Observations of the Surface Boundary Structure within the 23 May 2007 Perryton, Texas, Supercell

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ABSTRACT

In situ data collected within a weakly tornadic, high-precipitation supercell occurring on 23 May 2007 near Perryton, Texas, are presented. Data were collected using a recently developed fleet of 22 durable, rapidly deployable probes dubbed "StickNet" as well as four mobile mesonet probes. Kinematic and thermodynamic observations of boundaries within the supercell are described in tandem with an analysis of data from the Shared Mobile Atmospheric Research and Teaching Radar.

Observations within the rear-flank downdraft of the storm exhibit large deficits of both virtual potential temperature and equivalent potential temperature, with a secondary rear-flank downdraft gust front trailing the mesocyclone. A primarily thermodynamic boundary resided across the forward-flank reflectivity gradient of the supercell. This boundary is characterized by small deficits in virtual potential temperature coupled with positive perturbations of equivalent potential temperature. The opposing thermodynamic perturbations appear to be representative of modified storm inflow, with a flux of water vapor responsible for the positive perturbations of the equivalent potential temperature. Air parcels exhibiting negative perturbations of virtual potential temperature and positive perturbations of equivalent potential temperature have the ability to be a source of both baroclinically generated streamwise horizontal vorticity and greater potential buoyancy if ingested by the low-level mesocyclone.

1. Introduction

The long-standing conceptual model of the near-surface structure of a supercell thunderstorm presented in Lemon and Doswell (1979) displays two distinct downdrafts within the storm (their Fig. 7): a rear-flank downdraft (RFD) coincident with a hook echo in radar reflectivity [see Markowski (2002a) for a recent review] and a broader forward-flank downdraft (FFD) resulting from latent chilling through evaporation and melting as well as hydrometeor loading within the precipitation core of the supercell downwind of the updraft. The RFD, often visually manifested by a cloud-free region or clear slot, wraps around the updraft and forms a sharp kinematic and thermodynamic gradient along its leading edge with the storm inflow. However, the leading edge of the FFD outflow is typically less discernible visually and is described by Lemon and Doswell as “forming a relatively weak discontinuity at the surface on the forward and right flanks of the radar echo.”

In the years since the publication of Lemon and Doswell (1979), varying representations of FFD boundaries have been presented in in situ, Doppler radar, and three-dimensional numeric cloud model studies. For example, Dowell and Bluestein (2002a) found only subtle wind shifts located roughly north of the cyclonic mesocyclone in their pseudo-dual-Doppler analysis of the 8 June 1995 McLean, Texas, tornadic supercell while Beck et al. (2006) found no discernible wind shift near the...
surface, but a strong, convergent wind shift approximately 1 km above ground level (AGL) in a nontornadic supercell. Additionally, a dual-Doppler study by Frame et al. (2009) found minimal wind shifts along the leading edge of the forward flank and parcel trajectories that originated in storm inflow and pass through the forward flank from southeast to northwest.

The majority of three-dimensional numeric cloud model simulations of supercells denote the leading edge of the FFD outflow using the $-1-K$ perturbation isentrope of either potential temperature $\theta$ or virtual potential temperature $\theta_v$, which is typically located along or ahead of the forward, right flank of the simulated surface rainwater field (Rotunno and Klemp 1982; Klemp and Rotunno 1983; Rotunno and Klemp 1985; Davies-Jones and Brooks 1993; Wicker and Wilhelmson 1995; Adlerman et al. 1999). Several simulations have produced wind shifts within the forward flank running approximately northward from the cyclonic low-level mesocyclone (Rotunno and Klemp 1985; Wicker and Wilhelmson 1995; Adlerman et al. 1999) but these were not collocated with the $-1-K$ perturbation isotherm, which is similar to the radar-observed gust front structure presented in Romine et al. (2008). Additionally, recent simulations by Beck and Weiss (2008) have produced multiple, transient kinematic and thermodynamic boundaries within the forward flank rotating cyclonically around the center of circulation.

The contrasting representation of boundaries within the forward-flank regions of supercells highlights the need for high-resolution in situ surface observations within the region, such as those obtained with the deployment of a mobile mesonet (Straka et al. 1996) in the Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX; Rasmussen et al. 1994) and subsequent field campaigns. The mobile mesonet has vastly increased the available direct surface datasets from within supercells, which were previously limited to fortuitous passages over fixed observation sites (Johnson et al. 1987; Dowell and Bluestein 1997). Mobile mesonet data have primarily been utilized to study the RFD (Markowski et al. 2002; Markowski 2002b; Grzych et al. 2007; Hirth et al. 2008) with only one study focused on the forward flank (Shabbott and Markowski 2006). In their study, Shabbott and Markowski (2006) focused on observations made within the FFD outflow of 12 tornadic and nontornadic supercells and did not note distinct wind shifts within the region.

A shared finding from mobile mesonet studies is that small thermodynamic deficits of virtual potential temperature and equivalent potential temperature $\theta$, relative to near-surface inflow values in both the RFD and FFD result in an increased likelihood of tornadogenesis. These findings contrast those of several numerical modeling studies, which found baroclinically generated horizontal vorticity along sharp buoyancy gradients within the forward flank to be an important contributor to low-level mesocyclogenesis when air parcels in the region are stretched as they accelerate into the updraft, then are subsequently tilted into the vertical and further stretched within the updraft (Klemp and Rotunno 1983; Rotunno and Klemp 1985; Wicker and Wilhelmson 1995; Adlerman et al. 1999). However, as noted by Klemp and Rotunno (1983), Dowell and Bluestein (2002a), and Shabbott and Markowski (2006), significant streamwise vorticity can be generated along weaker buoyancy gradients given a long parcel residence time. Low-level mesocyclogenesis would then proceed in a similar manner to that shown in numerical modeling studies, but with more potentially buoyant air parcels entering the low-level updraft, allowing more substantial tilting of streamwise horizontal vorticity into the vertical and subsequent stretching.

