Surface Analysis near and within the Tipton, Kansas, Tornado on 29 May 2008

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ABSTRACT

Data collected by a mesonet within the near-tornado environment and in the Tipton tornado on 29 May 2008 provided a rare opportunity to analyze rear-flank downdraft (RFD) outflow properties closely bounding a tornado and to characterize parcel thermodynamics being ingested into a tornado from the rear-flank downdraft. Parcels moving into the tornado on its right flank had very small negative buoyancy and considerable potential buoyancy. Measurements within and very near the tornado showed similar buoyancy characteristics to the storm inflow. Analyzed surface divergence and videographic evidence indicated that the RFD outflow just to the right and wrapping in front of the tornado was supported by parcels moving out of a narrow downdraft bordering the right flank of the tornado. Surface flow field analysis showed that parcels moved out of the downdraft-associated divergence region and into the right side of, as well as in front of, the tornado. An internal RFD surge boundary was positioned roughly 0.5 km in front of the eastern edge of the analyzed divergence region and implied downdraft.

The broader RFD outflow thermodynamic characteristics were consistent with recent research with only small negative buoyancy and substantial potential buoyancy; however, convective inhibition was considerably higher than typically found in other tornadic cases. This latter characteristic was emblematic of the broader storm environment on this day. Parcels making up the RFD outflow originated from low-levels, consistent with recent findings for tornadic rear-flank downdrafts and in contrast to past historical indications for the rear-flank downdraft source region.

1. Introduction

The ability to understand the processes involved in tornadogenesis, maintenance, and decay is dependent, in large part, on obtaining observations in key regions of supercell thunderstorms that historically have been very difficult to gather. One such area is within roughly 1 km of the tornado or tornadogenesis region that contains the air parcels that ultimately comprise the tornado inflow. With the rapid evolution of mobile Doppler radar (Wurman et al. 1997; Bluestein and Pazmany 2000; Bluestein and Wakimoto 2003), a considerable number of kinematic datasets have been gathered in tornadogenesis or tornado proximate regions; however, very few thermodynamic datasets within this region exist. Observational studies have shown that rear-flank downdraft (RFD) outflow surrounds or nearly surrounds the tornado (e.g., Brandes 1977, 1978; Lemon and Doswell 1979; Markowski et al. 2002, hereafter MSR2002; Wurman et al. 2007b); thus, the properties of the near-tornado RFD outflow are especially important across the tornado life cycle. In particular, buoyancy characteristics of the RFD outflow 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 2002b; Markowski et al. 2003a, 2008).

The association between supercell thunderstorm RFDs and tornadoes has long been recognized (Markowski 2002b). More recent research has focused on direct measurements within the RFD outflow by utilizing a mobile mesonet (Straka et al. 1996). The analysis of MSR2002 and Grzych et al. (2007, hereafter GLF2007) revealed
compelling evidence supporting the general conclusion that tornadic and nontornadic supercells had differing RFD thermodynamic characteristics. Specifically, the results of MSR2002 (which are supported by GLF2007) show that tornado likelihood, intensity, and longevity increase as the near-surface buoyancy, potential buoyancy, and equivalent potential temperature increase in the RFD outflow, and as the convective inhibition (CIN) in the RFD outflow decreases.

Although a substantial number of mobile mesonet RFD outflow datasets have been collected and analyzed over the past approximately 16 years to determine the association between RFD outflow thermodynamic and kinematic character and the tornadic nature of a supercell (Markowski 2002a; MSR2002; Lee et al. 2004; Finley and Lee 2004; GLF2007; Hirth et al. 2008), there exist comparatively few RFD outflow mesonet datasets with sampling within very close range of a tornado. Additionally, with the exception of the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX; Rasmussen et al. 1994) deployment on 8 June 1995 near Allison, Texas (Winn et al. 1999; MSR2002, see their Fig. 10), no published cases existed before the present dataset was obtained in which coordinated sampling of the near-tornado RFD outflow by a mobile mesonet was undertaken while in situ probes were collecting near and internal tornado observations.

During the Tactical Weather-Instrumented Sampling In/Near Tornadoes Experiment (TWISTEX), a mobile mesonet and an in situ thermodynamic probe called the Hardened In Situ Tornado Pressure Recorder (HITPR; Samaras and Lee 2004) collected data near and within the tornado that occurred in the vicinity of Tipton, Kansas, on 29 May 2008. Additionally, a seven-camera in situ video probe was deployed approximately 10-20 m south of the thermodynamic probe to record full 360° videography of the tornado passage. The tornado sampled (hereafter called the Tipton tornado) was just one of many tornadoes produced by its parent supercell (NCDC 2008). The Tipton tornado occurred in open country and received an EF-1 rating with damage relegated to power poles and trees during its estimated life of 23 min [based on TWISTEX tornadoogenesis observation and NCDC (2008) reported time of dissipation]. With the tornado passing over the in situ probes, one mesonet station positioned 235 m south of the HITPR (roughly 190 m south of the tornado edge) and another mesonet station located up to 1 km farther south, the dataset collected provides an opportunity to determine the thermodynamic character of the flow getting ingested into the tornado from the RFD outflow along the right flank (looking downstream) of the tornado. It is worth noting that just before the Tipton tornado dissipated, the next tornado from this storm formed near Glen Elder Dam and eventually produced EF-3 damage southwest of Jewell, Kansas (NCDC 2008).

