 2000; Bluestein and Wakimoto 2003), a considerable number of high-resolution kinematic datasets have been obtained from tornadic supercells. Given the difficulty involved in positioning near-surface observing systems, far fewer datasets, either mobile mesonet (Straka et al. 1996) or StickNet (Weiss and Schroeder 2008), exist to describe proximate tornado or tornadogenesis region thermodynamic and kinematic characteristics. Only a few mesonet studies provide a detailed description of the evolution of the RFD outflow in tornadic supercell cases (e.g., Lee et al. 2004; Hirth et al. 2008; Lee et al. 2010). Furthermore, the number of documented mobile mesonet datasets of the RFD region during a violent tornado [Fujita scale (F) and enhanced Fujita scale (EF) (≥F4 or EF4)] is very small. To our knowledge these cases include the 8 June 1995 Allison and Wheeler, Texas,
tornadoes (Markowski et al. 2002, hereafter MSR02); the 24 June 2003 Manchester, South Dakota, tornado (Lee et al. 2004); and perhaps the 2 June 1995 Friona and Dimmit, Texas, tornadoes (MSR02). The study herein provides analysis of RFD outflow thermodynamic and kinematic characteristics, internal gradients, and evolution over a large portion of a cyclic tornado supercell life span including near-tornado observations during a violent tornado. For economy, hereafter when we are referring to RFD outflow, we will simply use RFD.

Observational studies have shown that the RFD surrounds or nearly surrounds the tornado (e.g., Brandes 1977, 1978; Lemon and Doswell 1979; MSR02), thus, the properties of the RFD within a few kilometers of the tornado are especially important across the tornado life cycle. In particular, buoyancy characteristics of the RFD may play an important role in the development, intensification, maintenance, and diminution of near-surface rotation (e.g., Leslie and Smith 1978; Davies-Jones and Brooks 1993; Adlerman et al. 1999; Davies-Jones et al. 2001; Markowski 2002; Markowski et al. 2003, 2008; Marquis et al. 2012). The analysis of mobile mesonet measurements within the RFD by MSR02 and Grzych et al. (2007, hereafter GLF07) revealed compelling evidence supporting the general conclusion that tornadic and nontornadic supercells had differing RFD thermodynamic characteristics. Specifically, the results of MSR02 (and supported by GLF07) showed that tornado likelihood, intensity, and longevity increase as the near-surface buoyancy, potential buoyancy, and equivalent potential temperature (θe) increase in the RFD, and as the convective inhibition (CIN) in the RFD decreases.

Research focus on the RFD has recently expanded into internal RFD kinematic and thermodynamic gradients, which sometimes manifest as an RFD internal surge (RFDIS). An RFDIS represents a distinct acceleration of the outflow within a previously established RFD. A wind direction change often accompanies the surge. For the RFDISs analyzed herein, a wind speed increase exceeding 13 m s⁻¹ was observed in all cases (the largest wind speed change in a surge was over 28 m s⁻¹). The RFDIS boundary (RFDISB) delineates the kinematic leading edge of the surge. Analysis of mobile mesonet data has associated the onset of the RFDIS to tornadogenesis or tornado intensification (e.g., Finley and Lee 2004; Lee et al. 2004; Finley and Lee 2008; Lee et al. 2010). A broad range of thermodynamic characteristics in these surges have been found, but in cases of tornadogenesis or tornado intensification, the surges have been only weakly negatively buoyant with considerable potential buoyancy [i.e., sizeable parcel convective available potential energy (CAPE)]. In some of these cases the RFDIS displayed substantial increases in virtual potential temperature (θv) and θe from the RFD air preceding it. In mesonet analysis from the 29 May 2008 Tipton, Kansas, tornado, in addition to again finding the RFDIS juxtaposed with the tornado, analysis revealed parcels with only very weak negative buoyancy and considerable potential buoyancy moving out of the left flank of the surge (looking downstream) and into the tornado (Lee et al. 2011). Recent radar observations (e.g., Wurman et al. 2007; Marquis et al. 2008; Skinner et al. 2010; Wurman et al. 2010; Marquis et al. 2012) have also documented the RFDIS and RFDISB (sometimes referred to as a secondary RFD gust front), with a similar storm-relative position to mobile mesonet observations. Using dual-Doppler wind synthesis, Marquis et al. (2012) suggest that for some tornadoes, the RFDISB and RFDIS may play an important role in tornado maintenance by influencing the convergence field surrounding the vortex and through baroclinic generation and tilting of horizontal vorticity.

On 22 May 2010, a cyclic tornadic supercell produced a family of tornadoes near U.S. Highway 12 (HW 12) in north-central South Dakota ([National Climatic Data Center] NCDC 2010). The largest and most intense of the tornadoes occurred near Bowdle, South Dakota, and produced EF4 damage (hereafter called the Bowdle tornado). The Tactical Weather-Instrumented Sampling in near Tornadoes Experiment (TWISTEX) mobile mesonet was able to take coordinated observations within and very near the hook echo region of this storm (hereafter called the Bowdle supercell) for an approximate 2.5-h period starting near the time it attained supercell characteristics (Browning 1964; Rotunno 1993). Within this extended deployment, the notable aspects of the data sampling include the following: 1) a near-ideal sampling array across the tip of the hook just prior to and during development of a significant tornado immediately preceding the Bowdle tornado; 2) observations within the RFD, much of the time at close range, covering nearly the entire life span of the Bowdle tornado; 3) at least five RFDISs, some of which were concurrent with tornado development, intensification, or dissipation; and 4) sampling the RFD and RFD gust front (RFDGF) through numerous low-level mesocyclone (LLM) cycles.

TWISTEX is an ongoing tornado research project with a complement of four mobile mesonet vehicles: M1, M2, M3, and M4. One project team transports an array of quickly deployable probes (Karstens et al. 2010a) designed to sample the tornado and near-tornado environment. The primary objective of the field portion of TWISTEX is to collect thermodynamic and kinematic data with a mobile mesonet in the hook echo/RFD region
of supercells, while also gathering thermodynamic and kinematic data with probes in or very near tornadoes.

2. Synoptic and mesoscale environment

Conditions over portions of South Dakota on the evening of 22 May 2010 were quite favorable for tornadic supercells. A southwest-flow upper-level pattern was present over the northern plains as shown in the 2300 UTC Rapid Update Cycle (RUC) model (Benjamin et al. 2004) 500-mb analysis in Fig. 1. As seen in the 850-mb vector winds in Fig. 1, a strong low-level jet stretched from the upper Midwest into the central plains. During the late afternoon a weak surface low developed in central South Dakota within a trough of low pressure as shown in the 2300 UTC surface analysis in Fig. 2. Southerly to south-southeasterly winds of 15–25 kt (1 kt = 0.5144 m s\(^{-1}\)) were present over southern and eastern South Dakota within the warm sector of this cyclone. Between 2200 and 0100 UTC the winds over northern and northeast South Dakota, southeast North Dakota, and western Minnesota backed, likely in response to a north-northeastward moving area of divergence that was associated with the upper-level jet stream (not shown). Of relevance to the evolution of the Bowdle supercell, winds north-northeast of the surface low and just north of the warm front (Fig. 2) were east-southeasterly to easterly based on mobile mesonet observations. Just prior to and during storm development, mesonet-observed dewpoints in this area were around 70°F with dewpoint depressions roughly in the 6°C–9°F range. The cell that would eventually become the Bowdle supercell formed at approximately 2200 UTC within a short north–south-oriented line segment of cells near the Missouri River north of the surface low.