The 2007 Multiple Observations of Boundaries in the Local-Storm Environment experiment (MOBILE-07), conducted by Texas Tech University (TTU), utilized a fleet of 22 unmanned, durable, rapidly deployable surface stations and a four-probe mobile mesonet with an emphasis on collecting observations within the forward flank of supercells. The primary research goals of the project were to

- identify the prevalence and characteristics of kinematic and thermodynamic boundaries within the forward flank of supercells and
- sample the thermodynamic deficits within the forward flank of tornadic and nontornadic supercells to add to the dataset presented by Shabbott and Markowski (2006).

This study will focus on observations collected within a weakly tornadic, high-precipitation (HP) supercell near Perryton, Texas, occurring on 23 May 2007. A description of the instrumentation, data collection, and analysis methods will be presented in section 2. Analysis of the 23 May 2007 case will follow in section 3, focusing on observations within the forward flank, and discussion, conclusions, and future recommendations will be presented in section 4.

2. Methodology

a. Definition of the forward-flank reflectivity gradient (FFRG)

This paper roughly follows the definition of the forward flank put forth by Shabbott and Markowski (2006) as “the region of low-level radar reflectivity on the forward
side of a line drawn orthogonal to the major axis of the echo, through the radar-observed circulation center” (their Fig. 4). Shabbott and Markowski (2006) used the term “FFD outflow” to describe air parcels within the forward flank. In this study, forward-flank reflectivity gradient (FFRG) is utilized in place of FFD outflow as observations along the right-forward flank of the Perryton supercell indicate air parcels in the region are better characterized as modified storm inflow. The FFRG is broadly defined herein as the region to the right of a line bisecting the forward-flank precipitation shield (Fig. 1).

b. StickNet

Due to the limitations of using manned instrumentation, such as a mobile mesonet, in hazardous environments, the TTU Atmospheric Science Group and Wind Science and Engineering Research Center have developed a suite of ruggedized surface-observing probes dubbed “StickNet” (Schroeder and Weiss 2008; Weiss and Schroeder 2008). The 2007 incarnation of Project MOBILE marked the first mass deployments of StickNet in a supercell environment. Twenty-two probes were available to MOBILE-07 utilizing two different instrument packages (Table 1). Ten “type A” probes (Fig. 2a) are equipped to measure temperature, relative humidity, pressure, wind speed, and wind direction at either 1-, 5-, or 10-Hz sampling intervals. Two additional type A probes were only equipped to measure wind speed and direction in MOBILE-07. The remaining 10 type B probes (Fig. 2b) utilize a Vaisala WXT510 “all in one” instrument that produces measurements of temperature, relative humidity, barometric pressure, wind speed, and wind direction, as well as estimates of accumulated rainfall and hail size at a 1-Hz interval. Instrumentation for each probe is mounted on a Crane Tall TriMax tripod and data are collected via Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) programs running on a National Instruments Compact FieldPoint module housed within a Campbell Scientific data acquisition (DAQ) box. An external battery box can be affixed to each probe for long-term (greater than 18 h) deployments. All probes are equipped with a flux-gate

![Fig. 1. Schematic illustrating the near-surface representation of the forward-flank (hatched) and forward-flank reflectivity gradient (crossed). [Adapted from Shabbott and Markowski (2006)].](image-url)
A compass that allows wind direction values to be corrected to magnetic north, a GPS antenna/receiver that records probe position and synchronizes observation times, and a bubble level to permit rapid leveling of the probe during deployment.

For a short-term (thunderstorm) deployment, a team of two people will extend, secure, and level the tripod, attach the DAQ box and plug in connections for the flux-gate compass and instrumentation package, anchor the probe using 0.5-m stakes, then turn on the power and ensure data are being collected. A single probe can be expected to be fully deployed in under 2 min. Spring load tests conducted by the TTU Wind Science and Engineering Research Center suggest that a probe deployed in a long-term configuration (which includes the external battery box) is capable of withstanding a maximum 3-s wind gust of 63 m s$^{-1}$.

In transit, the probes are housed in two trailers outfitted to store 12 probes apiece. The DAQ box and external battery are connected to one 10-bank and one 5-bank battery recharger in the fore of the trailer allowing them to be recharged in transit. Additionally, each DAQ box is networked to a local Ethernet hub, which allows data to be downloaded following each deployment. During deployments, five probes are removed from each trailer and carried by pickup trucks using custom-fitted racks to permit greater maneuverability.

In MOBILE-07 a one-road deployment strategy was utilized for StickNet. The two trailers (identified as SN3 and SN4) would deploy a coarse array with approximately 3-km probe spacing centered about a point identified to be the approximate location at which the storm updraft will cross the array. The trailers move only southward during the deployment to ensure a safe exit from the storm environment. As the updraft approaches the coarse array, a finescale array is laid out by the two pickup trucks (SN1 and SN2) with 0.8-km spacing between probes. These more nimble vehicles are capable of moving northward to adapt to changes in the estimation of the updraft passage over the array without risking their safety.

c. Mobile mesonet

A four-probe mobile mesonet was also operated in MOBILE-07 in association with the Department of Atmospheric, Oceanic, and Space Sciences at the University of Michigan. The TTU mobile mesonet design is based on Straka et al. (1996) with small alterations as described by Hirth et al. (2008). The deployment strategy of the mobile mesonet was to perform transects across
the right-forward flank of the storm. Due to potentially hazardous conditions and low visibility within the forward flank, one probe remained equatorward of the storm within the storm inflow. The "field coordinator" or FC probe produced estimates of updraft location for StickNet and mobile mesonet probes, set endpoints to mobile mesonet transects, and collected storm-inflow data to be used as a base state in calculations of thermodynamic perturbations.

d. Quality assurance

1) STICKNET

StickNet data collected during MOBILE-07 were initially reduced to 1 Hz for each probe to ensure consistency. Data spikes and dropouts were objectively removed by quality assurance software, and additional dubious observations were subjectively flagged and removed from the record. Further, due to the large network of probes available, several occurrences of instrument malfunction were identified and removed from the data record (Table 2). Time series and radar overlay plots were created using a 5-s moving average of quality-controlled observations.