TWISTEX was conducted during May and June of 2008 with a domain that included regions from the upper Midwest through the southern Great Plains. The project had a typical complement of three mobile mesonet vehicles and a probe vehicle that transported an array of HITPR probes and two video probes [see Karstens et al. (2010), their Fig. 3]. The primary objective of the field portion of TWISTEX was to gather thermodynamic and kinematic data with a mobile mesonet in the RFD outflow region near tornadoes and the adjacent RFD gust front (RFDGF) region while concurrently gathering thermodynamic data with the HITPRs in or very near tornadoes. The sampling goal was designed such that a combined thermodynamic and kinematic mapping could be done in the tornadogenesis and tornado maintenance regions while also addressing project objectives involving near-surface tornadic flow field analysis with the aid of the video probes.

2. Synoptic and mesoscale environment

Conditions over northern Kansas and southern Nebraska on the evening of 29 May were generally very favorable for tornadic supercells. The outbreak was associated with a southwest flow upper-level pattern in place over the southwestern and central United States as shown in the 0100 UTC Rapid Update Cycle (RUC) model (Benjamin et al. 2004) 500-mb analysis in Fig. 1. During the day on 29 May a short wave moved into the central plains, and by evening the right entrance region of the jet streak associated with this short wave was located over northwest Kansas and southwest Nebraska as shown in Fig. 1. This jet streak was apparent up to the 350-mb level. An upstream short wave may be seen over Arizona and western New Mexico but it is not believed to have played a role in influencing the deep-convective environment for this case. In conjunction with the central Plains short wave passage, a strong low-level jet was in place across much of southern and eastern Nebraska and most of Kansas, as seen in the 850-mb vector winds in Fig. 1. A substantial area within this region extending from west-central Kansas to south-central Nebraska had 850-mb southerly winds exceeding 25 m s$^{-1}$. When coupled with the surface flow to be presented next, the deep-layer vertical wind shear environment over much of Kansas and eastern Nebraska was quite favorable for supercell thunderstorms.

At the surface, an area of low pressure was situated under the right entrance region of the upper-level jet streak in northwest Kansas (Fig. 2). Strong southerly to
south-southeasterly winds were present over much of the Kansas portion of the warm sector of this cyclone with seasonally high dewpoints and narrowing dewpoint depressions as the evening progressed over the northern Kansas area of interest. The cell that would eventually become the cyclic tornadic supercell associated with the Tipton tornado (hereafter this storm will be designated the Tipton supercell or Tipton storm), formed within a broken line segment of developing storms at 2148 UTC in far west-central Kansas about 78 km south of Goodland, as shown in Fig. 2. Initial cell formation with this broken line commenced much earlier at 1915 UTC near the dryline. The Tipton storm took on supercell characteristics (Browning 1964; Rotunno 1993) by 2238 UTC just south of Oakley, Kansas. By 0100 UTC the supercell had moved into north-central Kansas as indicated in Fig. 2 and was located in central Osborne County. Dewpoint depressions at this time were only in the $6^\circ$–$9^\circ$F ($3^\circ$–$5^\circ$C) range based on indications from the mesonet and 0100 UTC RUC surface analysis.

To assess the deep convective environment for the Tipton storm, RUC 0100 UTC analysis data were used to create a representative sounding and hodograph for central/eastern Osborne County. This approach was preferred over applying modifications to regional 0000 UTC soundings taken at considerable distances from the storm. Based on the sounding and hodograph shown in Fig. 3, the conditions just preceding the Tipton storm at 0100 UTC were generally quite favorable for supercells, with some parameters very favorable for tornadic supercells, provided a storm could form or persist within an environment with large convective inhibition. Considerable conditional instability was present with surface-based and lowest 50-mb mixed parcel convective available potential energy (CAPE) of 2291 and 2619 J kg$^{-1}$, respectively. CIN for surface-based (232 J kg$^{-1}$) or lowest 50-mb (156 J kg$^{-1}$) parcel ascent was remarkably high for an environment sustaining tornadic supercells (Rasmussen and Blanchard 1998). 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. Along with the large CIN, the sounding profile below 3 km above ground level (AGL) yielded no CAPE in this layer for either surface-parcel or lowest 50-mb parcel ascent. This tornadic supercell case runs counter to expectations based on Rasmussen (2003) for typical values of 0–3-km CAPE in environments supportive of supercells producing significant tornadoes (middle two quartiles of 0–3-km CAPE in Rasmussen’s sounding distribution range from 18 to 92 J kg$^{-1}$). Finally, the surface parcel–based lifting condensation level (LCL) was 620 m for this sounding (865 m for lowest 50-mb parcel ascent). Low-LCL environments such as this have been shown to be associated with significant tornadoes (Rasmussen and Blanchard 1998; Thompson et al. 2003).

The low and deep-layer shear environment for north-central Kansas was very conducive for storm midlevel and low-level rotation. The hodograph in Fig. 3 has large looping clockwise curvature with a profile indicative of
strong directional and speed vertical wind shear. Deep layer 0–6-km vector shear of 30.8 m s$^{-1}$ was more than sufficient to support supercells, consistent with past modeling and observational research (Weisman and Klemp 1982; Rasmussen and Blanchard 1998; Thompson et al. 2003). To calculate storm-relative helicity (SRH; Davies-Jones et al. 1990) at 0100 UTC, a cell motion of 250$^\circ$ at 15.4 m s$^{-1}$ was determined using Weather Surveillance Radar-1988 Doppler (WSR-88D; Klazura and Imy 1993) level II data from Hastings, Nebraska. In part because of the marked low-level jet (Bonner 1968) in place (>25 m s$^{-1}$ between 700 and 1500 m), SRH values were especially large with a 0–1-km SRH of 462 m$^2$ s$^{-2}$ and 0–3-km SRH of 669 m$^2$ s$^{-2}$. Based on the storm environment parameter studies of Rasmussen and Blanchard (1998) and Thompson et al. (2003), the 0–3-km SRH was very supportive of supercells, and the 0–1-km SRH value suggests enhanced potential for tornadic supercells (Rasmussen 2003; Thompson et al. 2003). The 7.6 EHI should be considered a very large value based on these past studies.

