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A Significant Tornado in a Heterogeneous Environment During VORTEX-SE

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ABSTRACT

On 1 March 2016, an EF2 tornado occurred near Birmingham, AL, and was examined as part of VORTEX-SE. The boundary-layer environment near the tornadic supercell was heterogeneous in space and unsteady in time, with what typically would be considered an excellent proximity sounding. In this case, however, the proximity sounding severely underestimated the CAPE. SPC mesoanalyses substantially underestimated the CAPE and wind shear as well. Tornadogenesis occurred near a weak, frontogenetical thermal boundary, where evaporation from antecedent light showers had also increased dewpoint values. A local maximum in surface dewpoint (and instability), and a local maximum in helicity both existed near the region of frontogenesis. As a QLCS moved into the region of higher CAPE air, part of it became supercellular. Tornadogenesis occurred near the local maximum in surface dewpoint.

1. Introduction

On 1 March 2016, a significant tornado occurred in the southwestern Birmingham, AL suburb of McCalla. Based on the damage survey, it had peak winds near 55 m s^{-1} (EF2), a maximum path width of 425 m, and a path length of 9 km. Six homes were destroyed and 20 were damaged (NWS 2017). Tornadogenesis occurred at 2343 UTC, and the tornado lasted 7 min. This tornado was examined as part of the Verification of the Origins of Rotation in Tornadoes Experiment in the Southeast (VORTEX-SE). The environment over most of central Alabama on 1 March 2016 appeared (initially) to be only weakly supporting severe local storms, with low CAPE and only moderate wind shear. The Storm Prediction Center (SPC) issued a severe thunderstorm watch at 2325 UTC, just 18 min prior to the tornado, and the tornado warning had negative lead time (a witness who lost his roof heard the tornado sirens first go off after his roof was gone). However, SPC mesoanalyses greatly underestimated CAPE and low-level wind shear. Additionally, a sounding that would normally be considered in excellent proximity to the tornado also underestimated CAPE. We hypothesize that large spatial heterogeneities (and rapid evolution) in dewpoint and in wind shear were produced by previously unresolved boundary layer (BL) processes. These heterogeneities were associated with a weak thermal boundary, frontogenetical processes, and antecedent light showers ahead of the quasi-linear convective system (QLCS) and supercells.

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Supercell interactions with thermal boundaries have received attention in the literature (e.g., Maddox et al. 1980; Markowski et al. 1998; Atkins et al. 1999; Rasmussen et al. 2000; Bluestein et al. 2007; Laflin and Houston 2012). However, the boundary on 1 March 2016 was frontogenetical, and there was apparently a thermally direct circulation (e.g., Holton 1992) that caused large heterogeneities in wind shear. Large gradients in moisture and CAPE also occurred through moisture flux convergence, and due to antecedent showers ahead of the QLCS. NASA Lightning Mapping Array (LMA) data show a peak in activity as the convective system, initially a weakly organized QLCS, moved near the boundary and became cellular. The main focus of this paper is on the boundary-layer heterogeneities, in both wind shear and instability, that preceded the rapid development of an EF2 tornado in an environment that did not appear conducive to any tornadoes (according to standard synoptic and mesoscale analyses).

Data and methodology are discussed in section 2. The mesoscale environment near the thermal boundary and the location of the tornado are examined in detail in section 3. The dynamics and structure of the parent thunderstorms, including the one associated with the tornado, are examined in section 4. A summary is presented in section 5, and a discussion and conclusions relevant to operations in section 6.

2. Data and methodology

The mesoscale environment of the tornado and its parent supercell were measured in a number of ways. Mesoanalyses from the Storm Prediction Center (SPC, Bothwell et al. 2002) and from Plymouth State University are used to show meso-β scale analyses of dewpoint, helicity and CAPE. Data from the High-Resolution Rapid Refresh model (HRRR; Benjamin et al. 2016) are used to show surface confluence. Objective meso-γ scale analyses of temperature and dewpoint also were performed to quantify frontogenesis and provide high-resolution diagnosis of the surface moisture maximum. These analyses were done using surface stations archived by Mesowest (Horel et al. 2002), obtained from sources including the Federal Aviation Administration (FAA), Remote Automatic Weather Stations (RAWS), and the Citizen Weather Observer Program (CWOP).

Many of the data points from the 0000 UTC sounding at Birmingham, AL (KBMX) were used to determine CAPE and wind shear in the region near the tornado. Despite proximity to tornadogenesis (the sounding was released at 2302 UTC, 41 min prior to tornadogenesis and 30 km southeast of the location of tornadogenesis), given the large mesoscale gradients in temperature and dewpoint, the sounding had to be modified using SHARPpy (Blumberg et al. 2017). This was performed using 2300 UTC surface temperature and dewpoint from Mesowest station AU204 (a Davis Instruments Vantage Pro station) in Helena, AL, 14 km northwest of KBMX, and only 12 km east-southeast of the tornadogenesis location. The lowest levels of the sounding were adjusted to align with the difference in surface parameters measured at AU204 as opposed to KBMX. The KBMX surface data had a dry bias relative to AU204, but note the increasing difference in dewpoint between the two as a moisture pool develops (Fig. 1b).

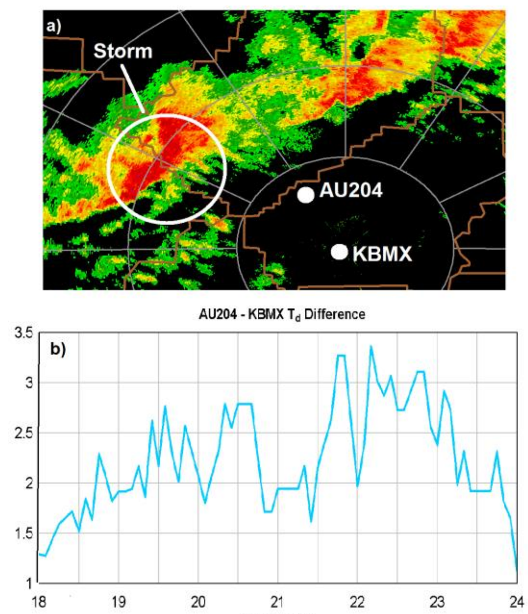

Figure 1: a) Radar reflectivity image (0.5° beam elevation) at 2325 UTC, showing the location of the storm that would produce the tornado, the KBMX sounding location, and the position of the AU204 mesonet site. Range rings are every 25 km. b) Difference in dewpoint between AU204 and KBMX during the 6-h period 1800–0000 UTC. *Click image to enlarge*.

Data from the WSR-88D radar at KBMX are used to show the structure and evolution of the parent supercell. Coarse level-3 velocity-azimuth display (VAD) wind profiles from multiple WSR-88D radars across the region, including KBMX, are also used to calculate storm-relative helicity and its tendency (surface wind observations were included). Rotational velocity was determined using the equation

$$V_{ROT} = \Delta V/2 \qquad (1)$$

where ΔV is the difference in the maximum inbound (V_{IN}) and maximum outbound (V_{OUT}) Doppler radial velocities. Pseudo-vorticity ζ_0, the best estimate of vorticity that can be derived from radial velocity, was calculated using a variation of the method described by Desrochers and Harris (1996). Pseudo-vorticity is defined by the following equation:

$$\zeta_0 = 2\Delta V \sin\theta D^{-1} \qquad (2)$$

where θ is the angle relative to a radial of a line segment between the locations of the maximum V_{OUT} and V_{IN} (this term is included so radial divergence is removed), and D is the diameter of the most intense part of the Rankine vortex. The factor of 2 is included since the total vorticity is equal to $dv/dx - du/dy$ in any (x,y) coordinate system.

3. Mesoscale environment

a. Spatial and temporal variation in CAPE

SPC mesoanalysis at 2300 UTC (Fig. 2) showed very weak surface-based CAPE (SBCAPE) in the region where tornadogenesis occurred, with the northern extent of the 250 J kg^{-1} isopleth running east-to-west through Alabama near the surface thermal boundary. Significant convective inhibition (CIN), greater than 100 J kg^{-1}, was indicated only 25 km north of the 250 J kg^{-1} SBCAPE isopleth, over the cold pool. However, in the zone parallel to, and up to 100 km northwest of the thermal boundary, SPC mesoanalysis showed most unstable CAPE (MUCAPE, not shown) from 100 J kg^{-1} to 500 J kg^{-1}. This indicates elevated instability to the northwest of the surface thermal boundary.

Due to rapid changes in surface dewpoint with time thanks to a large horizontal gradient in dewpoint, the CAPE was drastically different at the location of tornadogenesis than at KBMX. The 0000 UTC KBMX sounding (released at 2300 UTC) is shown in Fig. 3a. The surface-based CAPE was only 11 J kg^{-1}. However, dewpoints rose steadily to the northwest of KBMX, including at station AU204, where the dewpoint increased about 1.5°C in 90 min. AU204 indicated a dewpoint of 15.5 °C at 2325 UTC, 2.5 °C higher than at KBMX, and 1.5°C

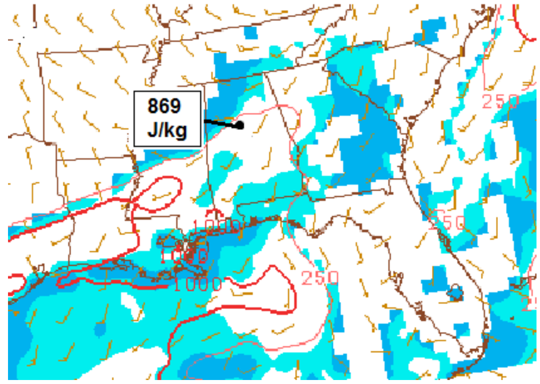

Figure 2: 2300 UTC SPC mesoanalysis showing SBCAPE (J kg^{-1}, red contours) and CIN (J kg^{-1}, shaded). The black dot indicates the calculated CAPE associated with Mesowest station AU204, based on the modified KBMX sounding. *Click image to enlarge*.