To assess the deep-convective environment for the Bowdle supercell (see Fig. 2 for cell location), RUC 2300 UTC analysis along with mesonet surface conditions were used to create a representative sounding and hodograph for western Edmunds County (Fig. 3) in north-central South Dakota. This approach was preferred over applying modifications to the Aberdeen, South Dakota, 0000 UTC soundings given the substantial mesoscale wind and thermodynamic gradients in this area. Very large conditional instability was present with lowest 50-mb mixed-parcel CAPE of 4840 J kg\(^{-1}\). CAPE in the 0–3-km layer was 171 J kg\(^{-1}\), a value considered favorable for tornadic supercells (Rasmussen 2003). CIN for the lowest 50-mb parcel ascent was 52 J kg\(^{-1}\). The virtual temperature correction was applied to the parcel temperature ascent curve as described in Doswell and Rasmussen (1994) for the CAPE and CIN calculations. The lifting condensation level (LCL) was 575 m, representing another significant tornado environment attribute (Rasmussen and Blanchard 1998; Thompson et al. 2003).

The low- and deep-layer shear for north-central and northeast South Dakota was conducive for storm rotation. Deep-layer 0–6-km vector shear of 32 m s\(^{-1}\) was more than sufficient to support supercells (Weisman

![Fig. 1. Geopotential height field at 500 mb (m, solid lines) and vector winds at 500 (black arrows) and at 850 mb (gray arrows) for 2300 UTC 22 May 2010 (from RUC analysis). (bottom right) The maximum wind vectors (m s\(^{-1}\)) are shown.](image1)

![Fig. 2. Surface synoptic analysis at 2300 UTC 22 May 2010 with mean sea level pressure and subjective frontal positions. Temperature (°F), dewpoint (°F), and wind speed (half barb 5 kt, full barb 10 kt) are plotted in the station models. Isobars are shown every 2 mb. The gray dot locates the Bowdle supercell at 2300 UTC.](image2)
and Klemp 1982; Rasmussen and Blanchard 1998; Thompson et al. 2003). Storm-relative helicity (SRH) of 306 m$^2$s$^{-2}$ for the 0–3-km layer was favorable for supercells (Rasmussen and Blanchard 1998; Thompson et al. 2003) and SRH of 240 m$^2$s$^{-2}$ for the 0–1-km layer suggested enhanced potential for tornadic supercells (Rasmussen 2003; Thompson et al. 2003). The 0–1-km energy helicity index (Hart and Korotky 1991) of 7.3 and significant tornado parameter of 9.8 were very favorable indicators of a significant tornado environment as shown by Rasmussen (2003) and Thompson et al. (2003, 2004), respectively.

3. Data collection and methodology

A mobile mesonet (hereafter, mesonet) with station design similar to that presented by Straka et al. (1996) was used to measure temperature, pressure, humidity, and wind velocity in and near the supercell hook echo/RFD region. (Table A1 provides a list of mesonet station instrumentation and accessories used by TWISTEX.) Field procedures were developed such that a global positioning system could be used for vehicle direction at all times eliminating the need for a flux gate compass. Data were collected every 1 s.

Instrument bias correction and quality control procedures were similar to those described by MSR02 and GLF07, and are detailed in Lee et al. (2011). In addition, thermodynamic observations were removed from stations M1 and M3 between 2321:30 and 2329:40 UTC because of suspected thermistor wetting that occurred in the wake of a semitrailer truck that lofted a substantial spray plume. A check was made to identify time periods where tailwinds were present at an intensity to cause a substantial reduction in the flow through the “J”-shaped aspirated radiation shield housing the temperature and relative humidity sensors. The high-speed fans used in the TWISTEX mesonet radiation shields (see Table A1), with volumetric output about 1.5 times the fans used in the original Straka et al. (1996) design, mitigated this problem somewhat. Tailwind periods that likely reduced ventilation through the radiation shield were identified and indicated on the applicable graphics in section 4. These periods do not represent invalid data, but rather, the data may reflect a reduced effective response time.$^1$ Last, because of a temporary barometer dropout, pressure for M1 between 2330:00 and 2341:56 UTC was estimated from nearby mesonet stations using time and distance weighting. During this period the nearest station was within 0.5 km of M1 and the elevation difference between M1 and nearby mesonet stations was only a few meters. The M1 pressure errors from this estimation process were assuredly less than 1 mb resulting in negligible changes in the derived thermodynamic quantities described below.

Derived thermodynamic variables were calculated in addition to the variables measured directly by the mesonet. The equivalent potential temperature, $\theta_e$, was calculated as in MSR02 and GLF07 using the formula derivation of Bolton (1980). If moist entropy is approximately conserved for adiabatic processes, then $\theta_e$ can be useful in parcel origin height analysis, assuming a number of caveats outlined in section 4c. In surface parcel spatial comparisons, higher $\theta_e$ implies a rightward shift in the parcel path on a skew $T$–log$p$ diagram, and thus, higher potential buoyancy. Since fluctuations in the virtual potential temperature, $\theta_v$ (Glickman 2000), from a base-state value are proportional to buoyancy, $\theta_v$ was calculated to assess RFD buoyancy characteristics. No hydrometeors were assumed to be present for the $\theta_v$.

$^1$ Note that stagnation in the radiation shield only occurs for tailwind strength that roughly balances fan aspiration. Stronger tailwinds ventilate the radiation shield through rear-to-front flow.
calculations. We had little confidence in estimating the liquid water mixing ratio ($q_l$) from radar reflectivity since 1) the lowest elevation of the Weather Surveillance Radar-1988 Doppler (WSR-88D) radar beam from Aberdeen, South Dakota (KABR), was over 1 km above ground level (AGL) for much of the sampling period; and 2) the rain intensity, when encountered by the teams, varied markedly on small space and time scales. Fortunately, and due in large part to the Bowdle supercell maintaining a classic structure (Moller et al. 1994) for most of the operations period, precipitation exceeding a qualitative moderate intensity was only encountered by the teams during 1) a few brief periods of roughly 10–20 s where close-in teams encountered very narrow rain curtains, 2) an approximate 2-min period near the end of the Bowdle tornado at a point in the RFD evolution where outflow already had large negative $v_u$ departures from the base state, and 3) during a 1–2-min period relatively late in the seventh LLM cycle. Although the exclusion of $q_l$ in the formal calculation of $\theta_v$ results in less accurate values, only small errors in $\theta_v$ are expected given the rainfall intensity experienced during all precipitating periods except the short episodes listed above. For example, had the radar reflectivity been 40 dBZ when teams were in moderate precipitation, an overestimate in $\theta_v$ of about 0.23 K would be incurred from neglecting the $q_l$ estimated from the parametrization of Rutledge and Hobbs (1984). In the few and brief periods of substantially heavier precipitation, larger overestimates of $\theta_v$ as presented by Shabbott and Markowski (2006) would be expected. Teams observed falling hail in two brief instances near and north-northeast of the neck of the hook echo (Forbes 1978) along HW 12 (Fig. 4). In these cases, only a few hail stones were observed falling over a 1–2-min period. The stones were generally in the 2.5–4.3-cm-diameter range.