In summary, while the majority of key parameters were quite favorable for tornadic supercells, there were a few, such as the CIN and 0–3-km CAPE, that were atypical for tornadic supercells. Note that there were no storms in Kansas south of the Tipton storm through most of the supercell stage of its life, indicating that this storm existed on the very southern margin of where the atmosphere was capable of sustaining deep convection.

3. Data collection and methodology

The TWISTEX sampling array on 29 May consisted of two mobile mesonet stations and a probe deployment team with a full complement of six thermodynamic and two video in situ probes. The third mobile mesonet platform was unable to participate because of damage sustained in a previous operation. The mobile mesonet measures temperature, pressure, humidity, and wind velocity. Time and position were recorded using a global positioning system (GPS). The type of instrumentation and mobile mesonet station configuration were based on the design presented by Straka et al. (1996). Some instrumentation differences exist between those specified in Straka et al. and newer mesonet stations such as those used by TWISTEX and Texas Tech University’s Atmospheric Science Group, which share the same instrumentation [see Table 1 of Hirth et al. (2008)]. Field procedures were developed such that the GPS could be used for vehicle direction at all times, eliminating the need for a flux gate compass. The field data were collected every 2 s.

A narrow deployment window limited the number of in situ probes used to two HITPRs and one video probe. The rapidly deployable HITPR is aerodynamically shaped and engineered to obtain thermodynamic observations within the harsh tornado environment. The probe is outfitted with fast response time sensors that measure pressure, temperature, and humidity. An internal datalogger records the sensor readings at 10 Hz. The thermistor and hygristor are located near the top of the cone just above a set of ventilation holes that surround the probe. Details of the design of the HITPR may be found in Samaras and Lee (2004). Once deployed, the HITPRs taking measurements at about 0.12 m (AGL) effectively become part of the mesonet. On this day one of the HITPRs failed to record data. The video probe is outfitted with seven cameras that provide a tornado-relative reference for the sampling position of the HITPRs and provide videography for both vortex structural assessment and visual analysis of the near-tornado environment. These probes provide a full 360$^\circ$ field of view of the

![Fig. 3. Skew T-logp thermodynamic diagram and hodograph for central Osborne County, KS, at 0100 UTC based on RUC analysis. Temperature (heavy black line), dewpoint (medium gray line), virtual temperature (black dashed line), and 50-mb mixed layer parcel ascent path with virtual temperature correction (thick dark gray line) are shown. Altitudes (×100 m) and storm motion vector for the Tipton supercell at 0100 UTC are shown on the hodograph.](image-url)
evolving and translating near-ground flow-field as made visible by debris and/or condensation as the tornado passes as well as the evolving near-tornado cloud structure. Six cameras are positioned horizontally, each spanning a 60° horizontal view. The seventh camera is positioned vertically.

Owing to inaccuracies in the mesonet anemometry during significant vehicle accelerations, velocity data were removed in a similar manner as employed by MSR2002, Markowski (2002a), and GLF2007. The mesonet datasets were also quality-controlled for spurious meteorological readings and vehicle headings. Biases were removed by way of intercomparisons between mesonet stations for extensive periods when the caravan was in relatively uniform meteorological conditions and predominantly in transit.

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 MSR2002 and GLF2007 using the formula derivation of Bolton (1980). In the calculation of the virtual potential temperature \( \theta_v \) [see Glickman (2000), p. 820], no hydrometeors were assumed to be present. These data were collected on storms at a significant distance from the nearest WSR-88D site and since the rainfall intensity, when encountered by the teams, varied markedly on small space and time scales, we had little confidence in estimating the liquid water mixing ratio \( q_l \) from radar reflectivity. No hail was observed by any of the teams, and when the teams were in precipitation, the rainfall never exceeded a qualitative moderate intensity.

Although the exclusion of \( q_l \) in the formal calculation of \( \theta_v \) results in less accurate values, only small errors in \( \theta_v \) calculations are expected given the rainfall intensity experienced. For instance, had the radar reflectivity been 40 dBZ in this case, an overestimate in \( \theta_v \) of about 0.22 K would be incurred from neglecting the \( q_l \) estimate from the parameterization of Rutledge and Hobbs (1984).

The CAPE and CIN for all the mesonet data points were calculated using a sounding developed from RUC 0100 UTC analysis data with surface conditions in the sounding provided by the mesonet readings. The CAPE and CIN are based on surface parcel ascent and include the virtual temperature correction described in Doswell and Rasmussen (1994). Surface elevation for the sounding was adjusted to be consistent with the elevation of this event.

To obtain the perturbation equivalent potential temperature \( \theta'_e \) and perturbation virtual potential temperature \( \theta'_v \), base states were determined from mesonet station storm inflow observations similar to GLF2007 and Hirth et al. (2008). Note that this method differs from the technique used by MSR2002 whereby the base state was determined by a weighted mean of uncontaminated surface airway, aviation routine weather report, and Oklahoma Mesonet observations within a 400-km radius of the storm updraft. Because of hygristor differences between the HITPR and mobile mesonet stations, and noting the sensitivity of \( \theta_e \) to relatively small differences in water vapor content, we chose not to calculate \( \theta_e \) for the HITPR. Thus, graphics containing \( \theta'_e \) information will be for the mobile mesonet only. Additionally, because of instrument equilibration for the HITPR upon deployment, temperature and relative humidity data from the probe were not used until the instrumentation had equilibrated with site conditions.