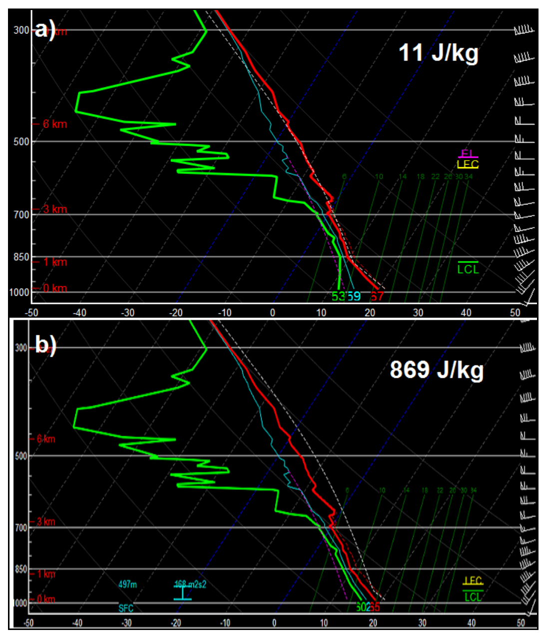

Figure 3: Skew *T*–log*p* plot of 0000 UTC KBMX sounding (released at 2300 UTC on 1 Mar 2016). Lifted parcel is surface-based, with virtual temperature correction. a) Plotted raw sounding data; b) Sounding adjusted to the surface temperature and dewpoint at station AU204, near tornadogenesis. Data only shown up to 300 hPa. *Click image to enlarge*.

higher than at Union Grove, AL, about 25 km southeast of KBMX. A high-resolution mesoanalysis of surface dewpoint (without KBMX) was performed (Fig. 4a). It shows an axis of maximum values in dewpoint very close to the point of tornadogenesis. Entering the surface temperature (18.5°C) and dewpoint (15.5°C) from AU204 for the surface environment in the KBMX sounding yields a large increase in buoyancy. The modified sounding (Fig. 3b) shows an SBCAPE of 869 J kg^{-1}, nearly two orders of magnitude larger than the unmodified sounding (Fig. 3a).

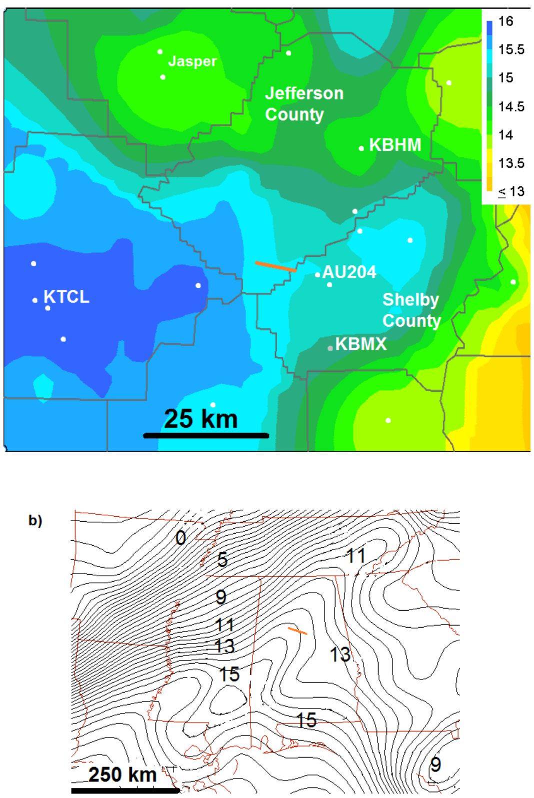

Figure 4: a) Meso-γ-scale analysis of dewpoints (°C) in the Birmingham metropolitan area at 2300 UTC 1 March 2016. Boundaries are counties, small white dots indicate surface stations used in the analysis, and gray dot indicates location of BMX sounding. b) Meso-β-scale analysis of dewpoints (°C) at 2300 UTC (from Plymouth State University). Red line segment indicates approximate tornado path in both panels. *Click image to enlarge.*

b. Local moisture maximum

A ridge in surface moisture was apparent at the meso-β scale across central Alabama (see Fig. 4b). But the distinct ridge in moisture at the meso-γ scale over the Birmingham metropolitan area (Fig. 4a) is a more accurate depiction of the water vapor field. Positive moisture advection was present ahead of the QLCS at low levels over central Alabama due to southwesterly flow from the surface up through 850 hPa ahead of the thermal boundary. Moisture advection values at 925 hPa were around 4×10^{-7} s^{-1}, or 0.15 g kg^{-1} h^{-1}, so differential moisture advection may have played a role in producing the moisture ridge. However, due to limited accurate surface wind observations, much less wind profiles, it is impossible to quantify.

The thermal boundary in question was rather weak, and difficult to separate from cooling associated with the QLCS. However, frontogenesis occurred over central Alabama due to differential heating and surface wind confluence during the afternoon hours (see Figs. 5,6). Clouds and rain were prevalent to the north of the leading edge of the boundary, while limited sunshine occurred to the south of the boundary (Fig. 5). For example, at KBMX (on the warm side of the boundary), the temperature increased 3.3°C with scattered to broken clouds and no precipitation during the period 1800 to 2300 UTC. During the same period, the temperature decreased 6.9°C at Jasper (on the cold side of the boundary) with overcast skies and 15 mm of rainfall. Comparison of these two stations, only 90 km apart, indicates frontogenesis on the meso-β scale over central Alabama over a period of 5 h. Near the leading part of the frontal zone, the frontogenesis was more intense between 2100 and 2300 UTC, with a temperature gradient of 6°C (100 km)$^{-1}$ at 2100 UTC increasing to 11°C (100 km)$^{-1}$ by 2300 UTC. Lagrangian frontogenesis at the leading edge of the boundary was 7.5 K (100 km)$^{-1}$ (3 h)$^{-1}$, a significant value.

There is typically upward motion and associated horizontal convergence on the warm side of a frontogenetical zone due to ageostrophic circulations (e.g., Holton 1992; Koch et al. 1995; Carlson 1998). In addition, there was confluence and convergence associated with the thermal boundary (Fig. 5c). Johns (1993) noted that areas of convergence sometimes lead to deepening moist layers, producing local maxima in surface dewpoints. Banacos and Schultz (2004) noted that moisture flux convergence is proportional to kinematic horizontal convergence. As discussed by

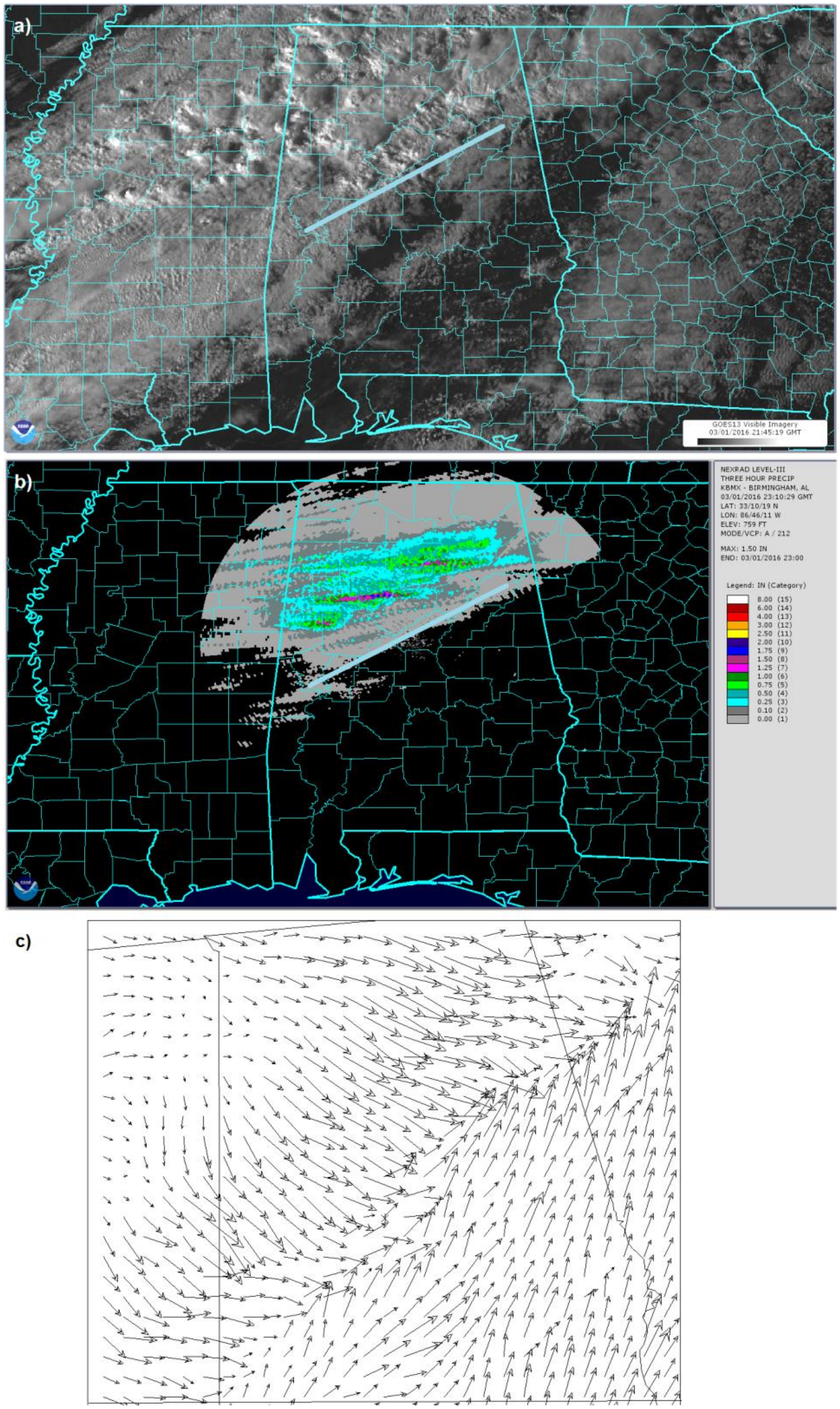

Figure 5: a) Visible satellite image at 2145 UTC 1 March 2016; b) Uncalibrated 3-h radar-estimated rainfall (in) from the KBMX WSR-88D, ending at 2300 UTC. c) HRRR model wind vectors at 0000 UTC. The center of the zone of frontogenesis is shown by a blue line segment in panels (a) and (b). *Click image to enlarge*.