The CAPE and CIN for all data points were calculated using the sounding developed from RUC 2300 UTC analysis data (Fig. 3) and surface conditions provided by the mesonet. The CAPE and CIN are based on surface parcel ascent and include a virtual temperature correction. Surface elevation for the sounding was adjusted to be consistent with the elevation of the mesonet data.

To obtain the perturbation virtual potential temperature ($\theta_v'$) and perturbation equivalent potential temperature ($\theta_e'$), base states were determined from mesonet storm-inflow observations similar to GLF07, Hirth et al. (2008), and Lee et al. (2011). It is noteworthy that the difference in inflow $\theta_v$ ($\theta_e$) at the beginning and end of the 2.5-h operations period was only $-0.4$ K ($-0.6$ K).

For portions of the analysis, data points were plotted relative to KABR radar data using time-to-space conversion as described by MSR02 (for reference, KABR is located 97 km east of Bowdle). This process put the mesonet data into the storm’s frame of reference. Time intervals of 5–6-min were used for most of the time–space conversion plots consistent with the approximate time for a single WSR-88D volume scan; however, kinematic and thermodynamic structures near the hook echo are not in steady state for this length of time, so the wings of plotted data carry less credence. For example, in a typical 5-min time–space analysis, a feature captured on the wings of the analysis (2.5 min from the analysis center time) moving 10 m s$^{-1}$ faster than the assumed storm motion could be depicted 1.5 km from its actual storm-relative position. Storm motion for time–space conversion was calculated from the average motion of the mesocyclone centroid (using KABR 0.5° radial velocity) except during the Bowdle tornado. In the latter case, the calculated motion of this tornado, which at times encompassed a substantial portion of the LLM, was used. To remove some of the very small time-scale fluctuations, 5-s averages were applied to the wind and thermodynamic data except where noted.

4. Observations and analysis

a. Deployment overview

The initial mesonet deployment targeted the hook echo/RFD region of the developing Bowdle supercell along U.S. Highway 83 in central Walworth County around 2235 UTC. The general mesonet deployment strategy on this day was to establish a north–south array in front of the RFDGF, let the RFDGF and RFD sweep over the mesonet, transect the hook with a moving array as the mesonet repositioned to get back in front of the RFDGF, and continue to repeat this process. This sampling strategy was made possible by a good road network and relatively low mean storm motion of 11 m s$^{-1}$ toward the northeast (early mature) or east-northeast to east (mature) as shown in Fig. 4. Of particular interest was the period between 2304–2348 UTC during which the supercell produced two substantial tornadoes, the second being the Bowdle EF4 tornado (Fig. 4). Data collection continued up to about 0100 UTC, at which time, the Bowdle supercell transitioned to a high-precipitation supercell structure (Moller et al. 1994). In summary, the mesonet took nearly continuous observations in/near the Bowdle supercell hook echo/RFD region from about 2235–0100 UTC.

b. Spatial analysis

Analysis of data collected over the fifth low-level mesocyclone cycle (LLM5, Fig. 4) is the primary focus of
this subsection. LLM5 developed about 2304 UTC and was larger and much more intense than previous cycles based on visual and radar observations. Two significant tornadoes formed during this cycle, the first of which developed at 2313 UTC and lasted 6 min. This visually substantial tornado, rated EF1 (NCDC 2010), stayed over open agricultural land, so there were few damage indicators aside from downed power poles to estimate tornado intensity. Teams positioned such that the hook echo/RFD would pass over the mesonet roughly 10 km northeast of Lowry (Fig. 4). The mesonet sampled the early RFD with this cycle as the RFDGF crossed over the teams between 2304–2305 UTC as shown in Fig. 5. The air immediately behind the RFDGF, as sampled by the three southern stations, was similar in thermodynamic character to the inflow air, but over the next several minutes as the mesonet sampled deeper into the RFD, $\theta_v$ and $\theta_e$ deficits were generally in the 1–2- and 6–8-K ranges, respectively. Within the first several kilometers west of the RFDGF, the ground-relative west to west-southwest winds were only in the 7–11 m s$^{-1}$ range.

The mesonet established a north–south array in front of the projected path of the tip of the hook echo as it evolved into a hammerhead shape between 2305 and 2309 UTC as shown in Fig. 6. During this time the LLM intensified markedly based on the visibly observed rotation rate of the associated wall cloud (Fig. 7). Near-ideal mesonet positioning in a north–south array covered most of the hook echo tip while a developing (tornado cyclone) TC-scale (Agee et al. 1976) cyclonic circulation (~2 km wide) passed over the northern part of the area.

![Figure 4. Bowdle supercell radar reflectivity (dBZ) at 0.5° tilt from KABR over a time period centered on deployments within LLM5 that cover the first and second tornadoes. Tornado paths are depicted with approximate width and red triangles show the location of the tornadoes at the radar update time. The bold dark gray lines denote primary mesonet deployment routes. Dashed white lines separate precipitation core regions between radar frames. Dashed rectangles correspond to display regions for Figs. 6, 11, and 14. Inset shows tracks of the first 7 LLMs with cycle number and approximate beginning and ending times. Brown and green lines in inset are reference highways and county boundaries, respectively. All times are in UTC.](image-url)
of the mesonet as shown in Fig. 6. The hammerhead hook echo tip shape appeared to be associated with counter-rotating circulation manifest in the storm-relative velocity data. This vortex couplet is strikingly similar to that shown in the numerical and observational research of Straka et al. (2007) and Markowski et al. (2008) in conjunction with their analysis of vortex arches and related baroclinic generation and tilting of horizontal vorticity. Perhaps related to the vortex couplet, the middle portion of the mesonet detected a boundary with limited southerly extent just leading the couplet (Fig. 6). Ground-relative wind speeds increased about 8 m s\(^{-1}\) just behind this boundary; however, this was substantially less than that observed for the RFDISs featured herein. This boundary may represent the leading edge of a late-stage RFDIS.