The calculation of StickNet biases is challenging as there are very limited periods of quiescent data available for each probe as present in most mobile mesonet datasets (Grzych et al. 2007; Hirth et al. 2008). Instead, instrument biases in StickNet probes were determined by intercomparing 60-min periods of data from mass tests in quiescent conditions performed prior to the start and at the conclusion of MOBILE-07. This method has the disadvantage of being unable to capture biases that developed over the course of the field project or dynamic biases dependent on environmental conditions. However, the majority of the StickNet biases detected in MOBILE-07 were consistent between the two mass tests, lending confidence to the validity of the bias values utilized. Due to the proximity in time to the Perryton deployment, biases in this study are determined using the mass test occurring prior to MOBILE-07 on 15 May 2007. Correction and removal of biased observations follows that of Markowski et al. (2002) with the exception of wind direction. Consistent wind direction biases were introduced in five StickNet probes during the Perryton deployment by errors in the flux-gate compass readings. The flux-gate compass of two probes (08A and 15B) failed, resulting in erroneous wind directions with respect to magnetic north. Each of these probes was located between two fully functioning probes that observed similar wind directions throughout the deployment. By calculating the mean wind direction for the fully functioning probes over a 10-min period of nearly consistent wind direction, the erroneous probe data were corrected using the mean value. Though large biases in wind direction of 70.2° (−36.3°) were corrected in probes 08B (15A), the mean wind direction between the fully functioning probes varied by less than 10° during the correction period. Three additional probes (01A, 02B, and 19A) incurred large, consistent biases in wind direction due to the flux-gate compass becoming dislodged and rotating with respect to the anemometer position. These probes exhibited similar wind direction biases with respect to surrounding probes during the Perryton case, as well as all later deployments and in the postseason mass test. Therefore, wind direction values are corrected using the bias detected in the postseason mass test despite being several times over the limit described in Markowski et al. (2002). A complete listing of StickNet bias corrections utilized for the Perryton case is presented in Table 3.

2) MOBILE MESONET

The quality assurance of mobile mesonet data followed precedents set by Markowski et al. (2002), Markowski (2002b), Shabbott and Markowski (2006), Grzych et al. (2007), and Hirth et al. (2008). Biases were determined using data collected as the probes traveled as a caravan through quiescent conditions prior to storm initiation and were removed according to the limits described by Markowski et al. (2002). Additional bias limits of 0.02 hPa were applied to observations of vapor pressure and saturation vapor pressure to ensure the accurate calculation of derived thermodynamic variables (Table 4). Kinematic values were flagged and discarded for periods when the magnitude of the vehicle acceleration vector exceeded 1 m s⁻² (Markowski 2002b; Grzych et al. 2007).

Thermodynamic data from the mobile mesonet were intercompared with StickNet data during periods when the two observing platforms were within 500 m of one another. It was found that the spatial bias introduced by the response time of the thermodynamic instrumentation affects the position and magnitude of thermodynamic gradients. Using an approximate time constant of 1 min for slow temperature and relative humidity values

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**Table 2. StickNet instrumentation malfunctions on 23 May 2007.**

<table>
<thead>
<tr>
<th>Probe ID</th>
<th>Issue</th>
<th>Corrective action</th>
</tr>
</thead>
<tbody>
<tr>
<td>03A</td>
<td>Temperature and RH erroneously low</td>
<td>Thermodynamic data discarded</td>
</tr>
<tr>
<td>08B</td>
<td>No compass reading</td>
<td>Wind data corrected</td>
</tr>
<tr>
<td>13A</td>
<td>Temperature and RH erroneously high</td>
<td>Thermodynamic data discarded</td>
</tr>
<tr>
<td>15A</td>
<td>No compass reading</td>
<td>Wind data corrected</td>
</tr>
<tr>
<td>21A</td>
<td>Temperature and RH erroneously low</td>
<td>Thermodynamic data discarded</td>
</tr>
</tbody>
</table>
(Straka et al. 1996), a mobile mesonet probe moving at approximately 13.5 m s\(^{-1}\) will travel ~800 m before fully responding to the new environment. The differing storm-relative motion of the StickNet and mobile mesonet observing platforms may act to either stretch or compress thermodynamic gradients where probes of both platform types interact (Skinner et al. 2010). To mitigate the inconsistencies between StickNet and the mobile mesonet analysis arising from this effect, observations from two mobile mesonet probes traversing thermodynamic gradients (T2 and T3) have been neglected in this study. The two remaining probes (FC and T4) remained outside of the FFRG in a region of relatively homogeneous thermodynamic conditions and are retained.

e. Derived variables

Virtual potential temperature including the effects of the condensate mixing ratio \(q_c\), also known as the density potential temperature \(\theta_p\) (Emanuel 1994), is calculated as in Shabbott and Markowski (2006) using

\[
\theta_p = \theta(1 + 0.61q_v - q_c),
\]

where \(\theta\) represents potential temperature and \(q_v\) is the water vapor mixing ratio. Calculations of virtual potential temperature \(\theta_v\) neglect the effects of \(q_c\) in (1).

Shared Mobile Atmospheric Research and Teaching Radar (SMART-R) (Biggerstaff et al. 2005) radar reflectivity is used to estimate \(q_c\) according to Hane and Ray (1985):

\[
q_c = \frac{1}{\rho} \left( \frac{10^\gamma}{1.73 \times 10^\pi} \right)^{4/7},
\]

where \(\rho\) is density and \(\alpha\) is equal to 0.1 \(\times\) the radar reflectivity factor (in dBZ). Errors are introduced into \(\theta_p\) calculations if a reflectivity gradient between the lowest available radar elevation angle and the surface is present and, also, if ice is present within the sample volume. As the lowest available SMART-R reflectivity data are approximately 490 m above the surface and hail was detected by multiple type B StickNet probes, as well as reported by the northernmost mobile mesonet probe (J. Merchant 2007, personal communication) within the FFRG, it is stressed that values of \(\theta_p\) presented herein represent a best available estimate. Furthermore, to account for the effects of storm propagation between radar scans, \(\theta_p\) is calculated over time-to-space-converted StickNet data using SMART-R reflectivity data coincident with the beginning of the time-to-space conversion analysis period. There will be additional error in the latter portions of the analysis period due to storm evolution, though it is noted that this error will be limited as the FFRG was exiting the finescale StickNet array during the analysis period.