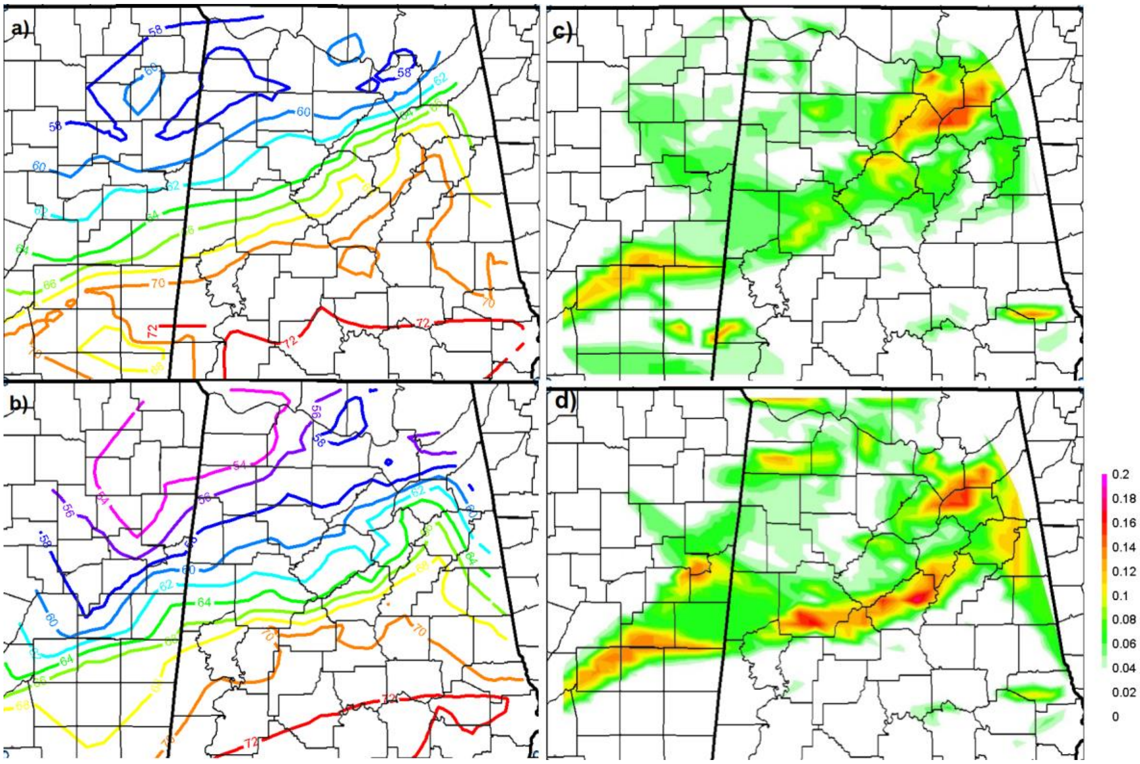

Figure 6: a) Objective analysis of temperature (°F) at a) 2100 UTC and b) at 2300 UTC. c) Objective analysis of the magnitude of the temperature gradient (K km^{-1}) at 2100 UTC and d) 2300 UTC. Analysis of θ_v (not shown) shows a similar tightening of the gradient. *Click image to enlarge*.

Markowski and Richardson (2010), while moisture flux convergence cannot directly increase the mixing ratio at the surface, it can cause an increase in the depth of relatively high values of mixing ratio; thereby mitigating the normal reduction in mixing ratio produced by turbulent mixing. In surrounding areas without convergence, mixing more effectively lowers the surface dewpoint. Moisture flux convergence near the thermal boundary may have contributed to the large meso-γ-scale gradient in dewpoint.

Also, light rain showers between 2100 and 2300 UTC produced a relative maximum in antecedent rainfall roughly collocated with the meso-γ-scale dewpoint maximum at 2300 UTC (see Fig. 7). The antecedent rainfall (2100–2300 UTC) was 0.25 to 0.75 mm at three mesonet stations within the moisture pool shown in Fig. 4a. and With that small amount of rainfall, a surface temperature drop of 2°C and a surface dewpoint increase of 1°C at station AU204 (Fig. 8) occurred. Therefore, the evaporation of rain also contributed to the development of the meso-γ-scale moisture maximum. In addition, the cooling slightly stabilized the lower BL, as evidenced by a temporary decrease in surface wind speeds and gusts at AU204 in the hour after the rain showers passed by (not shown). Stull (1988, p. 91) shows that turbulent flux decreases local moisture in the presence of a negative vertical gradient in mixing ratio. The temporary decrease in wind speed in this case likely decreased turbulent flux at AU204 within the moisture maximum.

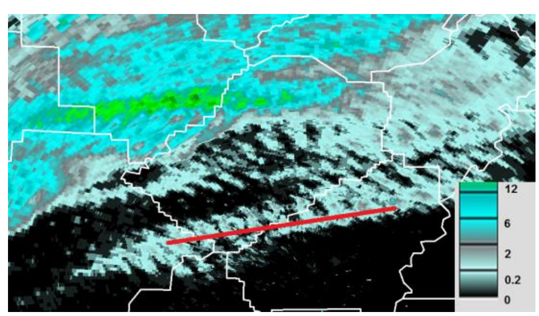

Figure 7: Uncalibrated, dual-polarization 1-h rainfall estimate (mm) from the KBMX WSR-88D ending at 2300 UTC.. Approximate position of moisture ridge shown by red line segment. *Click image to enlarge*.

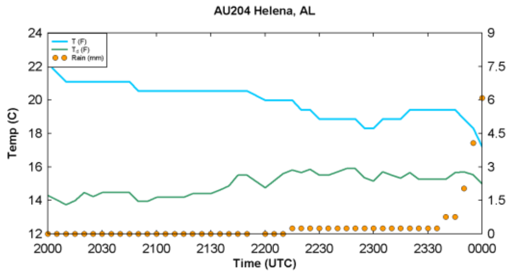

Figure 8: Temperature (blue), dewpoint (green), and accumulated rain (mm) vs. time at station AU204. *Click image to enlarge*.

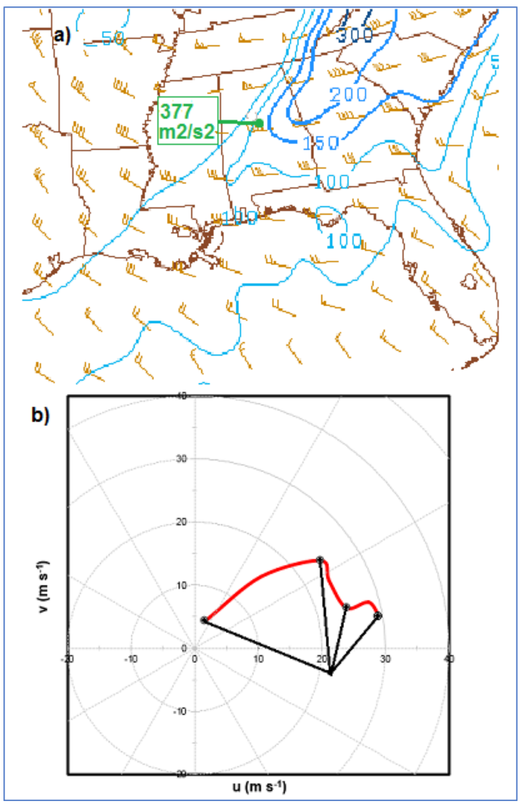

Figure 9: a) 0–1-km AGL SRH (blue contours, $m^2\ s^{-2}$), and storm motion (wind barbs, each full barb represents 5 $m\ s^{-1}$) at 2300 UTC from SPC mesoanalysis, and b) 0–3-km hodograph (SR inflow lines shown at 0, 1, 2, and 3 km AGL) from KBMX 0000 UTC sounding. Observed storm motion used. This indicated 0–1-km AGL SRH was 377 $m^2\ s^{-2}$, as noted at the location of KBMX (green dot) in panel (a). *Click image to enlarge*.

The gradient in dewpoint shown in Fig. 4a was ≈0.07°C km^{-1}, or 7°C (100 km)$^{-1}$. This was a well-defined, narrow band of surface moisture, oriented west-southwest to east-northeast and roughly 30 km wide in its narrowest region, centered just south of the Jefferson/Shelby County line. The tornado occurred within this narrow band of enhanced dewpoint (and associated CAPE).

c. Local shear maximum

SPC mesoanalyses showed 0–1-km AGL storm-relative helicity (SRH) values at 2300 UTC between 100–150 $m^2\ s^{-2}$, decreasing with time as synoptic-scale forcing, including low-level height falls, moved away to the east) over the Birmingham area (Fig. 9a). However, the KBMX 0000 UTC sounding (released at 2302 UTC) indicated 0–1-km SRH of 377 $m^2\ s^{-2}$. A map showing the 0–1-km SRH at ≈2300 UTC at seventeen WSR-88D locations around the Southeast, using the observed storm motion in central Alabama and VAD wind profiles (Fig. 10a), indicates a distinct maximum in SRH near the frontogenetical thermal boundary over central Alabama. Additionally, the time series of 0–1-km SRH at the KBMX radar site (Fig. 10b) shows a dramatic increase in SRH from ≈250 to ≈400 $m^2\ s^{-2}$ between 2100 and 2300 UTC.

The rapid increase in wind shear may have been associated partially with the afternoon-to-evening transition (AET), when shear and helicity sometimes increase as vertical mixing subsides (Wingo and Knupp 2015; Coffer and Parker 2015). However, the local maximum in wind shear was likely also the result of a thermally direct circulation due to frontogenesis (see Fig. 6c, d), and due to low-level stabilization in antecedent showers (discussed in Section 3b). Using the time series of VAD wind profiles (including surface winds) at KBMX, the front-normal component of wind (from 150°) was calculated (Fig. 10c). This analysis shows increasing vertical shear in the front-normal direction consistent with a thermally direct circulation. The front-normal component of flow below 150 m AGL decreased between 2000 and 2300 UTC while the front-normal flow increased during this same time period between 400 and 1000 m AGL, acting to lengthen the 0–1-km AGL hodograph.

4. The storms and the tornado

a. Evolution of the convection

During the late afternoon, a QLCS moved southeastward at 12 $m\ s^{-1}$ through northwestern

Alabama. The band organized and intensified between 2130 and 2230 UTC, as it moved into an environment with slightly higher values of surface θ_e, determined by superimposing Mesowest surface data over radar reflectivity (not shown). The storms remained quasi-linear through about 2230 UTC, then transformed to a more cellular structure upon moving into an even higher-θ_e environment over central Alabama between 2231 and 2336 UTC (see Fig. 11).

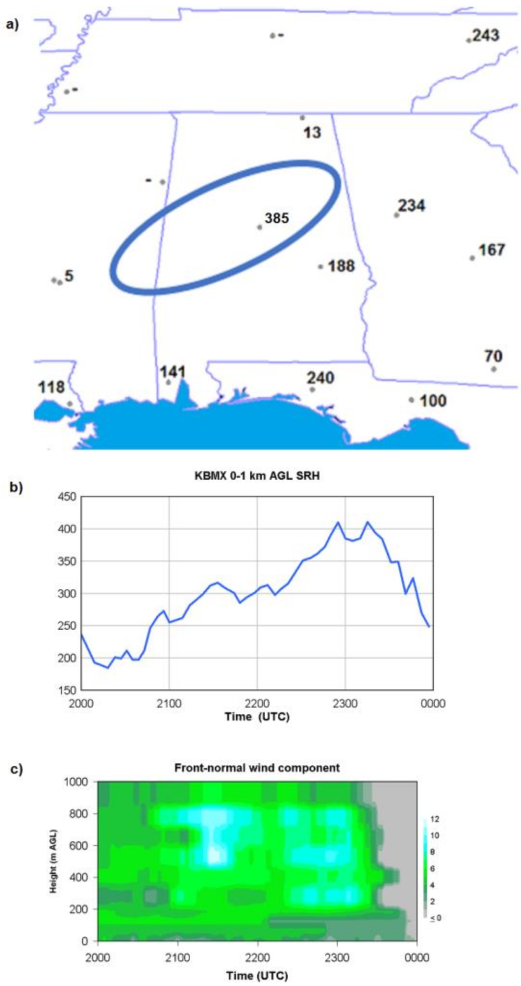

Figure 10: a) ≈2300 UTC 0–1-km SRH ($m^2 s^{-2}$) at various radar sites (negative values are simply shown as dashes); b) time series of 3-volume-scan moving average of 0–1-km SRH ($m^2 s^{-2}$) at the KBMX radar site; and c) front-normal wind component (from 150° azimuth) at KBMX ($m s^{-1}$). All computed using NEXRAD level-3 VAD wind profiles and observed surface winds. *Click image to enlarge*.