As shown by MSR02 and GLF07, tornado likelihood and intensity appear related to thermodynamic characteristics of the RFD outflow. For the analysis centered on 2309:03 UTC (Fig. 6a), deficits in \(\theta_e\) are small throughout the hook echo tip, with values generally between 1 and 2.5 K. The magnitude of the \(\theta_e\) departures, reflective of only weak negative buoyancy, are generally consistent with those associated with tornado environments by MSR02 and GLF07. In contrast with the relative consistency of \(\theta_e\) across the hook echo tip, \(\theta_e\) varied markedly. In the middle portion of Fig. 6b large south–north \(\theta_e\) gradients were present across the hook echo tip, with the largest \(\theta_e\) deficits along the north side of the TC and in a region about 3 km south of the TC near an anticyclonic circulation in the wind field. Across the middle portion of the array \(\theta_e\) increased from east to west (i.e., farther into the RFD). For much of the hook echo tip, especially west of an approximate north–south line bisecting the hook tip, \(\theta_e\) deficits were near those found by MSR02 for RFDs associated with significant tornadoes.

The mesonet array across the hook echo tip afforded the opportunity to analyze the divergence field. A two-pass Barnes objective analysis scheme (Barnes 1964; Koch et al. 1983) was applied to the time–space converted mesonet velocity components, confined by the mesonet station positions, to interpolate the data to a two-dimensional grid for divergence analysis. To prevent overweighting the analysis with closely spaced west–east points compared to the north–south data point spacing (dictated by the mesonet team spacing of roughly 1100 m), data were subsampled at 30-s intervals before the objective analysis. This process resulted in average east–west data spacing of approximately 300 m. The average data spacing used in calculating the smoothing parameter in the weighting scheme and in selecting the interpolation grid spacing was 600 m [computed as suggested by Koch et al. (1983) for data distributions with a substantial degree of non-uniformity]. The interpolation grid spacing was 250 m.

As shown in Fig. 6a, a well-defined divergence–convergence couplet exists with a convergent wind field in/near the TC and divergent wind field bounding this region to the south and southeast. Peak divergence and convergence in these areas were \(6 \times 10^{-3} \text{s}^{-1}\) and \(1.5 \times 10^{-2} \text{s}^{-1}\), respectively, limited in magnitude somewhat by the objective analysis interpolation grid. The divergence field closely matches that documented to the right of the tornado track by Lee et al. (2011) for the 29 May 2008 Tipton, Kansas, tornadic supercell. In the Tipton case, parcels possessing only very weak negative buoyancy moved out of a bounding downdraft and into the right and front flank of the tornado. Similarly, in this analysis parcels with only weak negative buoyancy (\(\theta_e\) deficits of 1–2 K) are moving out of the divergence/downdraft region and being ingested into the right and front flank of the TC. Parcels within this region of the RFD had large potential buoyancy with CAPE in the 3300–3700 J kg\(^{-1}\) range.

A noteworthy aspect of Fig. 6a is the north–south convergence region aligned along an RFDISB that connects up to the TC convergence area. This RFDISB convergence pattern and interaction with a convergent TC is similar to that presented by Marquis et al. (2008, 2012) for dual-Doppler analysis of the LLM and RFDISB of the 30 April 2000 Crowell, Texas, tornadic supercell. Tornado formation herein occurred as the RFDISB translated around the right side of the TC (see Fig. 8). Marquis et al. (2012) suggested a tornado maintenance connection created by boundary-augmented convergence. The present case appears to extend this connection to tornado development.

The divergence analysis in Fig. 6a and \(\theta_e\) field in Fig. 6b (see section 4c for details on \(\theta_e\)-inferred parcel origins), imply a complex vertical velocity pattern in the hook tip. The enhanced divergence region within the RFD just south through east of the TC, suggests the possibility of localized downdraft forcing that may differ in mechanism from the broader RFD. The location and scale of this feature is suggestive of an occlusion downdraft similar to that shown in numerical simulations (e.g., Klemp and Rotunno 1983; Adlerman et al. 1999) and observations (e.g., Wakimoto and Cai 2000). Occlusion downdrafts are driven by a dynamically induced downward-directed vertical pressure gradient force associated with the intensification of low-level vertical vorticity. Outflow from this downdraft appears responsible for the boundary just east of the divergence region in Fig. 6. The hook echo tip is partially bisected by implied low-level updraft associated with RFDISB convergence.
that connects to the TC convergence/updraft area. A small-scale feature of interest in Fig. 6b is the very narrow arc of larger $\theta_e$ deficits that run from east of the TC to north-northwest of it. Video evidence reveals this region roughly corresponds to a narrow rain curtain rotating around the east and north side of the LLM. The time scale of this feature results in the time–space depiction of $\theta_e$ to locally break down as evidenced in
FIG. 6. (a) $\theta_v$ perturbations (K) and divergence and (b) $\theta_v$ perturbations (K) for a 5-min period centered on 2309:03 UTC KABR 0.5° tilt reflectivity. Winds are storm relative. Solid (outlined) lines are divergence (convergence) for values 0.005 and 0.0025 s$^{-1}$ ($-0.01$ and $-0.005$ s$^{-1}$). Largest divergence (convergence) isopleths are bold. The dashed bold line depicts an RFDISB and the thin dashed line designates a possible late-stage RFDISB. Extension to time–space analysis used to place RFDGF. Tornado track hatched. TC and anticyclonic circulations indicated. Other details are as in Fig. 5. See inset of Fig. 4 for storm-relative domain.
the large $\theta_e$ gradient across adjacent points in the analysis. As will be addressed in section 4c, parcels along the arc appear to have a descended from a higher origin level than those in adjoining regions.

Between 2310:40–2311:30 UTC, the RFDISB passed through the mesonet accompanied by an abrupt increase in wind speed and backing storm-relative direction (as indicated in Figs. 6 and 8). Associated with this RFDIS, just southwest of the TC, $\theta_v$ and $\theta_e$ increased by roughly 0.5–1.0 and 1.5–2.0 K, respectively (Fig. 8). While $\theta_v$ at the southernmost station increased by a similar amount, a much larger increase in $\theta_e$ of nearly 6 K was realized. In addition to parcels within the surge having only weak negative buoyancy, these parcels possessed large potential buoyancy with CAPE increasing to around 4000 J kg$^{-1}$. Tornado formation occurred ~2 min after RFDISB passage about 1.5 km east of the mesonet. Figure 7 shows this substantial tornado a few minutes later.

Although the foray of M4 into the forward-flank reflectivity gradient (FFRG) was brief (Fig. 8), the comparatively cool thermodynamics along the FFRG stand in marked contrast to those observed within the RFD. The peak $\theta_v$ and $\theta_e$ deficits ($-4$ and $-13$ K) tended to be slightly to moderately larger for $\theta_v$, and much larger for $\theta_e$, than typical for tornadic supercells based on the forward-flank downdraft analysis of Shabbott and Markowski (2006) and FFRG analysis of Skinner et al. (2011). Given the rearward FFRG sampling location, perhaps smaller $\theta_v$ and $\theta_e$ deficits lie farther east.