Pseudo-equivalent potential temperature \(\theta_{ep}\), which will be referred to as equivalent potential temperature \(\theta_e\) herein, is calculated according to the derivation of Bolton (1980). As noted by Markowski (2002b) and Shabbott and Markowski (2006), use of \(\theta_e\) as a tracer of parcel origin is problematic due to diabatic effects within the supercell environment and it is best viewed as the height on an inflow sounding at which a parcel originated.

f. Base state approximation

To produce analyses of perturbations to thermodynamic variables, it is necessary to define a base state for air parcels within the inflow of the storm. For MOBILE-07, the base state is calculated using averages of all probes residing outside of storm outflow and precipitation. The presence of precipitation is detected directly using the rainfall sensors on type B StickNet probes; otherwise, it was determined as areas where the reflectivity factor is greater than 25 dBZ, as in Shabbott and Markowski

\[\text{Table 3. StickNet bias corrections for 23 May 2007. Definitions as in Table 1.}\]

<table>
<thead>
<tr>
<th>Probe ID</th>
<th>(T (\degree C))</th>
<th>RH (%)</th>
<th>Pressure (hPa)</th>
<th>WD (°)</th>
<th>WS (m s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>01A</td>
<td>+0.88</td>
<td></td>
<td>-33.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02B</td>
<td>-0.81</td>
<td>+0.94</td>
<td>+28.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>03A</td>
<td></td>
<td></td>
<td>+14.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>06B</td>
<td></td>
<td></td>
<td>+10.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>07A</td>
<td>+0.67</td>
<td></td>
<td>-1.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10A</td>
<td></td>
<td>+0.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13A</td>
<td></td>
<td>-0.72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15A</td>
<td></td>
<td>+0.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16B</td>
<td></td>
<td>-0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17A</td>
<td></td>
<td>+0.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19A</td>
<td>+0.39</td>
<td></td>
<td>-56.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21A</td>
<td>+0.29</td>
<td></td>
<td>-10.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22B</td>
<td></td>
<td>-0.58</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>23A</td>
<td>+0.25</td>
<td></td>
<td>+0.31</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[\text{Table 4. Mobile mesonet bias corrections for 23 May 2007.}\]

<table>
<thead>
<tr>
<th>Probe ID</th>
<th>Fast (T (\degree C))</th>
<th>Slow (T (\degree C))</th>
<th>Saturated vapor pressure (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC</td>
<td>+0.34</td>
<td>-0.066</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>+0.34</td>
<td>+0.030</td>
<td></td>
</tr>
</tbody>
</table>

\[\text{1 Bolton’s (1980) Eq. (43) is used for calculation of equivalent potential temperature and Eq. (21) is used for condensation temperature.}\]
(2006). Based on these criteria, the base state is calculated from an average of the FC and T4 mobile mesonet probes over a 10-min period as the low-level mesocyclone crossed the instrument array.

g. Analysis techniques

If a steady-state feature of interest is propagating along a constant vector, point observations of the feature may be expanded in the horizontal plane using time-to-space conversion (Taylor 1938). The Taylor hypothesis is difficult to apply to supercells as they often evolve on rapid time scales, making the steady-state assumption problematic. Past studies (Markowski et al. 2002; Markowski 2002b) have assumed a steady state for small time periods (approximately 5 min) to limit the impacts of storm evolution on the analysis; however, this study will use a 10-min steady-state assumption similar to Hirth et al. (2008). Although cyclic mesocyclone genesis (Burgess et al. 1982) was observed as the Perryton supercell crossed the instrument array, the time-to-space-converted values encompass a much broader scale than the mesocyclone itself in order to assess the impacts of forward-flank inflow air properties on storm morphology and evolution. Therefore, errors associated with the steady-state assumption will minimally impact the analysis and conclusions.

A second difficulty in performing time-to-space conversion is specifying the motion of the feature of interest. Past studies have performed tornado-relative (Hirth et al. 2008) or storm-relative time-to-space conversions based on the highest observed reflectivity factor (Shabbott and Markowski 2006). Storm motion of the Perryton supercell is estimated using the motion of the intersection point of the RFGF fine line in the SMART-R data with the FFRG, as this was the most reliably identifiable feature available with cyclic mesocyclogenesis ongoing during the analysis period. All time-to-space-converted data presented will be referred to as relative to the RFGF as the boundary may move independently of other storm features.

Time-to-space-converted observations are gridded onto a two-dimensional plane and interpolated using a Barnes objective analysis scheme (Barnes 1964). Due to the time-to-space-converted values having much higher spatial resolution tangential to storm motion, every hundredth time-to-space-converted observation is included in the objective analysis and an anisotropic Barnes weighting function is employed (Trapp and Doswell 2000):

\[ w = \exp \left( -\frac{t^2}{\kappa_t} - \frac{n^2}{\kappa_n} \right), \]

where \( w \) represents the weight function; \( t \) and \( n \) are the distances from the current grid point to the data point being considered tangential and normal to storm motion, respectively; and \( \kappa_t, \kappa_n \) represents a “smoothing parameter” tangential (normal) to storm motion as defined by Koch et al. (1983),

\[ \kappa = 5.052 \left( \frac{2\Delta n}{\pi} \right)^2, \]

with \( \Delta n \) representing the mean spacing between observations. A \( \Delta n \) of 0.7 km (1.4 km) is utilized for data collected tangential (normal) to the Perryton storm.