For portions of the analysis, data points were plotted relative to Hastings, Nebraska, WSR-88D (KUEX) radar data using a time-to-space conversion as described by MSR2002. This process put the observational mesonet data into the storm’s positional frame of reference. Five-minute time intervals were used in these time–space conversion plots consistent with the approximate time for a single WSR-88D volume scan; however, aspects of the storm kinematic and thermodynamic structure near the hook echo are not in steady state for this length of time, so the wings of plotted data carry less credence. The Tipton tornado was estimated to move at the same speed and direction as the radar-induced low-level mesocyclone (from 255° at 14.6 m s⁻¹) during the approximate center of the observing period (i.e., the time centered around 0122:14 UTC). Videography and damage track analysis support this estimate. Time series analysis was used to identify kinematic and thermodynamic transitions of the flow field as concurrently observed by the array. To remove some of the very small time scale fluctuations, 6-s data averages were used in the analysis except where noted.

In accordance with the motion of the Tipton storm, teams set up in a north–south observing array along Kansas Highway 181 (K-181) and in the storm-relative position shown in Fig. 4. The HITPR and video probe were farthest to the north and in the path of the tornado, with mesonet stations M3 and M2 positioned progressively farther south.

4. Observations and analysis

a. Storm inflow observations and event/deployment chronology

Arriving ahead of the Tipton storm hook-echo passage over K-181, teams were able to collect inflow observations at a location 8.5 km to the northwest of Tipton, Kansas (Fig. 4). In a 5-min period just preceding the passage of the
storm’s RFDGF over K-181 at 0119:27 UTC, strong storm-relative inflow winds were approximately 25 m s\(^{-1}\) from the east-northeast. These inflow observations reveal small dewpoint depressions of approximately 3.5°C and reflect the low LCL storm environment noted in section 2. The low cloud bases seen at 0116:04 UTC in Fig. 5a are indicative of this low LCL environment. At this time teams were observing increasing low-level rotation as a clear slot associated with subsiding air in the RFD (Markowski 2002b) wrapped into the south side of the visual low-level mesocyclone. CAPE and CIN for storm-inflow surface-based parcel ascent were 2120 and 304 J kg\(^{-1}\), respectively. The notably large inflow CIN and sounding structure seen in Fig. 3 are likely responsible for the remarkably sculpted and laminar striated appearance of the Tipton storm from a location well east of the deployment position, as seen in Fig. 5d. A short-lived tornado was first observed by the deployment teams at 0117:48 UTC. The Tipton tornado developed shortly thereafter at 0118:35 UTC. With the trend in the tornado visual appearance indicating a nontransient event (see Fig. 5b for 0118:53 UTC), both mesonet and probe teams were able to calibrate their positions along K-181 for feature-relative data sampling. Upon arriving at the point along K-181 where the tornado was anticipated to cross, the probe deployment team was approximately 1 km east-northeast of the tornado, which took on a considerably wider profile than that observed approximately 3 min earlier as shown in Fig. 5c.

The HITPR and video probe deployments were successful, with the southern portion of the tornado tracking over the probes at 0122:53 UTC. A pressure drop of 15 mb was recorded by the HITPR (Fig. 6), with M3 recording a nearly 6-mb pressure drop at a distance of 235 m south of the HITPR. Note that M3 took up a stationary position for about 2 min during the time the tornado and accompanying strong RFD winds crossed K-181. Given video probe evidence of the tornado-relative position of the HITPR, and an estimated vortex width of 250 m, M3 was located roughly 190 m south of the southern edge of the tornado. Note that in the absence of a very close radar to determine the tornado core flow diameter, the 250-m tornado width was estimated using the tornado translation speed in concert with the video probe-derived
transect duration of the concentrated near-surface debris annulus. Corroborating width estimates were similarly made with the tornado translation speed and the HITPR pressure trace profile. M2 was generally mobile during this key observing period while sampling the RFD outflow region 1 km south of M3. More details of the pressure traces from the HITPR and M3 along with tornado structure inferences from these data and the video probe recordings may be found in Karstens et al. (2010).

b. Spatial analysis

The most important analysis period is shown in Fig. 7, centered on the KUEX WSR-88D 0122:14 UTC 0.5° base reflectivity scan since key storm features moved over the array within a few minutes either side of this time. The tornado passed over K-181 and the in situ probes at 0122:53 UTC. The mesonet observed the RFDGF passage at 0119:27 UTC and thus began sampling the RFD outflow less than 1 min after the estimated time of tornado genesis. A comparison between the inflow conditions shown in Fig. 4 and conditions west (behind) the RFDGF in Fig. 7 indicates that the RFDGF represented a strong kinematic boundary with only meager thermodynamic changes across the boundary. Of kinematic importance, the mesonet data indicated an internal RFD surge boundary behind the RFDGF similar to other recent mesonet data analyses (Finley and Lee 2004; Lee et al. 2004; Finley and Lee 2008; Hirth et al. 2008) and to recent radar observations (Wurman et al. 2007a; Marquis et al. 2008a,b). This surge appears closely juxtaposed with the tornado, not unlike the scenarios detailed in Finley and Lee (2004, 2008) and Marquis et al. (2008a).

Fig. 5. View of Tipton supercell low-level mesocyclone region and tornado looking (a) west at 0116:04, (b) west at 0118:53, (c) west-southwest at 0121:45, and (d) west at approximately 0130:00 (all times UTC). The image in the last panel is courtesy of Chris Collura.