At 2231 UTC the storms were still quasi-linear, but two areas of enhanced cyclonic shear appeared in storms A and B (to the northeast of Birmingham, see Fig. 11d), and a mesovortex was associated with a line echo wave pattern in storm C, to the northwest of Birmingham. By 2310 UTC, the storms had become more cellular. Cyclonic shear was associated with storm D over northeast Jefferson County, and a weak mesocyclone was associated with storm E over western Jefferson County, where a weak echo region (WER) and slight low-level reflectivity appendage were present. The storm that would eventually produce the tornado (storm F) was intensifying over Tuscaloosa County at 2310 UTC. That storm showed weak cyclonic rotation (primarily aloft) at 2310 UTC, while maximum reflectivities increased somewhat between 2231 UTC and 2310 UTC.

By 2336 UTC, the mesocyclone in storm E had weakened somewhat, but storm F had moved into Jefferson County, home of Birmingham. It evolved rapidly into a high-precipitation supercell (e.g., Moller et al. 1994) by 2336 UTC, with a "hook echo" in reflectivity, a weak echo region (WER), and a mesocyclone with pseudo-vorticity around $2 \times 10^{-2} s^{-1}$.

b. The mesocyclone and tornado

Figure 12a depicts a time-height section of maximum reflectivities (Z) at each elevation scan for storm F. Precipitation was intense (Z greater than 60 dBZ) at 2305 UTC, and the storm contained deep, but only moderate, cyclonic pseudo-vorticity ($\sim 2 \times 10^{-2} s^{-1}$, Fig. 12b). However, storm tops were rather low, with the 30-dBZ echo only extending to about 10 km ARL (not shown). As the storm moved through the local moisture maximum, especially after 2325 UTC, reflectivities at low levels increased rapidly. This pattern is consistent with an intensifying updraft at low levels associated with horizontal convergence and increasing CAPE.

The local maximum in storm-relative helicity also may have enhanced the low-level updraft through tilting of vorticity and resulting pressure perturbations (note the maximum in vorticity near 2 km ARL at 2336 UTC in Fig. 12b). The storm was also moving through the region of maximum surface θ_e between 2325 and 2341 UTC (see Fig. 13).

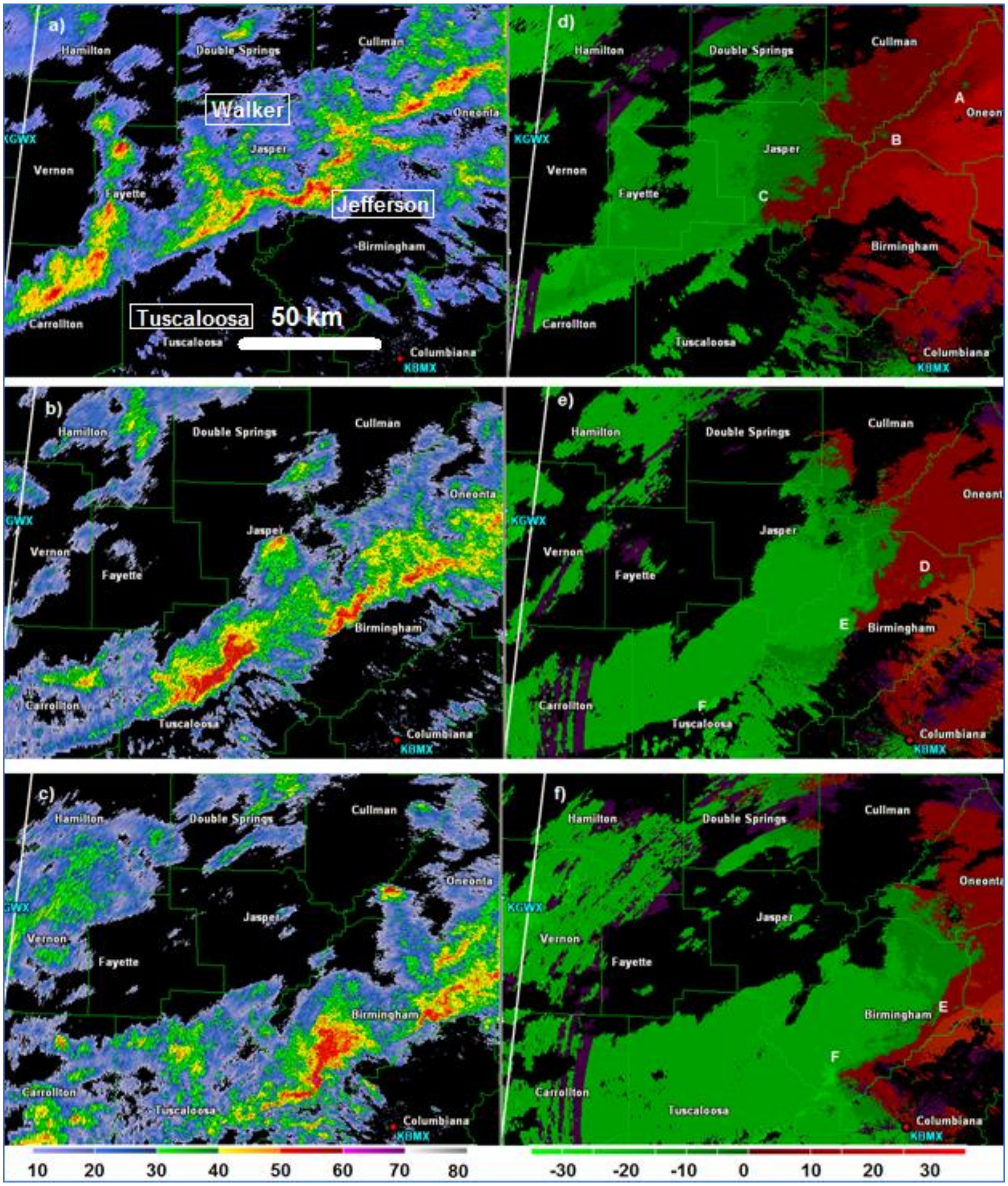

Figure 11. KBMX radar reflectivity (dB*Z*) at 0.5° beam elevation at a) 2231 UTC, b) 2310 UTC, and c) 2336 UTC on 1 March 2016. d), e), and f) are radial velocities (m s^{-1}) at the same times as a), b), and c) respectively. Radar site is at the southeast corner (lower right) of each panel. Individual storms are lettered A, B, C, D, E, and F. County names are shown in panel a. *Click image to enlarge.*

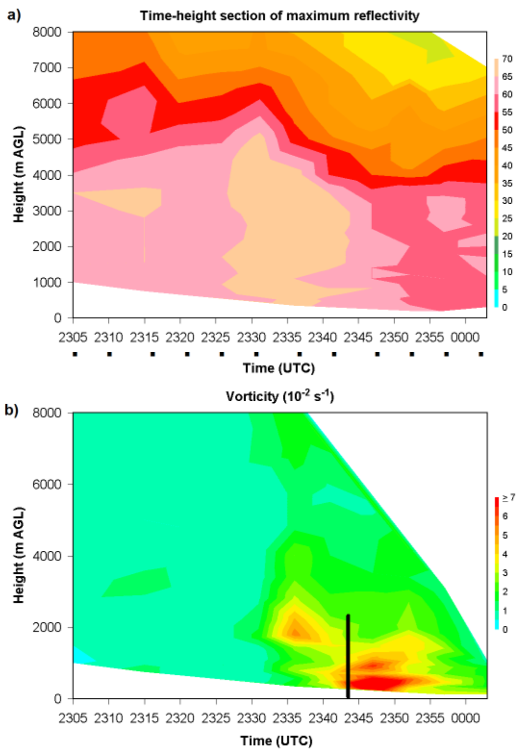

Figure 12: Time vs. height sections of a) maximum storm reflectivity (dB*Z*) at each elevation angle and b) ζ_0 (10^{-2} s^{-1}) for storm F. Black squares below panel a indicate volume scan times (also shown in Fig. 13). Time of tornadogenesis shown by vertical line in panel b. *Click image to enlarge*.

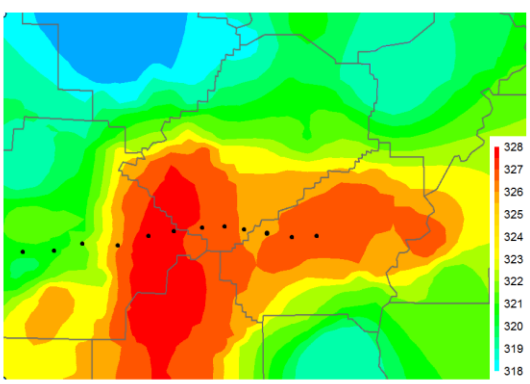

Figure 13: a) Equivalent potential temperature (θ_e, K) at 2300 UTC. Dots indicate location of low-level mesocyclone at each radar volume scan between 2305 and 0003 UTC (Fig. 12a). *Click image to enlarge*.

Large pseudo-vorticity (>3 × 10^{-2} s^{-1}), associated with the developing mesocyclone, did not appear until 2336 UTC (near 2 km AGL). The vorticity of the mesocyclone at the lowest (0.5°) elevation scan of the BMX radar, or 200–400 m AGL, then increased rapidly in storm F and peaked at 2346 UTC as the storm moved into the moisture pool and associated surface θ_e ridge. During this time the storm also was located within the meso-β-scale maximum in SRH, and was moving through the area where antecedent showers had slightly decreased near-surface flow, likely further increasing SRH at the meso-γ scale. Lowest-level mesocyclone pseudo-vorticity (in 10^{-2} s^{-1}) increased rapidly from 0.8 at 2331 UTC, to 2.7 at 2341 UTC, then spiked to 8.0 at 2347 UTC before quickly decreasing to 3.2 at 2352 UTC. The storm contained a well-defined inflow notch and "hook echo" at 2336 UTC, displayed a weak echo region at 2341 UTC, and then started to occlude by 2347 UTC. The occlusion process was complete by 2352 UTC (Fig. 14).