3. 23 May 2007, Perryton, Texas, supercell

a. Storm evolution

On 23 May 2007, Project MOBILE-07 targeted a warm front extending from roughly Amarillo, Texas (KAMA), northeastward through northwestern Oklahoma and into south-central Kansas. The air mass behind the front was conditionally favorable for surface-based convection with greater than 1000 J kg\(^{-1}\) of mixed-layer convective available potential energy (CAPE) as per the 0000 UTC KAMA sounding (Fig. 3). It is likely that higher values of CAPE were present in the environment of the Perryton supercell as the KAMA sounding was located approximately 140 km southwest of the StickNet deployment and exhibited surface dewpoint values roughly 2 K lower than the base state of the Perryton storm. Southeasterly surface winds at 7–10 m s\(^{-1}\) under the southern portion of a 500-hPa velocity maximum of approximately 20 m s\(^{-1}\) resulted in favorable conditions for supercell development, with 0–6-km shear greater than 25 m s\(^{-1}\) in the KAMA sounding and clockwise curvature in the low levels of the hodograph (Fig. 3).

Convection initiation occurred shortly after 2100 UTC to the southwest of Perryton (KPYX). This convection, hereafter referred to as “storm A,” rapidly became supercellular and produced a brief tornado at 2131 UTC in rural areas to the northwest of Miami, Texas (NCDC 2007). MOBILE-07 targeted storm A for deployment shortly after initiation; however, due to the lack of an acceptable road network, the deployment began well ahead of the storm along Highway 83 to the southeast of KPYX (Figs. 4a and 4b). Shortly after the initial deployment began, additional convection initiated along the right, rear flank of storm A. “Storm B” quickly became the dominant cell and the deployment was shifted to the southeast after five probes were placed in the path of storm A (Figs. 4c–f). A total of 20 StickNet probes and the four-probe mobile mesonet were aligned from northwest
to southeast along an approximately 35-km stretch of Highway 83 as storm B approached (Figs. 5 and 6).

Additional convection continued to develop along the southwestern flank of storm B and it evolved into an HP supercell embedded in a broken line of convection as it crossed the instrument array. Storm Data (NCDC 2007) reported that storm B produced a brief tornado rated as EF0 on the enhanced Fujita scale between 2239 and 2240 UTC less than 5 km to the south of the northwesternmost three StickNet probes. This tornado is evident in SMART-R 0.75° elevation radial velocity data with greater than 50 m s⁻¹ gate-to-gate shear sampled approximately 490 m above the surface at 35-km distance from the radar (Fig. 5b). Analysis of SMART-R radial velocity data shows storm B underwent cyclic mesocyclogenesis over the 20 min following tornado dissipation as it crossed the StickNet array. As the storm impinged on the finescale array around 2245 UTC, the parent mesocyclone of the tornado had weakened considerably and the RFGF had moved well ahead of it (Figs. 5c and 5d). By 2250 UTC, inbound velocities within the RFD and outbound velocities within the forward flank had accelerated and a broad mesocyclone signature was present over the western portions of the finescale array (Figs. 6a and 6b). By 2255 UTC, vertical vorticity associated with the new mesocyclone began to decrease as the storm began a more northward propagation (Figs. 6c and 6d). Storm B merged with the trailing convection shortly after 2300 UTC; however, it produced two additional brief tornadoes between 2330 and 2345 UTC when it was embedded in the line.

As storm B approached the instrument array, the majority of the probes, including the entire finescale array, sampled conditions along the FFRG. The probes then sampled the RFD of the storm as the low-level mesocyclone passed to the north of the finescale array. Three probes originally deployed for storm A remained to the north of the mesocyclone and sampled the RFD trailing the center of circulation.

b. Time series analysis

Time series of the thermodynamic and kinematic observations of each probe were analyzed. For brevity, five probes spanning the breadth of the instrument array (Fig. 7) are presented here.

The two northwesternmost probes (14B and 16B) begin the data record in residual RFD outflow from storm A. Probe 14B remains in this outflow to the north of the precipitation core of storm B throughout the
period and experiences light and variable winds accompanied by strong thermodynamic deficits (Fig. 8a). The data record of probe 16B (Fig. 8b) begins in a similar environment to 14B, although the probe experiences higher wind speeds within the precipitation core of storm B. Over the period from 2236 to 2240 UTC, the wind direction observed by 16B veers to nearly due easterly and a gradual acceleration is observed after 2240 UTC. A subtle increase in $\theta_v$ ($\theta_e$) of 1 (3) K is observed during the wind shift, bringing probe 16B into an environment more similar to probe 19A to the southeast than probe 14B to the northwest. Though this boundary passage is nearly coincident with tornadoogenesis approximately 5 km to the south-southwest of probe 16B, it is unclear if the boundary extended southward to the immediate environment of the tornado.

During the 10 min following tornado dissipation from 2240 to 2250 UTC, probes 16B (Fig. 8b) and 19A

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**FIG. 4.** KAMA 0.5°-elevation scan reflectivity (dBZ) for (a) 2110, (b) 2131, (c) 2152, (d) 2213, (e) 2230, and (f) 2251 UTC. StickNet probes deployed at the time of each scan are indicated by dark circles.
FIG. 5. StickNet and mobile mesonet observations overlaid with the SMART-R 0.75°-elevation scan (a),(c) reflectivity (dBZ) and (b),(d) radial velocity (m s$^{-1}$) at (a),(b) 2239 and (c),(d) 2245 UTC. The station plot includes virtual potential temperature (K, bottom left) and equivalent potential temperature (K, top left); full wind barbs represent 5 m s$^{-1}$. Subjectively analyzed gust front positions, mesocyclone position, and tornado position are denoted by solid lines, M, and T, respectively. Range rings every 5 km are included with the SMART-R location approximately 10 km east of the bottom-right corner of each image.