The Bowdle tornado developed at 2319 UTC roughly concurrent with the dissipation of its predecessor. The remnant circulation of the first tornado appeared to merge with a TC-scale circulation associated with the Bowdle tornado. Tornado track and intensity characteristics, determined from damage survey information by the National Weather Service and TWISTEX, along with extensive videography, are shown in Fig. 9 (see Karstens et al. 2010b for details). The tornado formed 11 km west-southwest of Bowdle and moved at an average speed of about 8 m s$^{-1}$ to the east-northeast over its 27-min life span. Peak damage path width of 1100 m and EF4 intensity (NCDC 2010) occurred to the northwest and north of Bowdle.

The mesonet quickly repositioned on HW 12 during the genesis and early development of the Bowdle tornado (Figs. 4 and 9). The tornado began as a broad circulation that quickly developed secondary vortices, one of which became dominant (Fig. 10a). After a brief period of weakening, the tornado rapidly grew in width and intensity (Fig. 10b) near the time it passed over HW 12 at 2324:20 UTC. Over the following 5–6 min the tornado became wide (nearly 1 km) and very intense (Figs. 9 and 10c). Most of the mesonet was embedded in RFD before tornado development.

M4’s positioning along HW 12 before the tornado crossed the road allowed RFD sampling within 2 km of the tornado 2–3 min after tornado formation. Figure 11 displays LLM-relative mesonet observations for a 6-min period centered on 2327 UTC. An RFDIS and associated boundary were detected along with an area of marked divergence about 1 km to the south and southeast of the tornado. Downdraft above this divergence region was evident in videography showing rapidly descending cloud tags. The location and scale of this feature, similar to that observed just before the previous tornado, is suggestive of an occlusion downdraft. The RFDIS was kinematically strong with peak 1-s wind speeds of 40 m s$^{-1}$ for both M1 and M4 south of the tornado. Perhaps related to this surge, an anticyclonic circulation juxtaposed to the east of the tornado became evident in videography roughly 5–6 min after the RFDISB passed over M1 and M4. Similar to the previous tornadic cycle, parcels with weak negative buoyancy were located near the tornado; however, farther rearward within the RFD, parcels were substantially more negatively buoyant ($\theta_e$ of $-4$ to $-5$ K) and had much larger $\theta_e$ deficits ($\theta_e$ of $-12$ to $-15$ K). Where
FIG. 8. (a) $\theta_v$ perturbations (K) and (b) $\theta_u$ perturbations (K) for a 6-min period centered on 2313:33 UTC KABR 0.5° tilt reflectivity. The tornado location at the analysis center time is indicated with a red triangle. RFDGF position is based on KABR radial velocity and consistency with prior time–space analysis. Other details are as in Fig. 6.
observations exist, the storm-relative flow was not transporting the larger $\theta_v$ and $\theta_e$ deficit air toward the tornado.

The positioning of M4 at locations along HW 12 as the tornado approached and then passed over the highway allowed the flow field bounding the tornado to be sampled. Figure 12 shows the tornado-relative position of M4 with parcel characteristics and tornado-relative winds for 2319:24–2329:37 UTC. This period corresponds to data collection roughly coincident with initial tornado development through a phase of rapid intensification and widening (Fig. 10). The central 6 min of this period correspond to an interval of M4 observations closely bounding the tornado that covers about a 280° arc around the circulation. Two boundaries are depicted in Fig. 12, both having kinematic and thermodynamic signatures, especially the southeastern RFDISB. The boundary northwest of the tornado may be the leading edge of a late-stage RFDIS that wrapped well around the LLM; however, the wind field change across and behind (east of) this boundary, modest relative to other surges presented herein, precludes a confident designation of the boundary being an RFDISB. For reference, KABR radial velocity at 2322:31 and 2327:00 UTC indicated a portion of the RFDGF was located along an arc roughly 3–4 km north through southeast of the approximate tornado location (Fig. 11). Deficits in $\theta_v$ bounding the tornado were small ranging from about 0.5 to 2.5 K (Fig. 12a). Notably, from east through northeast of the tornado aligned along the tornado track, $\theta_v$ was close to storm inflow values. Somewhat larger, but still relatively weak, negative buoyancy resides within about 2 km behind the southeastern RFDISB with $\theta_v$ ranging from $-1$ to $-2.5$ K. Considering the large radial component of the tornado-relative flow to the south and east through northeast, air ranging from near-neutral buoyancy to weak-negative buoyancy is quickly converging toward the tornado. The buoyancy environment is generally consistent with the findings of MSR02 and GLF07. Larger negative buoyancy exists beyond about 2 km southwest of the tornado; however, the motion of these parcels is not toward the tornado.

Air bounding the tornado had somewhat higher $\theta_e$ deficits than typically found in RFDs associated with supercells producing significant tornadoes ($<4$ K; MSR02). As shown in Fig. 12b, from northwest through east-southeast, $\theta_e$ deficits were generally 4–6 K. These values increased substantially within the southern RFDIS with $\theta_e$ deficits exceeding 8 K south of the tornado. Still larger deficits (>12 K) existed several kilometers farther

Fig. 9. Bowdle tornado track, life cycle stage, and general implied intensity.

Fig. 10. Bowdle tornado as observed from the (a) north by M4 at 2320:22 UTC (approximately 1.5 min after formation), (b) west by M1 at 2325:30, and (c) south by M2 at 2330:37 UTC. Note that all images are wide-angle perspectives.
west-southwest, but these parcels were not moving toward the tornado. Although relatively large, \( \theta_e \) deficits south of the tornado do not imply midlevel parcel origins as will be discussed in section 4c. The large gradient in \( \theta_e \), and to a lesser extent \( \theta_v \), underscore the thermodynamic heterogeneity found within the RFD of some supercells (e.g., MSR02; Finley and Lee 2008; Hirth et al. 2008; Lee et al. 2010). Similar to \( \theta_v \), the warmest RFD \( \theta_e \) values were found along the tornado track to the east-northeast.

Large potential buoyancy existed in the near-tornado environment as evidenced by CAPE values exceeding 3000 J kg\(^{-1}\) nearly surrounding the tornado (Fig. 12c). It is notable that CAPE values exceeded 4000 J kg\(^{-1}\) along the projected tornado track. Even well back into the cooler air 4 km southwest of the tornado, CAPE was still greater than 2000 J kg\(^{-1}\). CIN values were smallest along the projected tornado path with values around 100 J kg\(^{-1}\) (Fig. 12d). Overall, the CIN values

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**Figure 11.** (a) \( \theta_v \) perturbations (K) and (b) \( \theta_e \) perturbations (K) for a 6-min period centered on 2327:00 UTC KABR 0.5° tilt reflectivity. In the hook echo tip region, M4 is closest to the tornado, followed by M1 and M2. Other details are as in Fig. 8. See inset of Fig. 4 for storm-relative domain. The location of the RFDGF was based on KABR radial velocity.
nearly surrounding the tornado were similar to those found for RFD associated with significant tornadoes (MSR02).