Tornadogenesis occurred at 2343 UTC associated with storm F over extreme southern Jefferson County (counties are indicated in Fig. 14a). In a storm survey conducted by the lead author, sub-tornadic yet cyclonic wind damage was found for about 2 km prior to the location of the tornadogenesis point in the NWS storm survey. The tornado persisted for 7 min, and moved from 280° at 21 m s^{-1}, 20° to the right of the mean 0–6-km wind vector. The tornado achieved a relatively large path width of 425 m at ≈2347 UTC, and then dissipated around 2350 UTC after a path length of 9 km (NWS 2016). At 2347 UTC the tornado was at peak apparent intensity with a well-defined, shallow mesocyclone extending only up to 3 km AGL. A tornadic debris signature (TDS; Rhyzhkov et al. 2005) was present up to a height of 1.1 km AGL as soon as 2347 UTC, only 4 minutes after tornado formation (not shown).

Data from the NASA LMA (Koshak et al. 2004) indicate that the total lightning output from the storms showed a significant peak between 2300 and 0000 UTC (Fig. 15). This was the period when the storms interacted with the moisture maximum and the area of frontogenesis, and associated enhanced storm-relative helicity and inferred CAPE. This was also the period when tornadogenesis occurred.

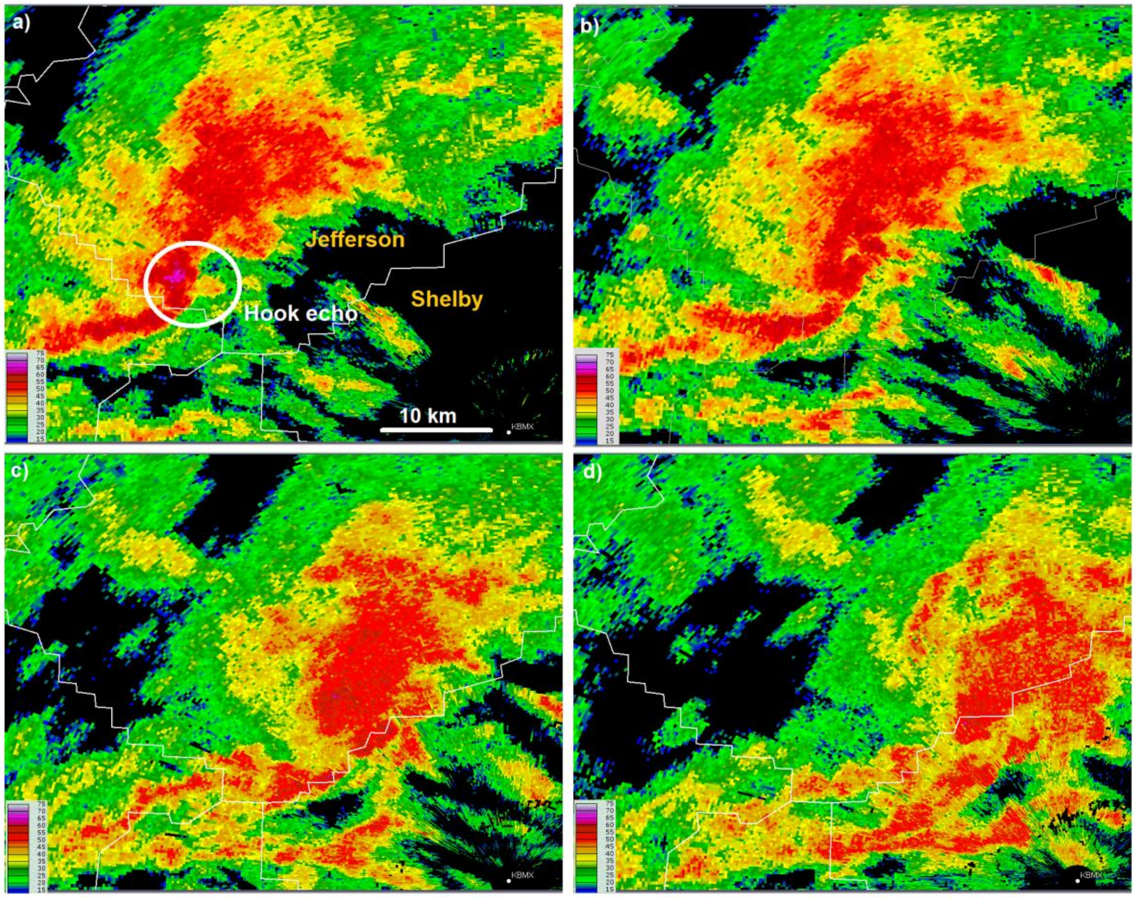

Figure 14: Radar reflectivity (dB*Z*) at 0.5° elevation at a) 2336 UTC, b) 2341 UTC, c) 2346 UTC, and d) 2352 UTC for storm F. Note that the radar site is located in the southeast corner (lower right) of each panel. The white line segment in panel b shows the tornado path. Tornado lifespan was 2343–2350 UTC. *Click image to enlarge*.

5. Summary

In the case of 1 March 2016, a QLCS began to intensify as it moved into slightly warmer air over northern Alabama. The QLCS intensified further and became supercellular as it interacted with a weak frontogenetical boundary and moisture maximum over central Alabama, near Birmingham. Despite an excellent proximity sounding indicating inferred CAPE of only 11 J kg^{-1}, and SPC mesoanalyses indicating SRH of only 125 m^2 s^{-2} (and decreasing with time), an EF2 tornado occurred in the southwestern suburbs of Birmingham.

Both the proximity sounding and the SPC mesoanalyses (which have only 40-km grid spacing) were unable to detect the extreme horizontal gradient in CAPE that developed. An area of enhanced moisture only about 30 km wide developed near the thermal boundary, probably associated with moisture flux convergence and low level evaporation from antecedent rain showers. Dewpoint gradients >5°C (100 km^{-1}) developed, with south-to-north gradients on the southern side of the local dewpoint maximum. Adjustment of the KBMX sounding using surface temperature and dewpoint, from a mesonet station located only 14 km north-northwest of KBMX, indicated a CAPE value of 869 J kg^{-1}, nearly two orders of magnitude larger than that at KBMX. The small area of relatively maximized moisture was only detectable in a meso-γ-scale analysis, using readily available MesoWest data. This illustrates the shortcomings of relying exclusively on objective mesoanalyses in the warning and forecast process.

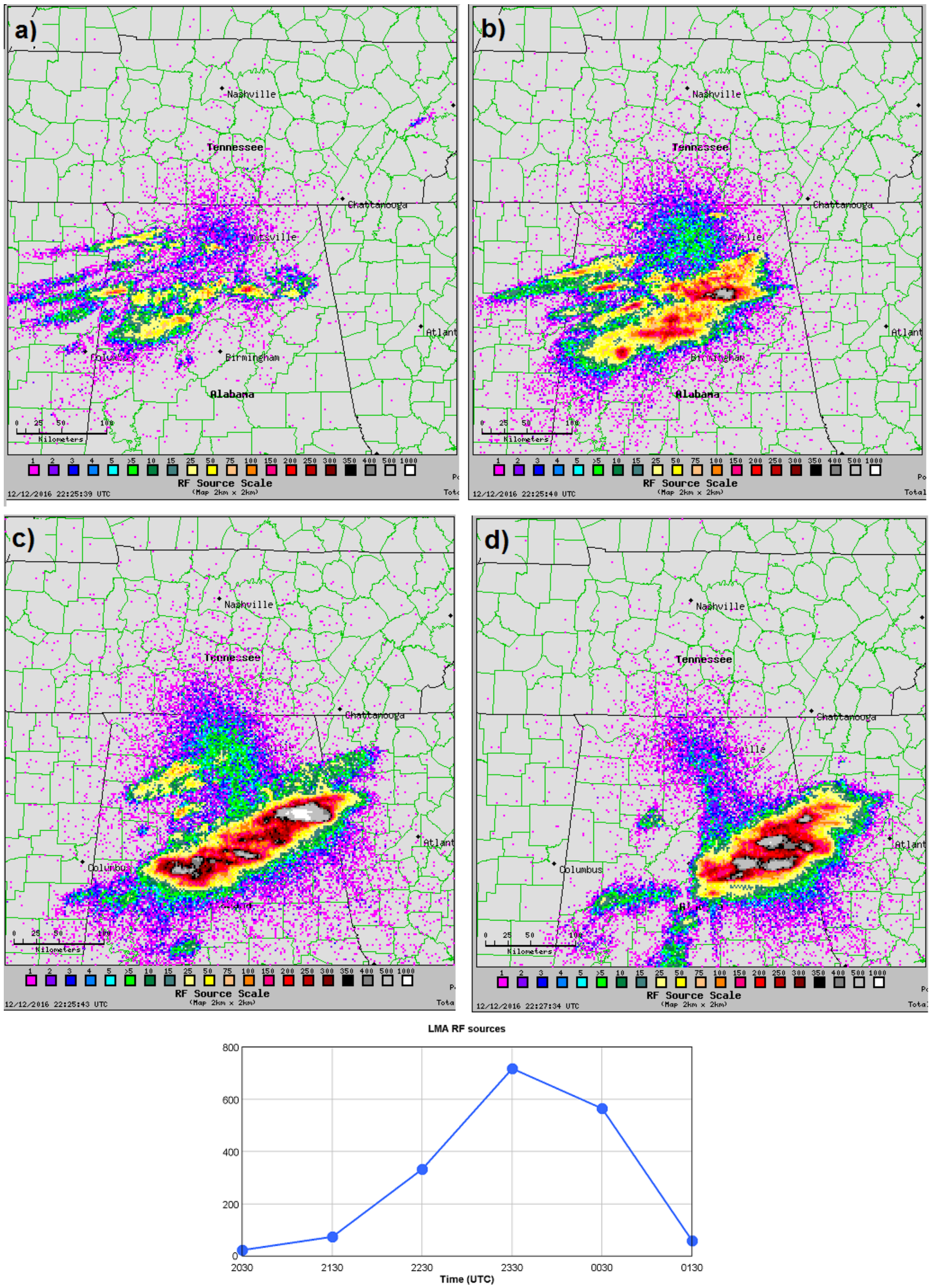

Figure 15: LMA RF source maps for the hours ending at a) 2200, b) 2300, c) 0000, and d) 0100 UTC. e) Time-series plot of total RF sources. Note peak near 2330 UTC. *Click image to enlarge*.