(Fig. 9a) experienced steadily accelerating, nearly easterly winds as cyclic mesocyclogenesis occurred to the south. Strong $\theta_v$ ($\theta_e$) deficits of approximately 5 (8) K were observed during this period, which coupled with evidence of a kinematic shift to the east of the probes in the SMART-R data (Fig. 5d), suggest the probes lie within the RFD of storm B to the north-northwest of the developing low-level mesocyclone. A secondary boundary passed over both probes between 2248 and 2251 UTC and was characterized by a rapid acceleration of wind speed to values greater than 20 m s$^{-1}$ (Figs. 8b and 9a), with divergence developing between the two probes (Figs. 6a and 6b), and a sharp increase in both $\theta_v$ and $\theta_e$ deficits to values greater than 7 and 14 K, respectively. The divergence between probes 16B and 19A and similarly large thermodynamic deficits observed suggest that the probes are sampling air parcels within a downdraft originating to the north and west of the mesocyclone. This downdraft is first observed by the StickNet array within the occlusion of the initial RFGF as analyzed in SMART-R data (Fig. 6b), suggesting that this boundary represents a secondary RFGF (Finley and Lee 2004; Lee et al. 2004; Marquis et al. 2008; Karstens et al. 2010; Lee et al. 2011). While $\theta_v$ and $\theta_e$ deficits within the RFD surge in the immediate vicinity of the tornado are unavailable, the steep decline in thermodynamic values associated with the passage of the secondary RFD boundary suggests that changes in thermodynamic character are possible between RFD surges in a single storm, similar to the findings of Finley and Lee (2004), Lee et al. (2004), Finley and Lee (2008), and Finley et al. (2010).

During the analysis period, the FFRG moved slowly northward across probes within the finescale array as the southern portion of the RFD impinged upon them from the southwest. Probes 22B (Fig. 9b) and 15A (Fig. 10) are representative of all probes within the FFRG and
exhibit little change in thermodynamic character, with a deficit of 1–2 K in virtual potential temperature and a modest surplus of 1–3 K in equivalent potential temperature compared to the base state. Kinematically, probes within the FFRG experienced similar values to the probes within storm inflow with east-southeasterly winds between 5 and 10 m s$^{-1}$, though a subtle backing of the winds is observed moving northward relative to the low-level mesocyclone. The passage of the RFGF is marked by a veering of the wind to south-southwesterly approximately 3 min prior to any response in the thermodynamic values. Approximately 2–3 min after the initial kinematic response, a nearly linear decrease in $\theta_v$ and a steep decline in $\theta_e$ is noted. There is subtle evidence of the passage of the secondary RFGF in probe 22B and other probes along the western edge of the finescale array at 2254 UTC, suggesting the possibility of the RFD surge propagating cyclonically around the low-level mesocyclone. The wind speeds observed with RFGF passage are weaker in probes located in the eastern portion of the finescale array, which is supported by a decrease in the radial velocities in the SMART-R data (Figs. 6c and 6d).

c. Time-to-space conversion and objective analysis

To better visualize the boundaries observed in the Perryton supercell, time-to-space conversion of StickNet and mobile mesonet data is conducted over a 10-min period centered on the time of low-level mesocyclone passage across the instrument array at 2250 UTC (Figs. 11–14).

The passage of the RFGF is apparent in the objective analysis as a sharp gradient in both the virtual and equivalent potential temperature trailing the initial wind shift. Winds along the RFGF veer to south-southwesterly, then gradually back within the RFD to southeasterlies as the mesocyclone moves north and decreases in intensity toward the end of the analysis period.2 Additionally, a secondary RFGF is likely present in the observation gap between probes to the northwest of the

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2 It is noted that the mesocyclone center analyzed in Figs. 11–14 was determined from SMART-R data at 2245 UTC. Therefore, wind observations from later in the analysis period will correspond to a mesocyclone position farther north and east than the denoted position.
mesocyclone center and the finescale array to the southeast of the mesocyclone based on analysis of probes 16B and 19A (Figs. 5, 6, 8b, and 9a).

The broad region of FFRG encompassed by the finescale array displays similar kinematic values to the inflow, but with a gradual backing of the wind as one moves northward with respect to the mesocyclone. In contrast to observations within the RFD, opposing perturbations of $u_v$ and $u_e$ are present across the FFRG. Small deficits of virtual potential temperature are present within the forward flank, resulting in a southeastward-directed buoyancy gradient. The buoyancy gradient is

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**Fig. 7.** Positions of StickNet probes displayed in Figs. 8–10. Positions are overlaid on SMART-R 0.75°-elevation scan reflectivity (dBZ) data at (a) 2239 and (b) 2250 UTC. Subjectively analyzed gust front positions, mesocyclone position, and tornado position are denoted by solid lines, M, and T, respectively. Range rings every 5 km are included with SMART-R location approximately 20 km southeast of the bottom-right corner of each image.

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**Fig. 8.** From top to bottom, plots of wind speed, wind direction, $u_v$ perturbation, and $u_e$ perturbation for (a) probe 14B and (b) probe 16B. Arrows indicate the subjective analysis of boundary passage.
more pronounced and more southward directed when density potential temperature is considered (Fig. 13). Analysis of the equivalent potential temperature reveals positive perturbations of the $\theta_e$ values within the FFRG with maximum positive perturbations coincident with higher radar reflectivities in the SMART-R data.

4. Discussion

a. The FFRG boundary

The primary boundary observed within the forward flank of the Perryton supercell occurred across the FFRG and was largely thermodynamic in nature (Figs. 11–13). The boundary was characterized by small deficits in virtual and density potential temperature coupled with positive perturbations in equivalent potential temperature. Little change in the kinematic variables was observed, with only a slight backing of the wind occurring across the FFRG coincident with the thermodynamic perturbations.