Noteworthy aspects of the flow field shown in Fig. 12 are the strong vertical vortex sheet and marked convergence aligned along the RFDISB to the east of the tornado. The cyclonic vertical vorticity and convergence calculated along the sheet are 0.04 and 0.05 s$^{-1}$, respectively, with the caveat that these are rough estimates due to the limitations of the sampling density near the RFDISB and of the time–space conversion. Importantly, given the flow field configuration, from a tornado-relative perspective, cyclonic vorticity appears to be moving into the front flank of the tornado through a layer starting from near the surface. Additionally, the strong RFDISB convergence zone appears to intersect the tornado. Although we cannot determine how long this potentially significant boundary–tornado interaction lasted, Marquis et al. (2012, see their Fig. 6) have recently shown very similar RFDISB–tornado/tornado cyclone configurations that lasted around 10 min.

During the period between 2329 and 2342 UTC over which the Bowdle tornado reached its peak width and intensity (Fig. 9), mesonet data were collected from
southwest through east of the tornado. The tornado was wedge shaped over much of this time as shown in Fig. 13. Starting at about 2337:30 UTC, a kinematically strong and relatively “warm” RFDIS was sampled (Fig. 14). The average increase in the 5-s winds for the mesonet was over 14 m s\(^{-2}\) with peak 1-s winds in this surge of between 30–32 m s\(^{-2}\) at the northernmost three stations. Directly after RFDISB passage, \(\theta_v\) and \(\theta_e\) increased by about 1 and 3–4.5 K, respectively, while CAPE rose to around 4300 J kg\(^{-2}\). Within this RFDIS \(\theta_v\) increased to within 1 K of storm inflow. Between 2337–2340 UTC, the tornado contracted from a wedge structure to a wide cylinder (Fig. 13) with violent motion observed near the surface. Damage survey evidence was consistent with the visual impressions (EF4, Fig. 9). The timing of this contraction and intensification appeared associated with this intense and relatively warm RFDIS.

Another RFDISB passed over the mesonet at about 2342 UTC with this surge having a drastically different thermodynamic character as shown in Fig. 15.\(^2\) The surge was accompanied by winds veering to the northwest at the northern stations and intensifying, with peak 1-s speeds of 25–30 m s\(^{-1}\) over the entire mesonet. The surge had large negative buoyancy with \(\theta_v\) dropping 5–6 K at all stations. A dramatic drop in \(\theta_e\) was observed with values falling about 15–18 K. Parcel potential buoyancy fell rapidly with CAPE dropping under 1000 J kg\(^{-1}\), while CIN rose to roughly 600 J kg\(^{-1}\). Notably, the onset of this cold surge coincided with the tornado contracting and ultimately dissipating near 2346 UTC.

c. Parcel origins

A comparison was made between the RFD \(\theta_e\) and the inflow sounding vertical profile of \(\theta_e\) (Fig. 16) to determine the height AGL on the inflow sounding with equivalent \(\theta_e\) values to those sampled. If the assumption is made that moist entropy is approximately conserved, it is possible that the height from which the surface outflow parcels originated was near the corresponding height on the inflow sounding with the same \(\theta_e\) value. Caveats to the application of this assumption include influences of entrainment and acknowledgment that a parcel path may include large vertical excursions before arriving at the surface. A limitation on the analysis involved a low-level \(\theta_e\) vertical profile that made it difficult to differentiate inflow sounding matching heights within the surface–950-m layer.

Consistent with past tornado-associated RFD thermodynamic studies of MSR02 and Lee et al. (2011), RFD parcel origin heights were not reflective of mid-level air, but relatively low-level source regions. For instance, when considering RFD in/near the hook echo tip in Figs. 6, 8, 11, 12, and 14, with some exceptions, the area largely contains parcels associated with the 1000–1300-m layer. Even in some regions with relatively large \(\theta_e\) deficits, matching inflow sounding heights were not particularly high because of the vertical profile of \(\theta_e\) that falls off very quickly with height above 1 km (e.g., \(\theta_e\) of \(-17\) K associated with 2 km AGL). The lowest parcel origination heights of roughly 1 km were found within the warm RFDIS shown in Fig. 14. In contrast, parcels associated with the largest heights of around 2100 m were found in the cold RFDIS shown in Fig. 15. Other locations of higher origination heights were found on the southern periphery of the hook echo tip in Fig. 6 (1700 m), within an arc of lower \(\theta_v\) aligned with a narrow rain curtain east and north of the TC in Fig. 6 (1600 m), along the FFRG in Fig. 8 (1900 m), and along the hook echo neck west of the tornado in Fig. 11 (1900 m).

It is plausible in RFD areas of modest \(\theta_e\) deficit that parcels originated in storm inflow below 1 km, rose some distance in the storm updraft, and then were forced to descend by a downward-directed dynamic pressure

\(^2\) Because of the tornado and LLM slowing to 2–3 m s\(^{-1}\), the spatial distribution of observations in the time–space format is compressed.
gradient force while undergoing some mixing with air along the trajectory. This process could lead to the observed lower $\theta_e$ values compared to storm inflow. Observed precipitation rates make hydrometeor drag a less likely primary downdraft forcing mechanism. Small $\theta_e$ deficits, largely reflective of only small temperature differences from inflow values, reduce the possibility that evaporative cooling is primarily driving the “warmer” portions of the strong RFD, especially when considering the vertical profile of dewpoint depression in the lowest 2 km of the sounding (Fig. 3).

d. **Contrasting RFD characteristics between and within LLM cycles**

The RFD heterogeneity over the duration of LLM5 is a striking feature of that cycle (section 4b); however, the
extended data collection also allows the comparison of RFD characteristics of different LLM cycles (see inset of Fig. 4). To facilitate the comparison of RFD characteristics between LLM cycles and to more readily present intra-RFD heterogeneity, sampling region information and thermodynamic and kinematic data analyses are presented in Fig. 17 and Table 1. Eight cases of RFD and RFDIS analysis are examined comprising several LLM cycles spanning a roughly 1.5-h period. In an effort to mitigate instrument equilibration

**Fig. 15.** (a) $\theta_v$ perturbations (K) and (b) $\theta_v$ perturbations (K) for a 5-min period centered on 2343:54 UTC KABR 0.5° tilt reflectivity. Data are separated by 20 s. Other details are as in Fig. 8. Nested inset shows area depicted in main graphic. Because of the difference between the slow LLM reference speed (2–3 m s$^{-1}$) and much-faster RFDISB speed (confirmed by KABR radial velocity), the time–space conversion depicts the RFDISB as being more north–south oriented than its actual configuration (northern portion of the boundary located farther east.)
effects on the analysis and to better represent airmass properties of the RFD or RFDIS being studied, mesonet thermodynamic data were not used within a 1-min period after crossing an RFDGF or RFDISB. Additionally, no mesonet data were used 3 km rearward of an RFDGF or RFDISB to better isolate readings to the feature being examined.