The proximity sounding at KBMX indicated a storm-relative helicity of 377 $m^2 s^{-2}$. Analyses of SR helicity across the southeastern U.S. using WSR-88D VAD wind profiles showed that, while the SPC mesoanalysis was correct regarding helicity values on the synoptic and meso-α scale, a significant local maximum developed rapidly over a period of 2–3 h in central Alabama on the meso-β scale. The rapid increase and local maximum in SR helicity was apparently associated with the frontogenesis occurring over central Alabama. A thermally direct circulation may be inferred from close examination of radar data.

The overall intensity of the convective system increased as it moved southward as indicated by lightning and radar reflectivity data. Low-level reflectivity increased in the tornadic supercell as it approached the narrow, local moisture maximum and subsequent θ_e ridge. Low-level forcing due to pressure perturbations associated with the local helicity maximum helicity also likely enhanced the updraft in the tornadic storm just before tornadogenesis. The vorticity in that supercell also likely was enhanced by interaction with the local maximum in storm-relative helicity.

6. Discussion and conclusions

This case illustrates a boundary layer that was heterogeneous in both kinematics and thermodynamics. A narrow corridor of relatively maximized moisture developed that could only be observed using mesonet observations. However, this feature was associated with CAPE that was nearly two orders of magnitude higher than that in an excellent proximity sounding. Locally enhanced storm-relative helicity increased rapidly in the region near tornadogenesis, to more than triple the value indicated by SPC mesoanalysis.

Mesoscale analysis, including the meso-γ scale, is a necessary part of a successful watch and warning program especially in marginal environments like the one on 1 March 2016. Wheatley and Trapp (2008) showed that both meso-β and meso-γ-scale processes can affect the intensity of mesovortices. Since analyses are complex and must be performed on a frequent basis, perhaps one meteorologist in the operational environment during a potential severe weather situation should focus solely on mesoscale analysis. This person could then relay information about critical phenomena to the people issuing the warnings since they are often overwhelmed with the volume of radar data alone, especially given frequent Supplemental Adaptive Intra-Volume Low-Level Scan (SAILS; Chrisman 2011) information.

Mesoanalysis must go beyond the hourly, model-guided analysis from SPC. Given the amount of available thermodynamic data at the meso-γ scale (RAWS, CWOP, MesoWest, Wunderground, etc.) and the computing power available today, perhaps an enhanced meso-γ-scale analysis of CAPE could be performed at the SPC or at the local WFO level even if it is an experimental product for internal use only. In addition, VAD wind profiles and proximity soundings should be used to analyze mesoscale changes in helicity. Such advanced analyses are especially important near atmospheric boundaries.

The tornado warning in this case was issued one minute after tornadogenesis. The authors, two of whom were directly involved in the warning and dissemination process on 1 Mar 2016, acknowledge that analysis of the mesoscale environment in cases like this one is easier to perform in hindsight than it is in real time when lives are on the line. The necessary data to diagnose the environment as potentially tornadic was available in real time, but in the heat of the moment some details are sometimes overlooked. However, both of these authors agree that, had the CAPE ridge along with the local maximum in helicity shown by VWP, been identified in real time, a tornado warning would probably have been issued sooner.

ACKNOWLEDGMENTS

This research was funded by the National Oceanic and Atmospheric Administration (NOAA) under VORTEX-SE. The authors also thank Mr. J. P. Dice of WBRC-TV for insightful discussions on the 1 Mar 2016 tornado, and Mr. Ben Allison for his detailed account of his experience in the tornado.

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REVIEWER COMMENTS

[Authors' responses in *blue italics*.]

REVIEWER A (Mario Majcen):

Initial Review:

Recommendation: Accept with major revisions.

General Comments: This paper presents an analysis of an interesting tornado event observed on March 1st 2016 during the Verification of the Origins of Rotation in Tornadoes in the Southeast (VORTEX-SE) experiment. The authors do a good job of presenting mesoscale analysis of storm environment and provide a comparison with operational forecasting products such as Storm Prediction Center and Plymouth State University mesoanalyses. In this review, I suggest additional work to clarify authors' points and I share a few concerns about inclusion of speculation in otherwise good analysis. Provided necessary changes are made, I think that this work provides a valuable addition to our knowledge of severe local storms.

Thank you for the helpful review. We have made numerous changes and added some new analyses to the paper, based on your comments and those from 3 other reviewers, that we feel have made the paper better.

Major comments: The leading edge of the strong temperature gradient on surface temperature analysis provided in Figure 6b suggests that at 0000 UTC 2 March 2016 (just 17 min after tornadogenesis) the frontal boundary was well to the southeast of the tornado location (as presented in Fig. 3b). This contradicts most of the mesoscale environment analysis presented in this manuscript by placing tornadogenesis well behind advancing cold front. Additionally, the figure caption does not clarify if this is surface temperature (I assumed it was) and analysis source is not mentioned. The wind shift depicted in the SPC mesoanalysis valid at 2300 UTC (1 March 2016) suggests that the frontal boundary was just to the north of tornadogenesis location at 2300 UTC, which seems more realistic so I suspect that there are problems with the analysis presented in Fig. 6b.

Fig. 6b was a surface temperature analysis, and we agree that it has problems. The source was Plymouth State. We have addressed this by replacing the Plymouth State surface temperature analyses with our own mesoanalyses. We used ~100 mesonet stations from MesoWest, including data from FAA sites, Remote Automatic Weather Stations (RAWS), and the Citizen Weather Observer Program (CWOP). The purpose of the original Fig. 6 was to show frontogenesis, but frontogenesis is still shown in Fig. 5, at higher resolution now.

The discussion of the source of moisture in the narrow band of elevated dewpoints still leaves some questions unanswered. In section 3b, authors correctly observe that moisture flux convergence cannot increase the surface mixing ratio but only increase the depth of relatively high values of mixing ratio. However, authors then claim that moisture flux convergence is responsible for producing large gradient in dewpoint near the frontal boundary. The contribution from antecedent precipitation was estimated using radar rainfall estimates. It would be interesting to consider precipitation data from nearby MesoWest stations.

This was initially a problem for us too. Markowski and Richardson (2010, pp. 195–197) explain how moisture flux convergence deepens moisture, reducing the drying effect of mixing. We clarified the sentences in the paper.

You make an interesting point regarding the antecedent rain showers. In checking MesoWest observations at two points within the moisture pool, the total measured 1-hourly precipitation as of 2300 UTC was 0.01 in (0.25 mm) at each one. However, at AU204, this 0.01 in (0.25 mm) of rain was associated with a drop in temperature and a rise in dewpoint, contributing to both the frontogenesis and the moisture pool. Some quantitative measured rainfall data were added to the text.

Given how interesting this case is, from both theoretical and operational perspective, I suggest that authors do not rely on prepared mesoscale analyses but create their own such as the one presented in Fig. 3a. Presenting their own meso-*β* and meso-*γ* analyses of the near storm environment would help elucidate and strengthen their case. About shortcomings of relying exclusively on SPC analyses in forecasting process: This would also improve the precipitation estimates that may reveal source of moisture responsible for suggested increased instability.

This is precisely what we did, for temperature and dewpoint, on a meso-γ scale (to show frontogenesis and moisture pooling). We added a statement in the summary of the paper addressing the improvement over SPC mesoanalysis.

Discussion of possible interactions with waves should either be strengthened with additional data. Authors present that near-storm environment would permit Kelvin-Helmholtz waves but observational evidence that these waves were observed is not provided. Because meteorological radar targets are not passive tracers equating observed reflectivity features and their motion with what authors call "wavelike reflectivity segments" is not supported by observations. Justification that because of low values of Richardson Number these "wavelike reflectivity segments" are likely Kelvin-Helmholtz waves excludes a plethora of other plausible explanations without observational evidence. In my opinion, the speculative nature of this section detracts from otherwise very good analysis presented in the rest of the manuscript.

You are right, the wave argument is somewhat speculative. We decided to leave mention of the waves in, but we changed the manuscript (section 4c) to reflect this speculation and uncertainty. We removed mention of waves from the abstract. We can remove the wave thing entirely if the editor thinks it is appropriate to do so.

[Minor comments omitted...]

Second review:

Recommendation: Accept.

General comment: I think that the authors have addressed my concerns adequately, except for section 4c (wave interaction). As [the Editor] and other reviewers have also indicated, it should be removed from the manuscript. *[Editor's Note: the Editor agreed with this and input from other reviewers in major and minor comments, and the discussion ultimately was removed.]*

REVIEWER B (Richard L. Thompson):

Initial Review:

Reviewer recommendation: Accept with minor revisions.

Substantive comments: The authors provide documentation of an isolated significant tornado that proved difficult to anticipate in real time, along with credible evidence of storm-scale variations in the environment that likely favored tornadogenesis in a small area. After some relatively minor changes, the paper will be suitable for publication in EJSSM.

The authors focused on a mesoscale maximum in surface moisture and related buoyancy, yet they presented some radar data (and related discussion) that appear to contradict their claims. For example, their argument that buoyancy was locally greater in the immediate area of storm intensification and tornadogenesis is supported by their data, yet they claim echo tops actually lowered during the time leading up to tornadogenesis. Lowering echo tops is clearly not evidence of larger buoyancy and a stronger/deeper storm updraft, but this storm was moving very close to the RDA near the time of tornadogenesis. A combination of additional radar data and their own plots can strengthen their arguments: 1) Fig. 3a suggests that the storm moved along the northeast edge of the richer moisture from Tuscaloosa Co. into

Jefferson Co., such that storm intensification should be expected (based on these data) in Tuscaloosa Co. as observed in radar and lightning data (also supported by Fig. 12); 2) an independent look at echo tops from KMXX suggests that the deeper updraft did not weaken until very near and after the time of tornadogenesis, which is also about the time the storm would have been exiting the greater moisture/buoyancy; 3) intensification of the low-level updraft should be tied closely with the tilting and stretching of the increased near-ground SRH, which matches the authors' other analyses. I suggest that the authors modify the discussion in the first paragraph of 4b to be consistent with both the thermodynamic and dynamic influences of the environment on the storm structure and subsequent tornadogenesis.

We agree regarding storm intensification due to moving into more moist and unstable air. In section 4a we stated that the storms intensified and organized as they moved into a more favorable environment, then eventually became supercellular.

Regarding the echo tops, we have examined Level-2 reflectivity data from KMXX and determined that you are correct, the storm top was not decreasing during the entire period between 2330–0000 UTC. However, given the distance from the radar, the scattered nature of pixels >15 dBZ (echo tops), and the vertical resolution (about 2 km) from KMXX at the range of the storm, we did not attempt to augment the reflectivity profile shown in the original Fig. 11a above 8 km ARL. The relatively low height of 30 dBZ echo was verified by KMXX, so we left that sentence in. Instead, we truncated both parts of Fig. 8 at 8 km, to avoid the appearance of the echo tops going down, while still showing the intensification of the low-level updraft. The mention of lowering echo tops was also removed from Section 4b.