The observation of equivalent potential temperature values higher than the base state is an important finding from Project MOBILE-07 and requires closer inspection. If values of $\theta_e$ are considered as heights on an inflow sounding at which air parcels originate (Markowski 2002b; Shabbott and Markowski 2006), it would necessitate parcel origins below ground in the Perryton supercell. As this scenario is obviously not possible, other sources for the origin of the positive $\theta_e$ perturbation values must be considered. One possibility is heterogeneity within the inflow resulting in a varying base state. Slight heterogeneity was observed between the two probes utilized to produce the base state for the Perryton supercell. However, differences between base states calculated from the two individual inflow probes differ by less than 0.5 K and a gradient of $\theta_e$ is evident between probes within the FFRG and the inflow probes (Fig. 12). Additionally, three of the other four cases analyzed in MOBILE-07 show similar positive perturbations of equivalent potential temperature across the FFRG with the remaining case exhibiting values similar to those observed by the inflow probe (Table 5). A separate complication in the Perryton supercell is that, due to the east–west orientation of the instrument array, it is uncertain if the positive perturbations of $\theta_e$ extend southward from the leading edge of the precipitation shield in regions west of the inflow probes. Separate deployments in MOBILE-07 conducted along north–south roads on 22 May 2007 near Hill City, Kansas, and 31 May 2007 near Hough, Oklahoma (Table 5), exhibit positive $\theta_e$ perturbations northward from the southernmost extent of the FFRG.
These observations, combined with the $\theta_e$ gradient observed across the eastern edge of the FFRG in the Perryton supercell (Fig. 12), suggest the possibility that the positive perturbations in $\theta_e$ are limited to within the FFRG of the Perryton storm as well. There is evidence of a slight decrease in $\theta_e$ of approximately 1 K in probes initially within the FFRG of the Perryton supercell as the precipitation shield exits the instrument array to the north, but positive perturbations in $\theta_e$ are retained through the duration of the deployment. As the identification of any base state is subjective, the magnitude of the $\theta_e$ perturbations with respect to true storm inflow is not fully known and the perturbations are best interpreted as being relative to that outside of the precipitation region of the supercell.

Though additional convection trailed the Perryton supercell (Fig. 4), no other convection existed ahead of the storm and it remained south of the warm front throughout its life cycle, likely precluding the possibility of higher-$\theta_e$ air being lifted over a denser air mass before descending in the downdrafts of the Perryton supercell (Hirth et al. 2008). However, this does not preclude the possibility of higher-$\theta_e$ air existing aloft in the environment of the Perryton supercell, possibly as a result of anvil shading (Markowski et al. 1998), and descending in the forward flank.

As equivalent potential temperature is strongly coupled to water vapor mixing ratio values, while virtual potential temperature is primarily dependent on temperature values (Fig. 10b), an increase in water vapor mixing ratio coupled with a decrease in temperature could produce opposing perturbations of $\theta_v$ and $\theta_e$. Analysis of water vapor mixing ratio perturbations within the Perryton supercell shows a broad swath of positive perturbations aligned roughly with positive perturbations of $\theta_e$ (Fig. 14), suggesting that a flux of water vapor is responsible for the positive perturbations in $\theta_e$. The origin of this flux is unclear; however, one potential source would be a flux of water vapor from a precipitation-moistened surface. Despite uncertainty as to the origin of the positive perturbations in $q_v$, the lack of a distinct wind shift across the FFRG coupled with small thermodynamic perturbations compared to those observed within the RFD suggest that air parcels within the FFRG are better characterized as modified storm inflow rather than outflow from the FFD. This result is kinematically similar to dual-Doppler studies by Beck et al. (2006) and Frame et al. (2009) as well as several simulations produced by Beck and Weiss (2008), which resulted in modest deficits of $\theta_e$ with little change in $\theta_v$. 

![Figure 10](image_url)
Parcel trajectories calculated in dual-Doppler and numerical modeling studies have identified near-surface air parcels along the FFRG as a source region for air entering the low-level mesocyclone (Klemp and Rotunno 1983; Rotunno and Klemp 1985; Davies-Jones and Brooks 1993; Wicker and Wilhelmson 1995; Adlerman et al. 1999; Dowell and Bluestein 2002b; Beck et al. 2006; Beck and Weiss 2008). However, parcel trajectories are not available for the Perryton supercell, so it is stressed that the potential impacts of the FFRG boundary on low-level mesocyclogenesis and maintenance are dependent on the ability of the low-level mesocyclone to ingest air parcels with a long residence time along the boundary, which likely varies considerably among supercells and even over the life cycle of a single storm.

Several numerical modeling studies have identified the tilting and subsequent stretching of baroclinically generated streamwise horizontal vorticity along strong buoyancy gradients within the forward flank as an important source of vertical vorticity in the low-level mesocyclone (Klemp and Rotunno 1983; Rotunno and Klemp 1985; Wicker and Wilhelmson 1995; Adlerman et al. 1999). Contrasting these findings, Shabbott and Markowski (2006) found that storms producing strong deficits of $\theta_v$ and $\theta_p$ within the forward flank, which results in greater potential for baroclinic generation of vorticity, produced weaker low-level mesocyclones and were less likely to be tornadic than storms with smaller $\theta_v$ and $\theta_p$ deficits. The association of small thermodynamic perturbations within the forward flank with stronger low-level mesocyclones is attributed to air parcels with...
greater potential buoyancy resulting in greater vertical accelerations within the low-level updraft, enhancing the tilting of streamwise horizontal vorticity into the vertical and subsequent stretching. Though storms with smaller thermodynamic deficits and greater potential buoyancy within the forward flank have been found to produce stronger low-level mesocyclones, the finding does not preclude baroclinically generated streamwise horizontal vorticity from being an important source for low-level mesocyclogenesis. As noted by Klemp and Rotunno (1983), Dowell and Bluestein (2002a), and Shabbott and Markowski (2006), significant baroclinically generated streamwise vorticity can be generated along weak buoyancy gradients given a long parcel residence time.

Small deficits of $u_v$ were observed within the FFRG of the Perryton supercell (Fig. 11), but were oriented nearly perpendicular to wind observations, which would limit the potential residence time of air parcels within the baroclinic vorticity generation region. However, deficits of $u_r$ within the FFRG are stronger than the $u_v$ deficits.