Fig. 6. Time series of temperature (°C), dewpoint (°C), and pressure (mb) for the HITPR for a 100-s period centered on the time the tornado passed over the HITPR (see legend). The dashed portion of the dewpoint trace indicates an instrument equilibration ramp. No moisture information is used from the HITPR during this equilibration period.
As shown by MSR2002 and GLF2007, tornado likelihood and intensity appear related to thermodynamic characteristics of the RFD outflow. Since fluctuations in $\theta_e$ from the base state are proportional to buoyancy, $\theta'_e$, was analyzed to assess the buoyancy within the RFD outflow, some of which is ingested into the tornado, noting the tornado-relative flow in the second panel of Fig. 7. Deficits in $\theta_e$ are quite small (<2 K) from behind...
the initial gust front to just west and southwest of the tornado. A local maximum in $\theta_v$ lies in the region near and within the tornado with values approximating the storm inflow. The small size of the $\theta_v$ departures near the tornado and to the east, south, and within the first kilometer west of the tornado are generally consistent with those associated with tornado environments by MSR2002 and GLF2007. Extended analysis of the RFD for the next 5-min period following that shown in Fig. 7 revealed no $\theta_v$ deficits larger than 2.7 K in the RFD outflow region 4 km farther to the west. Although no observations exist just to the north of the tornado, the tornado appears embedded in air having only weak negative buoyancy.

The $\theta_v$ deficits within the RFD outflow shown in Fig. 7 are also quite modest with values less than 3 K for regions east, south, and within the first kilometer west of the tornado. The $\theta_v$ deficits are generally consistent with those found by MSR2002 and GLF2007 for tornadic RFDs. Although $\theta_v$ deficits begin to exceed 3 K west of about 1 km from the tornado, extended analysis of the RFD for the next 5-min period following that shown in Fig. 7 revealed no $\theta_v$ deficits larger than 3.8 K in the RFD region 4 km farther west.

Given the focused mesonet sampling along and to the right side of the tornado and low-level mesocyclone track, a smaller region with a higher density of plotted observations (every 8 s) was analyzed to examine the two-dimensional flow field shown in Fig. 8. Over most of the sampled RFD outflow the implied streamlines reveal a generally diffuuent RFD outflow, with slightly cooler $\theta_v$ air being advected to the south and east in a storm-relative framework. Even the least buoyant RFD parcels to the west of the tornado had $\theta_v$ deficits of just 2 K, so during this sampling period the RFD outflow proximate to the tornado and low-level mesocyclone had only modest negative buoyancy.

In contrast to the diffuuent RFD outflow observed over a large portion of Fig. 8, a region of confluence exists within several hundred meters south and southeast of the tornado. M3 is close enough to the tornado for the winds to reflect the induced radial inflow as the center of the vortex passed by approximately 320 m to the north. Of particular interest, the flow analysis of Fig. 8 indicates a narrow, highly diffuent region bounding this confluent region in a partial arc from south-southwest through east-southeast and within 1 km of the tornado. A two-pass Barnes objective analysis scheme (Barnes 1964; Koch et al.}

**Fig. 8.** As in Fig. 7 (bottom), but a smaller and more highly populated analysis is shown with subjective streamlines. Divergence is hatched within an objectively analyzed region bounded by the mesonet station positions running from south-southwest to east-southeast of the tornado. Data points are separated by 8 s.
1983) was applied to the time–space converted mesonet velocity components in a similar region, confined by the mesonet station positions, to interpolate the data to a two-dimensional grid for divergence analysis. As shown in Fig. 8, this analysis region was largely divergent and peak divergence values were about $2 \times 10^{-2} \text{ s}^{-1}$. Supporting evidence for this partial arc of divergence was found in the videography provided by the in situ video probe. One of the six horizontal viewing angles was aligned looking to the east, a direction where visibility through the glass shield over the camera lens remained relatively free of rain and debris. Just after the tornado passed over the HITPR, the video clearly showed rapidly descending and evaporating cloud tags just to the right of the tornado (looking downstream), indicative of strong downdraft. In a tornado-relative framework the placement of this downdraft would align with the arc of divergence in Fig. 8. This region within the outflow also corresponds to an area of modestly greater buoyancy as seen in the $\theta_v$ deficits plotted in Fig. 8, especially when compared to the RFD outflow air to the west. We will show later in this section that parcels in this region possessed considerable potential buoyancy.

Based on the implied flow field near the tornado shown in Fig. 8, parcels move from a divergent portion of the RFD outflow (south-southwest through southeast of the tornado) into a confluent and convergent zone as they move toward and pass around and into the right and front side of the tornado. Several hundred meters farther to the east, parcels move out of a region of divergence and into the flow field just in front of the tornado (and presumably into the tornado). At this time, the near-tornado region has close to neutral buoyancy with the area just east and south of the tornado only slightly negatively buoyant. Of consequence, the mapping shows parcels having small $\theta_v$ values feeding into the tornado from the near-tornado RFD outflow along its right flank. Advection inferences along the streamlines in Fig. 8 are limited by two-dimensionality and the persistence assumption in time–space analysis. In regions impacted by large vertical motions such as the divergence arc south through southeast of the tornado, the flow moving along the depicted 3-m streamlines through or out of this region likely possess considerable influence from parcels within the strong downdraft above this region. Clearly the tornado is ingesting air with very little negative buoyancy from the region within several hundred meters south through east of it, as depicted in Fig. 8. During this analysis period, the somewhat more negatively buoyant air to the west likely does not make it into the tornado undiluted given the downdraft contributions to the flow nearer the tornado.