Regarding SRH and tilting (and resulting p') being partially responsible for the intensification of the low-level updraft, we added a sentence to Section 4b.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revision.

General comment: I've read over the revised draft, and only have the following minor comments…

[Minor comments omitted...]

REVIEWER C (Bart Geerts):

Initial Review:

Reviewer recommendation: Accept with minor revisions.

General comment: This certainly is an interesting case study, and quite relevant to the EJSWM. In general, this paper lacks context in terms of related literature, and it lacks a scientific objective. Rather than testing a hypothesis, it describes an extreme weather event, using a rich array of operational data.

[Editor's Note: As has been done with a few other EJSSM manuscripts, some comment-reply exchanges labeled "minor" appeared substantive enough scientifically to justify inclusion in the review record.]

Substantive comments: Section 1: Fronts or thermal boundaries are always frontogenetic: the convergent flow (inherent to any density boundary) tends to increase $\nabla\theta$, in this case the increase in near-surface $\nabla\theta$ may be aided by surface heating. Of course, this tendency can be offset by the vertical (frontogenetic) circulation. In any event, the 2D frontogenesis function is not shown here (it should). Also, I don't see how this differs from previous work (Markowski et al. 1998; Rasmussen et al. 2000; Bluestein et al. 2007).

As another reviewer pointed out, frontogenesis is a Lagrangian process, and the temperature gradient across this boundary was increasing with time. Not all boundaries are frontogenetic in a Lagrangian framework, some are frontolytic. Our point is that the frontogenesis is producing a thermally direct circulation. We do not feel it is necessary to add the 2D frontogenesis function to this operationally oriented paper, but we can if the editor feels it is necessary. And, it does differ in many ways from the three papers you cited. For example, none of those papers mentions frontogenesis. This paper deals with unusual gradients in dewpoint and CAPE, also.

Fig. 3b, Fig. 4, and others: The Plymouth State University "meso"analyses really are too coarse for this purpose. I recommend the use of HRRR as a far more detailed and accurate analysis. See http://nomads.ncep.noaa.gov/txt_descriptions/HRRR_doc.shtml
The point is that the true maxima and gradients will be far sharper than Plymouth State University analyses, and this will be key to understanding the fine-scale structure of the precip bands and the development of severe weather.

We agree and have removed all the Plymouth State University analyses except for one, the meso-β-scale analysis of dewpoint. I looked at HRRR analyses, and they were noisy on 1 Mar 2016 and we feel that the Plymouth analysis works better in this one case. As far as the meso-β frontogenesis and meso-γ-scale dewpoint, we did our own objective analysis using over 100 MesoWest stations and our own QC.

Fig. 8 and text regarding SRH: SRH values are affected also by storm motion. The SPC analysis (Fig. 8a) may have a different storm-motion vector than assumed for Fig. 8b, and the latter may have some uncertainty also, being based on a KBMX radar reflectivity animation.

Yes, we did use observed storm motion (280/21 m s^{-1}) on the VAD analysis. However, SPC charts indicate they used a very similar storm motion, near 280 degrees and about 17 m s^{-1}. Using the SPC storm motion and the BMX sounding only decreases the SRH from 377 to 332 m^2 s^{-2}, still far above the SPC mesoanalysis value of about 120 m^2 s^{-2}. We feel that the storm motion vector is as accurate as possible.

Interaction with waves: these are not just gravity waves that modulate stratiform precip. They seem to trigger deep convection (CI) in bands normal to the QLCS but aligned with the $\nabla\theta$. I am curious about their vertical structure—are they strongest near the UL jet or at low levels, near the BL top? I guess there was no profiling system in the right location. Also, do the KBMX base-level or higher-level radial velocity data show wave-like variations in these bands?

Unfortunately, we have limited information on the vertical structure of these reflectivity bands, since there was no profiler in place there, and they are nearly parallel to the radar beam, making Doppler velocity almost useless in determining their kinematics. We shortened the part of the paper about the waves, and added to the text the speculative nature of the waves. If the editor decides this part needs to be removed altogether, we will do so.

[Minor comments omitted...]

Second review:

Recommendation: Accept.

General comment: This manuscript has improved, especially in terms illustrations and overall motivation. I have no further comments and recommend acceptance.

REVIEWER D (Adam L. Houston):

Initial Review:

Reviewer recommendation: Accept with major revisions.

Summary: The authors present a mesoscale analysis of the environment associated with an EF2 tornado that occurred during VORTEX-SE. Focus is directed towards horizontal heterogeneity associated with a preexisting thermal boundary. The authors conclude that tornadogenesis was likely a consequence of the storm encountering a narrow zone with more favorable CAPE and shear.

This is an interesting case highlighting the potential role of mesoscale heterogeneity on storm evolution. It is obviously a problem with particular relevance to the southeast US but is important more generally as well. The methods adopted are appropriate, though, as noted below, more analysis is required before this manuscript is ready for publication. Because of these holes in the analysis, some of the essential conclusions lack support.

Thank you for the helpful review. We have made numerous changes and added some new analyses to the paper, based on your comments and those from 3 other reviewers, that we feel have made the paper much better.

Major comments: Local moisture maximum (Section 3b): The authors attempt to diagnose the cause of the near-surface dewpoint temperature ridge. They attribute this in part to a southwesterly jet at 925 hPa and 850 hPa.

- Is this really a jet? Low-level jets require negative $\partial^2 |\mathbf{U}| \partial z^2$ but this doesn't appear to be in place.
- The 850 hPa level appears to be above the BL so some explanation for its relevance should be included.
- The authors include moisture advection values of 0.15 g kg^{-1} h^{-1} at 925 hPa but the values at 1000 hPa (Fig. 4a) appear to be near zero. Why the discrepancy? Why report both levels?
- It's not self-evident what value is offered by "horizontal gradient in moisture advection". While I agree that this could theoretically account for the generation of a moisture gradient, a) the gradient of a gradient will be a very noisy field that could render it highly unreliable and b) the authors are attempting to diagnose a moisture ridge that is defined by more than just the gradient.
- The authors are using meso-β-scale advection to diagnose a meso-γ-scale feature.

Upon further analysis of model data, we have removed the mention of the southwesterly jet from the paper. That analysis was a mistake on our part. We were referring to a jet only in the horizontal sense (du/dx), but that was not even for sure upon a closer analysis. The jet was a last-minute addition and we did not analyze it properly.

We now only give a value for the moisture advection at 925 hPa, and removed the figure showing moisture advection entirely, due to comments from other reviewers.

You are also correct that we are using meso-β-scale advection to examine a meso-γ feature regarding the relevant meso-γ moisture ridge where the tornado occurred, however we also show a meso-β moisture ridge in Fig. 3b, so we leave a small part of the talk on moisture advection in. Basically we state that moisture advection was positive and fairly uniform, so differential horizontal moisture advection alone could not produce the local maximum in dewpoint.

Frontogenesis (Section 3b): The authors reference Figs. 5 and 6 in support of their assertion that "the boundary was frontogenetical".

- Figure 5 doesn't support this claim. I suppose the authors include Fig. 5 to show the position of the boundary but neither the visible satellite data nor the composite reflectivity provide compelling evidence (in and of themselves) for the position of the front over Alabama. I suggest including a different data source.
- Figure 6 doesn't provide compelling support for frontogenesis. Yes, the temperature gradient over Alabama appears to increase but 1) frontogenesis is a Lagrangian quantity, not Eulerian, 2) a qualitative analysis does not suffice, and 3) based on the temperature field presented, the front would be well south of the storm, which is inconsistent with previous analysis and is invariably a consequence of the smoothing that is required to generate this map. To elaborate further on this last point, it is this

smoothing that undermines the robustness of this analysis since the inferred change in the temperature gradient becomes suspect.

The authors assert that “frontogenesis was primarily due to differential heating” and offer the presence of clouds and rain north of the boundary as evidence. However, more support is required.

While frontogenesis is said to be “on the order of 1 K $(100\ \mathrm{km})^{-1}$ $(3\ \mathrm{h})^{-1}$” and that “there was also some confluence in BL flow”, neither the kinematic frontogenesis nor deformation fields are provided to support these claims.

We have replaced the old Fig. 5 with high-resolution satellite data, 3-hr radar QPE, and HRRR streamlines showing confluence, to show front-intensifying sources.

We have also replaced the entire temperature analysis with a much higher-resolution objective analysis of our own, using over 100 MesoWest stations. It shows the frontogenesis between 2100 UTC and 2300 UTC and allows for accurate quantitative values (that are included in the text). Interestingly, we did find that the tornado was slightly on the cool side of the leading edge of the boundary. This is consistent with Markowski et al. (1998) and Rasmussen et al. (2000). The thermal boundary is not that strong over central Alabama to begin with, but frontogenesis occurs due to differential heating.

You are correct that we need further support for the claim of heating due to sunshine and cooling due to clouds and rainfall. So, we used surface stations to show the meso-β frontogenesis over a 5-hour period, and the meso-γ frontogenesis over a 2-hour period. We added extensive text to section 3b, supplying this data. We have also now included high-resolution visible satellite data and radar QPE in Fig. 4, and high-resolution mesoanalyses of temperature in Fig. 5.

In this case, we calculated the frontogenesis using the mesoanalysis, and we do not feel that kinematic nor deformation fields are necessary. Never mind that, given the still-sparse nature of mesonet observations relative to the narrow frontogenetic zone (about 25 km), these fields would be difficult to calculate accurately.

Impact of the frontogenetic secondary circulation on BL shear (Section 3c): The authors assert that the frontogentical secondary circulation is manifested in the vertical shear within the lowest several hundred meters of the atmosphere as indicated by VAD-derived vertical wind profiles.

1. I’m highly skeptical that any frontogenetical ageostrophic circulation would manifest in the lowest several hundred meters of a well-mixed BL.

   We disagree with this. Numerous previous papers have shown the generation of horizontal vorticity due to thermal gradients, and the sea breeze is a classic thermally-direct circulation in the BL.

2. It’s important for the authors to note the lowest level at which VAD data produce VWPs. It can’t be much below 150 m, so I wonder how much focus should be placed on VAD-inferred changes near or below this level.

   NEXRAD Level-3 VAD wind profiles go as low as 43 m ARL, depending on the elevation of the radar. We also used surface data.

Role of convergence: The authors conclude (section 5) that “low-level forcing due to convergence (associated with the boundary) likely enhanced the updraft in the tornadic storm just before tornadogenesis”. However, this conclusion is not supported by the analysis. First, convergence is never shown. Second, the authors identified increased CAPE and increased shear as characterizing the region just south of the boundary. Either of these could have been responsible for inferred updraft intensification.