The initial deployment on the Bowdle supercell during its first LLM cycle (case 1) shared very similar RFD buoyancy and potential buoyancy characteristics to that observed for case 2 (RFD), and to slightly lesser extent, cases 3 (RFDIS) and 5 (RFDIS) of LLM5, with small θ_e deficits and very large CAPE (Table 1). A prominent difference between nontornadic case 1 and all LLM5 cases, especially those associated with significant tornadoes, was in the observed kinematic strength. Perhaps this is best seen in the maximum 20-s mean wind speeds (Max Wspd20s) with the peak speed in case 1 of only 8.9 m s⁻¹ compared with peak speeds exceeding 20 m s⁻¹ for all tornadic LLM5 cases.

Although stronger than case 1, RFD wind speeds associated with weakly tornadic LLM7 comprising cases 7 and 8 were substantially lower than the tornadic portions of LLM5. For context, at approximately 0004 UTC, tornado development was observed roughly 3 km north-northwest of Gretna (Fig. 4). Visibility of the tornado was lost at 0009:40 UTC as the wide, multiple-vortex circulation of relatively weak intensity became shrouded in precipitation. We believe this could be the EF0 tornado reported in Storm Data (NCDC 2010) with a dissipation time of 0012 UTC 6.5 km northeast of Gretna, albeit with a start time 6 min earlier than reported. The non-RFDIS part of the RFD of LLM7 (case

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**Fig. 16.** Vertical profile of θ_e (K) for the inflow sounding.

**Fig. 17.** Mesonet storm-relative sampling regions (gray) for RFD and RFDIS thermodynamic and kinematic characteristics presented in Table 1. The sampling regions depicted reflect mesonet data coverage (area within 1 km of a mesonet observation) and are limited in east–west dimension by the RFDGF (bold line), RFDISB (dashed bold lines), or a 3-km distance from boundary restriction (see text for details). The thin line corresponds to KABR 35-dBZ radar reflectivity at 0.5° tilt and outlines the Bowdle supercell hook echo at eight reference times (UTC). The filled circle indicates the approximate mesocyclone centroid indicated from 0.5° tilt KABR Doppler radial velocity.
had relatively weak winds very similar in strength to case 1 (Table 1). Although a distinct increase to 16.1 m s⁻¹ in the Max Wspd20s was observed in the RFDIS of LLM7 (case 8), the wind speed strength was substantially below the tornadic portions of LLM5 and the duration of the stronger winds in the RFDIS was quite short (~2 min). Case 7 had buoyancy, potential buoyancy, and θₑ values similar to that seen for other cases (e.g., case 3). In contrast, the RFDIS of this cycle (case 8) was associated with markedly falling values of these quantities and rising inferred parcel origin height and CIN. At comparative distances within a few kilometers of the tornado, this RFDIS was generally cooler than the surges observed in LLM5 except the final surge.

Large intra-LLM cycle RFD thermodynamic and kinematic variability is an obvious feature of this dataset as shown previously and quantified in Table 1. Considering, for instance, parcel buoyancy in LLM5, θₑ ranges from +0.7 K in the early RFD sampling to −6.8 K (case 2 vs case 6). The maximum–minimum spreads in θₑ for all three featured LLM cycles were substantial, with values of 9.4, 21.9, and 9.3 K for LLM1, LLM5, and LLM7, respectively. Large maximum–minimum spreads in parcel potential buoyancy, consistent with the considerable range in θₑ, deficit, was seen for these LLM cycles, with a remarkable intracycle CAPE difference (case 2 vs case 6) occurring for LLM5 of 3990 J kg⁻¹. Consistent with the large variance in CAPE for LLM5, CIN ranged from 56 to 622 J Kg⁻¹. Because of the vertical profile of θₑ in the inflow sounding (Fig. 16), even large θₑ deficits documented for LLM5 did not yield remarkably large differences in inferred parcel origin height when comparing case 2 (sub-950 m) to case 6 (2128 m). Another facet of internal RFD heterogeneity is seen in the general change in the core variables in a direction orthogonal to the boundary and farther into the air mass. For example, as shown in Table 1, out of the 8 RFD/RFDIS case samplings, θₑ(θₑ) stayed the same in 2 (0), decreased in 4 (8), and rose in 2 (2).

A final aspect to intra-LLM cycle RFD variability can be seen in the large changes in wind speeds. Increased peak wind speeds within the RFD associated with RFDISs can be readily seen for both LLM5 and LLM7 in Table 1. Of interest is the relationship between peak RFD winds and tornado presence and intensity. When comparing Max Wspd20s across LLM cycles, ranging from 8.9 m s⁻¹ in nontornadic case 1, to 16.1 m s⁻¹ in weakly tornadic case 7, to 35 m s⁻¹ in tornadic (EF4) case 4, the results are strongly suggestive that higher RFD wind speeds are related to tornado presence and intensity in the Bowdle storm. Even within LLM5 that produced two tornadoes, by a large margin, the highest

<table>
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Table 1. Thermodynamic and kinematic characteristics for eight cases of RFD or RFDIS sampling depicted in Fig. 17. Reference times are in UTC. Tornado presence/intensity designations associated with observing period for each case are no tornado (N) and the enhanced Fujita (EF) scale rating (only a single value is listed for the Bowdle tornado). Values of θₑ and θₑ are in K, values of parcel origin height (Z₀) are in m, and values of CAPE and CIN are in J kg⁻¹. Ground-relative maximum 5-s mean wind speed (Max Wspd5s) and maximum 20-s mean wind speed (Max Wspd20s) are in m s⁻¹. Internal RFD or RFDIS data collected within 1 min of a boundary crossing were not used in the thermodynamic max/min analysis (see text for details). The arrows indicate whether the core variable in that row set is generally decreasing (↓), increasing (↑), or remaining largely unchanged (⇒) in a direction orthogonal to the boundary and farther into the air mass [e.g., for case 6 the ↓ after the −2.0 in the Max θₑ row indicates that θₑ is decreasing (θₑ deficits increasing) farther into the air mass from the leading edge].
Max $W_{spd20s}$ values were associated with the EF4 tornado.

5. Summary and discussion

Extended-duration mesonet sampling in the hook echo/RFD region of the Bowdle supercell provided the opportunity to examine RFD thermodynamic and kinematic attributes and evolution. Special attention was given to characterizing numerous RFDISs and relating the surges to tornado development, or to changes in tornado intensity and size. Focused analysis of LLM5 that produced two significant tornadoes including the Bowdle EF4 tornado revealed four RFDISs. Part of the mesonet array was within 1 km of the tornadoes or their developing circulations during key deployments, lending confidence that the detected RFDISs and associated RFDISBs were interacting with the tornadic or pretornadic circulations.