Prior RFD outflow characterization studies by MSR2002 and GLF2007 found that RFD outflows of tornadic supercells usually possessed considerable potential buoyancy (as did some of the nontornadic supercells, although on average the nontornadic cases had substantially less potential buoyancy). To assess the potential buoyancy in this case, CAPE was calculated for all the mesonet data by inserting the mesonet data into the storm inflow sounding. CIN was also calculated with this surface parcel assumption. As shown in Fig. 9, the RFD outflow has substantial CAPE from just behind the RFDGF ($\sim 2200 \text{ J kg}^{-1}$) to the edge of the plotting region 2 km
west of the tornado (\(\sim 1300 \text{ J kg}^{-1}\)). Although CAPE values decrease markedly west of the tornado, the outflow parcels in this region still possess considerable potential buoyancy. Largely consistent with the \(\theta'_e\) and \(\theta'_u\) data, a local maximum of CAPE is present in a partial arc 0.5 km south of the tornado in the region that partially overlaps the region of divergence. This local maximum extends to the proximate area around and in the tornado.

A surprising characteristic of both the storm inflow and the relatively “warm” RFD outflow was the large values of CIN as seen in Fig. 9. The CIN ranged from about 280 J kg\(^{-1}\) just behind the RFDGF to around 470 J kg\(^{-1}\) west of the tornado with values in, near, and just south of the tornado ranging from approximately 330 to 370 J kg\(^{-1}\). These values stand in contrast with typical values for RFD outflow CIN documented in MSR2002 and GLF2007. Although some tornado cases cited in MSR2002 had considerably more RFD outflow CIN, average quadrant CIN for significant tornadoes ranged from 214 J kg\(^{-1}\) in quadrant III (generally southwest of the tornado) to 78 J kg\(^{-1}\) in quadrant II (generally southeast of the tornado). GLF2007 found average CIN values of 82 J kg\(^{-1}\) in the RFD outflow of nontornadic supercells. With only small RFD outflow thermodynamic departures from the inflow base state for a good portion of the RFD outflow depicted in Fig. 7, the large CIN values displayed in Fig. 9 are not surprising given the storm inflow CIN of 304 J kg\(^{-1}\) noted previously.

The atypically high RFD outflow CIN may have implications for the low-level mesocyclone-scale rotational dynamics that need be in place to induce the convergence and ascent of low-level parcels through a marked stable layer to support tornadogenesis. Since the storm inflow also had large CIN, understanding the flow field configuration that supports low-level mesocyclone development may have merit. We hypothesize that a very favorable low-level shear environment, as indicated by the 0–3-km SRH of 669 m\(^2\) s\(^{-2}\) and, perhaps more importantly, by the 0–1-km SRH of 462 m\(^2\) s\(^{-2}\), fostered low-level mesocyclone development as streamwise vorticity was tilted and stretched by the storm updraft. The resultant low-level mesocyclone, if of ample intensity, could dynamically impose vertical acceleration sufficient for lifting parcels low in the boundary layer through the low-level stable layer. In this scenario, the development of a vigorous low-level mesocyclone provides a mechanism for progressively accessing parcels closer to the surface. The general findings of Wicker (1996) regarding the importance of the environmental low-level vertical shear profile in low-level mesocyclone intensification may be particularly relevant. In a broader sense, the research of Markowski et al. (2003b), Rasmussen (2003), and Thompson et al. (2003) on the importance of 0–1-km SRH in discriminating between environments associated with supercells producing significant tornadoes and those associated with nontornadic supercells may also be relevant with respect to the relationship between the low-level vertical shear profile and low-level mesocyclone intensity.

c. Parcel origins

A comparison was made between the RFD outflow \(\theta_e\) and the inflow sounding vertical profile of \(\theta_e\) to determine the height on the inflow sounding with equivalent \(\theta_e\) values to those sampled in the RFD outflow. This height was just about 1 km (AGL) for most of the RFD outflow west of an approximate point 0.5 km behind the RFDGF for the analysis period shown in Figs. 7 and 8. If the assumption is made that moist entropy was approximately conserved, it is possible that the height from which the surface RFD outflow parcels originated was around 1 km. However, to some degree, lateral entrainment should not be ignored, especially in areas of strong vertical accelerations. Since RFD outflow \(\theta_e\) values are only about 2 K less than inflow values, especially within the local maximum in \(\theta_e\) just south of the tornado in Fig. 8, it is possible that RFD outflow parcels originated in the near-surface storm inflow and subsequent updraft and then were forced to descend by a downward-directed dynamic pressure gradient force or by hydrometeor drag while undergoing some mixing with air at higher elevations. This could lead to the slightly lower \(\theta_e\) values (when compared to storm inflow) that were observed at the surface in the RFD outflow. What appears clear in this case is that the RFD air reaching the surface was not predominantly made up of midlevel, nonupdraft parcels with a cold \(\theta_e\) signature. Instead, the origins of this air appear to be relatively low in the inflow sounding or from near-surface inflow that entered the updraft. This result is consistent with the findings of MSR2002 for tornadic RFD cases.

d. Time series analysis

To further analyze the kinematic character of the flow just south of the tornado track, time series of storm-relative wind direction and speed along with ground-relative speed are displayed for M3 in Fig. 10. As seen in this figure and noted previously, storm-relative inflow averaged close to 25 m s\(^{-1}\). RFDGF passage near 01:19:25 UTC was accompanied by a large drop in storm-relative wind speeds given the similarity between the ground-relative winds and storm motion velocity vectors. Ground-relative wind speeds intensified and storm-relative westerlies increased as the mesonet encountered an RFD surge at 0121:05 UTC (evident in Fig. 7). At M3’s location, storm-relative winds quickly backed in response to tornado-induced radial flow, as
seen in Figs. 7 and 8, with directions in the 180°–210° range preceding tornado passage (Fig. 10). However, M3’s storm-relative winds started backing sharply about 70 s before the tornado passed to the north. The initial flow backing was, in part, related to the surface divergence mentioned previously that was positioned in an arc from south-southwest through east-southeast of the tornado. Storm-relative winds increased rapidly and veered as the tornado passed to the north. At 0122:55 UTC, nearly at the time the tornado center was passing due north of M3, the peak 2-s M3 storm-relative wind speed reached 30 m s$^{-1}$ while the maximum ground-relative speed was 44 m s$^{-1}$. During a 20-s period centered on the tornado passage to the north, the ground-relative wind speed averaged 39 m s$^{-1}$. After tornado passage, storm-relative winds veered from a northwesterly to northerly direction, consistent with the diffluent RFD outflow shown in Fig. 8, and eventually to a northeasterly direction.