We agree that the convergence is speculative. We removed mention of it from section 5, and downplayed it in section 4b.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revisions.

General comment: The authors have improved the manuscript in addressing the reviewers' suggested changes. A number of issues still need to be resolved before it's ready for publication. As is often the case, I have no idea whether these changes are "minor" or "major", but I would imagine that they could be addressed fairly easily.

Your first review helped make the paper much better, and this review has helped us to more specifically outline the real purpose of the paper (demonstrating large heterogeneities in CAPE and shear) and to make additional changes that help the paper to be more credible to the reader. Thank you for the review. We have made some changes and added some new analyses to the paper, based on your comments. You were the only reviewer to raise any further issues, but frankly you make good points and we have addressed them the best we can.

Major comments: Local moisture maximum (Section 3b): The removal of text that previously focused on the low-level jet and on the "horizontal gradient in moisture advection" does clarify the narrative but several issues remain.

The authors argue that "moisture advection was fairly uniform horizontally, so differential horizontal moisture advection alone could not have produced the significant ridge in surface dewpoint". However, no evidence for this is offered. It seems as if they're using meso-β-scale advection as the basis for this assertion but this can't explain the meso-γ-scale moisture ridge. Given that they're trying to explain the origin of the moisture ridge, which is a justified objective, they need to dig a bit deeper into the possibility that meso-γ-scale differential advection is important.

Given the lack of accurate meso-γ scale surface wind observations, much less wind profiles, we cannot accurately calculate the meso-γ-scale moisture advection using observations. Even the HRRR model, with 3-km resolution, initialized at 02/00 UTC with some noisy winds ahead of the QLCS. So, while differential moisture advection may have played a role in producing the moisture maximum, it is not possible to quantify it. We have added text stating this.

The authors argue that "moisture flux convergence near the thermal boundary likely contributed to the extremely large meso-γ gradient in dewpoint near the boundary shown in Fig. 4a associated with the local moisture pool." This is an unsubstantiated conclusion. Moreover, I'm just not following the overall argument here. The authors seem to be saying that meso-β/α frontogenesis is leading to convergence and that this convergence is leading to a meso-γ-scale moisture pool. Assuming that frontogenesis is occurring (as noted below, this is still to be determined), I won't dispute that large-scale convergence is likely occurring. However, I just can't see how this would yield a meso-γ-scale moisture pool.

We have adjusted the wording to reflect that moisture flux convergence is occurring due to frontogenesis and due to the convergent boundary zone itself, and changed Fig. 5c to show this. We continue to back off on frontogenesis as the primary factor, and include it as one of many factors. With further examination of surface observations, we believe the antecedent showers played a role in producing the meso-g scale moisture pool. These showers raised the dewpoint at AU204 by 1°C, and dropped the temperature by 2°C. This has a twofold effect on increasing surface moisture: 1) the direct increase T_d due to evaporation, and 2) the cooling of the temperature stabilized the lower part of the BL a little bit, reducing turbulent flux.

If one examines Stull (1988), eq. 3.4.4b, term X is negative to the total derivative of moisture, but this slight cooling from showers would reduce this negative term. If one examines wind speed and gust observations from AU204 (we understand that the speeds are not likely accurate due to trees, but the relative change in wind speed is relevant), the winds decreased temporarily at AU204 after the rain moved over the station [gusts decreased from 5–12 mph (2.2–5.4 m s^{-1}) before rain to 2–3 mph (0.9–1.3 m s^{-1}) for almost an hour *once rain began]. This temporary stabilization also likely enhanced the convergence, but that becomes nonlinear and beyond the scope of this paper!*

We added a short summary of this process to the paper. So, how did a meso-γ scale moisture pool develop? Through a combination of moisture flux convergence (due to frontogenetical forcing, kinematic convergence due to the QLCS/CBZ, and kinematic convergence due to stabilization by the showers), possibly differential moisture advection, direct addition of moisture due to antecedent showers, and indirect increase in moisture due to rain-cooled air having less turbulent flux.

Frontogenesis (Section 3b): The authors are converging on a better approach to analyzing frontogenesis but it still needs a bit of cleaning up. The authors use the temperature tendency at pairs of surface stations to determine if the front is frontogenetic but this is less than compelling. After all, a moving steady-state front (F = 0) could exhibit the same signal.

We agree that two observation points are not proof of frontogenesis, but in this case one observation point was on the cold side and one was on the warm side, and the changes are not, in our opinion, primarily related to frontal movement. At Jasper, the initial temperature drop occurred between 1800–2000 UTC, with a wind shift only from 200°–220°. We feel that the two stations illustrate the frontogenetical processes, but this is an editor call, and we can remove it if necessary.

I like the inclusion of the temperature distribution (Fig. 6) since this is a better basis for assessing frontogenesis. However, why not take it one more step and calculate ∇T at both of these times so we don't have to rely on subjective eye-balling. You could even calculate the kinematic frontogenesis since you have temperature and winds but this is not absolutely necessary.

The magnitude of the gradient in temperature has been calculated and included as part of the new Fig. 6. We really cannot determine kinematic frontogenesis because reliable surface wind observations are on the meso-b scale, while surface T/T_d observations are on the meso-γ scale.

SRH: One of the key motivations for this work (as noted in the Introduction and Conclusions) is that the "SPC mesoanalyses greatly underestimated…low-level wind shear". The authors try to support this assertion by calculating the SRH from KBMX (e.g., Fig. 10b) but they use actual storm motion and not estimated storm motion. Comparing these values of SRH to the mesoanalysis is not an apples-to-apples comparison since the mesoanalysis uses estimated storm motion. I suspect that it's easier to recalculate the KBMX SRH using the approach to estimating storm motion adopted in the mesoanalysis than to recalculate the mesoanalysis so I suggest doing this. Moreover, the hourly SRH values at KBMX from the mesoanalysis need to be plotted on Fig. 10b to facilitate comparison. Given that the trend in mesoanalysis-SRH was also something noted in the text, it's even more important to plot the mesoanalysis-SRH at KBMX.

We used observed storm motion (280°/21 m s^{-1}) on the VAD SRH analysis in Fig. 10b. However, SPC charts indicate they used a very similar storm motion (near 280°/17 m s^{-1}). Using the SPC storm motion and the BMX sounding only decreases the SRH from 377 to 332 m^2 s^{-2}, still far above the SPC mesoanalysis value of about 120 m^2 s^{-2}. So we feel the comparison is fair.

Storm interaction with locally higher SRH: The authors argue that storm intensification occurred while "the storm was also located in the local maximum in SRH". However, the authors are basing the existence of this local maximum on Fig. 10 which shows a value at KBMX that is larger than the values calculated at the nearby 88Ds but is incapable of revealing the spatial scale of the higher SRH. The storm may have very well been encountering SRH that was the same or even higher than at KBMX well before intensification was observed.

Yes, this is possible. We have adjusted the wording to indicate it was in the larger-scale maximum in SRH (indicated by BMX VAD and sounding). In addition, the antecedent showers and stabilization of the lower BL actually increased shear (and presumably SRH) within the moisture maximum, and we added a statement on that to the paper too, but indicated the speculative nature.

<u>Impact of the frontogenetic secondary circulation on BL shear (Section 3c):</u> Unfortunately, the authors have done little to convince me that the frontogenetic circulation is responsible for the observed BL shear. The thermally-direct circulation owing to frontogenesis is a meso-β/α-scale phenomena driven by the atmosphere's response to restoring thermal wind balance. I have never seen evidence that this will manifest in vertical shear over 150-m-deep layer near the ground even if PBL processes are neglected. Assuming, as it appears the sounding from Fig. 3a justifies, a well-mixed PBL, the assumption that the vertical shear in the lowest 150 m is a manifestation of this meso-β/α-scale circulation seems even less plausible. The authors argue in their response that "numerous previous papers have shown the generation of horizontal vorticity due to thermal gradients". I agree. For example, a density current and its associated thermal gradient will be associated with very strong horizontal vorticity. But this vorticity is not a consequence of frontogenesis (the density gradient can be steady state and there would still be horizontal vorticity that is upwards of 2 orders of magnitude larger than planetary vorticity). My point is that, while there seems to be an increase in shear in the lowest 150 m of the well-mixed PBL at KBMX, and there very well may be frontogenesis occurring, ascribing cause-and-effect is not justified.

We simply disagree with the reviewer here. In a future study, we plan to examine this case and others using EVAD, since the vertical resolution of NEXRAD Level-3 VWP is only ~300 m. We see frontogenesis at the meso-β scale (the old Plymouth figure) and at the meso-γ scale (Fig. 6), given small-scale, thermally direct circulations that we have observed along Lake Wheeler in northwestern Alabama, frontogenesis seems like the logical reason why the SRH is so high at BMX, on the sounding and VWP.

<u>Wavelike reflectivity segments (Section 4c):</u> There is a lot of speculation in the section describing the WRS. Notably, it's just not clear how or when the WRS "interact" with the mesocyclone. I doubt there's any way that the data available could be analyzed differently to tease out the nature and timing of this interaction so I strongly encourage the authors to remove this subsection.

We agree and have removed the mention of waves from the paper entirely.

[Minor comments omitted...]

Third review:

Recommendation: Accept with minor revisions.

General comment: I agree with the authors that the Editor will probably need to resolve the three remaining unresolved issues (summarized below). The rest of my suggestions can be addressed easily without need for additional review.

Thanks again for taking so much time with this review. This is a cool paper and I will be presenting it at the WAF conference in June in Denver.

Unresolved issues:

<u>Pseudo vorticity:</u> *[From a prior minor comment]* I still contend that the use of "vorticity" to describe a quantity based on radial velocity alone is not accurate. In prior work, this quantity is (more accurately) referred to as pseudo-vorticity, or quasi-vorticity, or Azshear, but not "vorticity*". [Editor's Note: The final decision was for pseudo-vorticity computation.]*

We agree. The math works, but without dual-Doppler we are still making an estimate. The references to vorticity where radar was used were changed to pseudo-vorticity throughout the paper.

<u>Frontogenesis (Section 3b):</u> The quantification of temperature gradient made the case for frontogenesis such stronger than it was in previous versions of the manuscript. I don't think it's necessary to include the temperature tendency a KBMX and Jasper since it contributes little to the case being made.

We feel that these stations' data illustrates the frontogenesis for the reader. We added that the stations are "only 90 km apart".

Impact of the frontogenetic secondary circulation on BL shear: No need to repeat the criticisms I levied in my second review; they remain the same.

We understand your concerns, but we want to leave this in given the magnitude of frontogenesis. We changed the main sentence on this to read [that the local maximum in wind shear was likely also the result of a thermally-direct circulation due to frontogenesis]. We removed the word "primarily" and added "likely". Hopefully this is satisfactory.

[Minor comments omitted...]