The first RFDIS of LLM5 had a marked kinematic signal and was accompanied by increased parcel buoyancy, potential buoyancy, and $\theta_e$. Tornado formation was concurrent with the translation of the RFDISB around the right flank of a TC-scale circulation. The convergence pattern produced by the interacting RFDISB and convergent TC is similar to that found in dual-Doppler wind synthesis by Marquis et al. (2012) for cases where RFDISB-augmented convergence near a tornado was potentially important for tornado maintenance. For the first tornado, it appears the RFDISB played a role in tornado development, and likely, early maintenance. A well-defined cyclonic–anticyclonic vortex couplet had quickly developed before the RFDIS moved into, or formed within, the southern portion of the hook echo tip. The development of this vortex couplet may have been related to outflow and an accompanying boundary, perhaps associated with a late-stage RFDIS, just leading this feature (Fig. 6). The presence of counter-rotating vortices is suggestive of baroclinic vorticity generation associated with an RFD “cool” pool and subsequent tilting of the vortex lines by an updraft (vortex line arches discussed by Straka et al. 2007; Markowski et al. 2008). An augmented convergence zone from the RFDISB–TC interaction that acted on the cyclonic vertical vorticity pool may have represented the final step in the tornadogenesis process. Of note, prior to surge arrival, near-surface parcels with only weak negative buoyancy and considerable potential buoyancy were streaming into the TC from a downdraft of scale and location suggestive of an occlusion downdraft along its right flank similar to the Tipton, Kansas, tornado of 29 May 2008 (Lee et al. 2011).

An RFDIS coupled with a convergent, near-neutrally buoyant and very potentially buoyant RFD flow field appeared to play an important role in the rapid intensification stage of the Bowdle tornado. As RFD air was converging on the tornado from the east and northeast, a kinematically strong RFDIS with larger, but still relatively weak, negative buoyancy interacted with the tornado and the “warm” inflow. With convergent flow within this surge bounding the tornado to the south, convergent flow in place to the east and northeast, and a strong area of convergence and cyclonic vertical vorticity along the RFDISB that appeared to intersect the front flank of the tornado, a favorable setup was in place for inward transport of angular momentum and vertical vorticity stretching near the tornado. The location and scale of the downdraft associated with the RFDIS was suggestive of an occlusion downdraft. An anticyclonic component to a counter-rotating vortex couplet was observed a short time after the RFDISB passed the mesonet.

The Bowdle tornado primary intensification stage, as illustrated in Fig. 18, may represent an optimal situation combining the following: 1) RFD thermodynamics with just enough negative buoyancy for baroclinic vorticity generation, but not so much as to be detrimental (i.e., the “Goldilocks” scenario as mentioned by Markowski et al. 2008), in this case the baroclinity was provided by an RFDIS; 2) an augmented tornado/TC convergence zone due to the RFDIS and RFDISB interactions with the vortex; 3) near-neutrally buoyant and very potentially buoyant air converging on the left flank of the tornado;
and 4) a strong vertical vortex sheet aligned along an RFDISB oriented such that cyclonic vorticity moves into the front flank of the tornado through a layer starting from near the surface.

The final two RFDISs of LLM5 were kinematically strong, but had vastly different thermodynamic characteristics. The first of these occurred concurrent with what appears to be a second tornado intensification period that included EF4 damage. In this warm surge, $\theta_v$, $\theta_e$, and CAPE increased within about 1 km of the tornado. We speculate that the added convergence from this surge, acting on the already intense circulation pool of the very large tornado, fostered tornado contraction and intensification through vortex stretching. In the short term, the influx of near-neutrally buoyant air with very large potential buoyancy may have aided tornado intensification via enhanced vortex stretching. The last RFDIS, having large negative buoyancy and CIN, coincided with the tornado contracting and ultimately dissipating. Although mesonet observations are not available on the left flank of the tornado during the dissipation stage, the close proximity of observations to the tornado on its right flank lead us to conclude that tornado demise was due to the strong cold pool accompanying the final RFDIS replacing more buoyant and far more potentially buoyant RFD air bounding the tornado. Additionally, this strong surge appears to have influenced the alignment of the tornado with the storm midlevel updraft. Dowell and Bluestein (2002) and Marquis et al. (2012) have shown that the misalignment of tornado and storm updraft is related to tornado demise. Shortly after surge passage over the mesonet, the tornado was displaced westward with respect to the hook echo tip and midlevel updraft (inferred from the supercell weak echo region), toward the neck of the hook. Based on KABR radial velocity with supporting mesonet data, the core of the RFDIS passed roughly 1–1.5 km south of the tornado, initially placing the tornado within the northern periphery of the surge. Expansion of the RFDIS south through east of the tornado, consistent with a surge-associated divergent flow field, was evident in the radial velocity display. This outflow expansion likely accounts for the late northward turn of the tornado and end to its eastward movement (Fig. 9).

The vast majority of RFD parcels had comparative $\theta_e$ values to those found on the inflow sounding between 1 and 1.3 km. For some areas of the RFD, the parcel origin height was likely lower considering some mixing with lower $\theta_e$ air during vertical excursions. It was difficult to find midlevel air in the RFD observations over the full 2.5-h sample. The highest parcel origin heights between 1.9 and 2.1 km were found within the final RFDIS of LLM5, sometimes near the neck of the hook, and in a short-duration sampling within the FFRG region.

There appeared to be a relationship between the RFD kinematic strength and the occurrence of significant tornados. LLM5 had far greater RFD winds than other LLMs sampled, while also producing the only two significant tornados during the sampling period. This relationship held within LLM5, as the strongest of the RFD winds in this cycle, associated with surges, were sampled during the Bowdle tornado. The kinematically strong RFDISs, excluding the last RFDIS of this cycle, were coupled with air possessing only weak negative buoyancy and large potential buoyancy. This coupled RFDIS kinematic and thermodynamic signal is similar to that analyzed for other cases of strong or violent tornadoes (e.g., Lee et al. 2004; Finley and Lee 2008; Lee et al. 2010). Last, just as the largest internal RFD kinematic variability was embodied in the surges, so too was the largest thermodynamic variability with differing surges exhibiting vastly different thermodynamic characteristics (Table 1).

Analysis of numerous hook echo/RFD datasets covering conditions supporting a variety of tornado events will be required to understand the following: 1) the role and frequency RFDISs play in tornado development, intensification and demise, 2) whether the RFDIS is a manifestation of an intrinsic change in the LLM/TC strength or structure that might also have a role in tornado development or evolution, 3) the prevalence of strong RFDISB vertical vortex sheets and how often they align to provide a source of cyclonic vertical vorticity for the tornado, and 4) if the combination of strong RFD winds, relatively weak negative buoyancy, and substantial potential buoyancy bounding or partially bounding the tornado is a necessary condition for the development, intensification, and maintenance of strong tornadoes.

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APPENDIX

Mobile Mesonet Instrumentation and Accessories

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