Time series of $u_y$ for the mesonet shown in Fig. 11 depicts a modest local maximum just behind the RFDGF with a subsequent small decrease in parcel buoyancy up to the time of tornado passage. Note that only small $u_y$ deficits of generally less than 1 K were present in the RFD outflow just south of the tornado track up to and through tornado passage. The internal RFD surge boundary delineates a change (lessening) of the local time rate of change of $u_y$ with values that plateau in the −0.8 to −1.0 range before $u_y$ rises for all stations roughly concurrent with the tornado passage. Interestingly, the probe samples its warmest $u_y$ during the time of tornado passage with the mobile mesonet also recording $u_y$ increases, although much smaller. The spike in $u_y$ for the probe is largely due to the pressure drop in and very near the tornado given the dependence of $u$ on pressure and noting that the temperature remained relatively constant through the tornado. For reference, the HITPR pressure, temperature, and dewpoint are plotted in Fig. 6 for a 100-s period bounding the approximate midpoint of the tornado passage over the HITPR. One might have expected $u$ to remain roughly constant and temperature to fall in association with the rapid pressure drop. The only minor change in temperature for the HITPR during the tornado transect may be explained in two ways. A leading possibility is that the HITPR was sampling the interior of a two-cell vortex (consistent with observations for the Tipton tornado; see Karstens et al. 2010) with parcels at least partially reflecting the axial downdraft, thus yielding the absence of falling temperatures associated with the pressure drop in the HITPR trace. A second possibility is that the response time of the HITPR thermistor was insufficient, for an unknown reason, to reflect a temperature drop (if one existed). Perhaps debris loading over a portion of ventilation holes during tornado passage reduced the circulation through the HITPR. If this second reason were true, the HITPR $u_y$ trace during the tornado transect in Fig. 11 would look more similar to that of M3. After
tornado passage the $\theta'_e$ time series for all stations drop, consistent with the gradually cooler pool of air noted to the west of the tornado in Figs. 7 and 8. The outflow of this event with $\theta'_e$ deficits never larger than 2.7 K over the roughly 10.5-min sampling period was quite warm compared with the nontornadic RFD group documented in MSR2002.

The time series of $\theta'_e$ shown in Fig. 11 also reflect an environment that is thermodynamically similar to those found by MSR2002 and GLF2007 for RFD outflows accompanying tornadoes. After a $\theta'_e$ local maximum measured just after the RFDGF passage that was temporally similar to that observed for $\theta'_v$, $\theta'_e$ drops to its lowest pretornado passage level with $\theta'_e$ of about $-2.7$ K. Notably, $\theta'_e$ then trends upward in the air mass west of the RFD surge boundary up to the time of tornado passage to the north. Even though $\theta'_e$ decreases after tornado passage, values of $\theta'_e$ generally stay in the $-2$- to $-3.5$-K range through the sampling period. Once again, with these modest $\theta'_e$ deficits, the RFD outflow was quite warm compared with the nontornadic RFD group documented in MSR2002.

![Fig. 11. Time series of (a) $\theta'_v$ for M2, M3, and HITPR and (b) $\theta'_e$ for M2 and M3 (see legend). The vertical lines A, B, and C identify the respective passage of the RFDGF, the internal RFD surge boundary, and the tornado. The bold line along the time axis identifies the period the tornado was in progress during the sampling period.](image-url)
5. Summary and discussion

Data collected by a mesonet within the near-tornado environment and in the Tipton tornado on 29 May 2008 provided a rare opportunity to analyze RFD outflow characteristics closely bounding a tornado and to characterize parcel thermodynamics being ingested into a tornado from the RFD. Field sampling was concentrated in a region from the tornado track (HITPR) through 1 km south of the track (mobile mesonet). RFD sampling began less than 1 min after the estimated time of tornadogenesis. As shown in the time–space and time series analysis, the overall thermodynamic signal of the Tipton supercell RFD outflow was consistent with the thermodynamics of RFD outflow associated with tornadoes as documented in MSR2002 and GLF2007. Parcels within the RFD outflow to the east, south, and within the first one kilometer west of the tornado had small $\theta_v$ and $\theta_e$ deficits of less than 2 K and 3 K, respectively. More specifically, nearly all observations to the south, east, and very near/in the tornado had $\theta_v$ deficits less than 1 K. In addition to having only weak negative buoyancy as indicated by the small $\theta_v$ deficits, all RFD parcels sampled had considerable potential buoyancy. Parcel CAPE exceeded 1600 J kg$^{-1}$ from southwest of the tornado up to about 2200 J kg$^{-1}$ just behind the RDFDG. RFD outflow CIN, which ranged from about 280 J kg$^{-1}$ just behind the RDFDG to 470 J kg$^{-1}$ west of the tornado, stands in contrast to typical values found by MSR2002 and GLF2007 for tornadic cases. The RFD CIN in this case is emblematic of the large CIN in the broader storm environment.