![Fig. 12. As in Fig. 11, but for equivalent potential temperature perturbation (K).](image)

**Table 5.** Maximum positive perturbation values of $\theta_e$ observed within the FFRG for each of five cases in MOBILE-07 as well as perturbation value of $u_v$ at time of max $\theta_e$.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Tornadic/nontornadic</th>
<th>$\theta_e'$</th>
<th>$u_v'$</th>
<th>Probe ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 May</td>
<td>Hill City, KS</td>
<td>Tornadic</td>
<td>1.775</td>
<td>-2.891</td>
<td>24B</td>
</tr>
<tr>
<td>23 May (case 1)</td>
<td>Perryton, TX</td>
<td>Tornadic</td>
<td>3.546</td>
<td>-0.189</td>
<td>18B</td>
</tr>
<tr>
<td>23 May (case 2)</td>
<td>Canadian, TX</td>
<td>Nontornadic</td>
<td>0.607</td>
<td>-0.771</td>
<td>T4</td>
</tr>
<tr>
<td>31 May (case 1)</td>
<td>Keyes, OK</td>
<td>Nontornadic</td>
<td>1.770</td>
<td>-1.750</td>
<td>23A</td>
</tr>
<tr>
<td>31 May (case 2)</td>
<td>Hough, OK</td>
<td>Tornadic</td>
<td>2.517</td>
<td>0.194</td>
<td>T2</td>
</tr>
</tbody>
</table>
and are oriented more favorably for longer parcel residence times along the buoyancy gradient (Fig. 13). Given favorable parcel trajectories, air parcels traveling along the FFRG of the Perryton supercell would have the potential to generate substantial streamwise horizontal vorticity for ingestion by the low-level updraft.

Equivalent potential temperature is commonly used as a parcel tracer because it is conserved for both dry- and moist-adiabatic processes. Therefore, an increase in surface $\psi$ would result in a rightward shift in the parcel path of surface air on a skew $T$–log$p$ diagram. Consequently, despite air parcels within the FFRG being more dense than inflow parcels near the surface due to lower $\psi$, the positive perturbation in $\psi$ represents an increase in potential buoyancy due to the rightward shift of the parcel path. If air parcels traveling through the FFRG of the Perryton storm were forced to rise to their level of free convection (LFC) by convergence under the low-level updraft, they would have greater CAPE than parcels originating elsewhere in the storm inflow. The positive perturbations in $\psi$ would likely also be characterized by lower values of convective inhibition (CIN), a lower lifted condensation level (LCL), and a lower LFC than for the base-state storm inflow, each of which has been associated with an increasing likelihood of tornadogenesis (Rasmussen and Blanchard 1998; McCaul and Weisman 2001; Markowski 2002b; Davies 2004).

The presence of negative perturbations in $\psi$ and $\psi_v$ coupled with positive perturbations in $\psi_e$ across the FFRG in the Perryton supercell suggest the possibility that a supercell can ingest air parcels containing both substantial amounts of baroclinically generated streamwise horizontal vorticity and greater potential buoyancy than parcels residing in the unmodified inflow environment. It is once again stressed that thermodynamic perturbations along the FFRG only offer potential impacts on low-level mesocyclogenesis and maintenance. Parcel trajectories, residence times along buoyancy gradients, depths of the thermodynamic perturbations, and contributions from air parcels originating in the RFD likely all

**Fig. 13.** As in Fig. 11, but for density potential temperature perturbation (K).
play a role in low-level mesocyclogenesis and can vary among storms and even the life cycle of a single supercell.

b. Conclusions and future work

Surface observations collected within the 23 May 2007 Perryton, Texas, supercell have been presented. The following conclusions are presented following our analysis of 20 StickNet probes, two mobile mesonet probes, and SMART-R radar data.

- Air parcels residing within the FFRG of the Perryton supercell appear to be representative of storm inflow modified through latent chilling and a flux of water vapor.
- A thermodynamic boundary consisting of negative perturbations of $\theta_e$ and $\theta_p$ and positive perturbations of $\theta_v$ can develop across the FFRG of supercells. This boundary is a potential source of low-level baroclinically generated streamwise horizontal vorticity that can be tilted into cyclonic vertical vorticity by the updraft and contains air with greater potential buoyancy and smaller convective inhibition than inflow parcels residing outside of the FFRG that can increase vertical accelerations and enhance stretching of cyclonic vertical vorticity within the updraft.
- Supercells may exhibit a multiple RFGF structure with surges exhibiting distinct kinematic and thermodynamic characteristics from the broader-scale RFD.

To fully address the impacts the FFRG has on supercell evolution, much further research is needed. Primarily, dense observations of the FFRG need to be integrated with dual-Doppler generated parcel trajectories or assimilated into three-dimensional numeric cloud models to identify which air parcels, if any, within the FFRG are ingested by the low-level mesocyclone. Additionally, a three-dimensional analysis provided by dual-Doppler analyses and/or storm-scale numerical models will allow for a full vorticity budget of the low-level

![Fig. 14. As in Fig. 11, but for water vapor mixing ratio perturbation (g kg$^{-1}$).](image)
mesocyclone to be developed to quantify the impacts of the FFRG boundary. A case study of a single storm has been presented in this paper. To identify the prevalence of opposing perturbations of $\theta_e$, $\theta_u$, and $\theta_e$ within supercells, many additional cases from nontornadic, weakly tornadic, and strongly tornadic supercells are needed to perform a statistical analysis of the presence and character of the FFRG boundary. Finally, only near-surface observations of the FFRG are available in this study. Observations obtained by radiosondes, unmanned aerial systems, or thermodynamic retrieval of temporally resolve dual-Doppler analyses would be beneficial in diagnosing the character of the FFRG aloft. It is noted that datasets collected during the second Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX2) have the potential to address all of the items listed above.

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