Comparison of $\theta_v$ values within the RFD outflow with those in the storm inflow sounding indicated that the origins of the parcels appear to be relatively low in the inflow sounding or from near-surface storm inflow that entered the updraft and was forced back to the surface. In the former case, $\theta_v$ of RFD parcels matches the inflow sounding at about 1 km AGL, similar to MSR2002 for tornadic events; however, entrainment into the downdraft prompts a more qualitative assessment of potential parcel origin. In the latter case, parcel excursions may have been large with updraft parcels possibly forced back down to the surface by a downward-directed dynamic pressure gradient force or by hydrometeor drag while undergoing some mixing with air at higher elevations. This mixing would result in the somewhat cooler RFD outflow $\theta_v$ than seen in the near-surface inflow.

Analysis of the flow field adjoining the right flank of the tornado, made possible by very close positioning of M3, indicated that tornado-relative inflow was comprised of RFD outflow parcels with only very weak negative buoyancy and substantial potential buoyancy. Although we cannot address the thermodynamic character of the flow field on the left flank of the tornado, as long as a weak buoyancy and potential buoyancy gradient was maintained from roughly southwest through east-southeast of the tornado, parcels entering the right flank and wrapping around the front side of the tornado would have minimal negative buoyancy and considerable potential buoyancy.

The thermodynamic mapping prompts a fundamental question: what process or processes influenced the thermodynamic structure of the near-tornado RFD in the Tipton case? With an arc of divergence within 1 km of the tornado from south-southwest through east-southeast and videographic evidence of downdraft aligned above this region, it appears that a narrow downdraft to the right of the tornado influenced the near-tornado RFD outflow thermodynamic character. The near-surface flow field indicated that parcels moved out of this divergence region and into the right side of the tornado. Slightly farther to the southeast, parcels moved out of the divergence arc and into the flow field just in front of the tornado (and presumably into the tornado). Interestingly, the identified internal RFD surge boundary was positioned only about 0.5 km in front of the eastern edge of the calculated divergence region and implied downdraft. The connection between the near-tornado downdraft on the tornado’s right flank providing thermodynamically “warm” parcels that become part of the tornado inflow represents a potentially important association from a tornadogenesis and maintenance perspective. The small $\theta_v$ associated with this part of the RFD outflow suggests that evaporation was likely not driving this downdraft. Precipitation experienced by the teams in the region was not heavy, thus reducing the probability that precipitation drag was largely producing the downdraft. A downward-directed dynamic pressure gradient force appears a likely candidate for driving this near-tornado downdraft. In addition to better understanding the near-tornado downdraft driving mechanisms, a topic for future research involves understanding the relationship, if any, between tornado strength and/or size and the intensity and size of the downdraft closely bounding the tornado.

The thermodynamic gradients identified in the 10.5 min of RFD mesonet sampling for the Tipton case were well delineated and had similar tornado-relative positions to some datasets in which RFD observations were collected relatively close to a tornado (e.g., MSR2002); however, in cases such as in MSR2002 (see their Fig. 7), Lee et al. (2004), and Finley and Lee (2008), the local warm pool within the RFD on the right flank of the tornado was much more pronounced. This is due to the introduction of warmer parcels from a surge or pulse in the RFD into cooler air already residing in the broader RFD outflow. In the Tipton case, this preexisting relatively cooler air was not present, or at least, not sampled.
This study has demonstrated the value of mesonet RFD observations within the nearest 1 km of a tornado, including data collection much closer to a tornado. Other documented mesonet datasets of RFDs, while not sampling as close to the tornado as that reported herein, have revealed marked thermodynamic and/or kinematic variability on relatively small scales within the RFD (MSR2002; Finley and Lee 2004; Lee et al. 2004; Hirth et al. 2008; Finley and Lee 2008). Further evidence of likely important processes on small scales and in close proximity to tornadoes, or tornadogenesis locations, continues to grow. As an example, Kosiba and Wurman (2008) recently reported on Doppler on Wheels (DOW; Wurman et al. 1997) observations of very small-scale outflow surge phenomenon within the RFD of the 23 May 2008 Quinter, Kansas, tornadic supercell that appeared associated with the transition of a multiple-vortex low-level mesocyclone configuration to one with a single tornado. Finley and Lee observed a similar strikingly small outflow surge within the RFD of a multiple-vortex mesocyclone that just preceeded one of the tornadogenesis cycles in the 22 May 2008 Hoxie, Kansas, tornadic supercell. The documented internal RFD outflow variability strongly suggests differences in the RFD drivers (Markowski 2002b) supporting specific portions of the RFD at a given time. A compelling need exists for mesonet RFD sampling that includes observations in the first kilometer bounding the tornado or tornadogenesis location to compliment the much larger body of radar observations.

The evolving thermodynamic character of the RFD has been noted in MSR2002 and shown in thermodynamic time series in Lee et al. (2004) and Hirth et al. (2008); however, given the difficulties of staying with a particular storm that usually involve road logistics and/or storm motion, evolutionary mesonet datasets with good RFD coverage are very rare. It is difficult to comprehensively address tornado maintenance processes or cyclic tornadogenesis without longer-duration RFD outflow thermodynamic evolution sampling. This evolutionary sampling from a mesonet may be particularly valuable for connecting polarimetric radar signatures within supercells with the near-surface thermodynamics (Romine et al. 2008). StickNet, an array of portable instrumented meteorological platforms developed by Texas Tech University (Weiss and Schroeder 2008), when deployed in two or more arrays orthogonal to the storm motion can capture some of the RFD evolution. StickNet is especially useful when a tornado is associated with a high-precipitation supercell (Moller et al. 1994) or when storm severity outside the tornadic region limits the coverage of a mobile mesonet. In a good road network where storm motion allows continuous or nearly-continuous deployment, the agility of a mobile mesonet makes it the optimal platform for RFD evolution sampling. Considerably more RFD outflow evolution datasets need to be obtained and analyzed to better understand changes in key processes that control tornado maintenance.

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