J4.1 CENTRAL NORTH CAROLINA TORNADOES FROM THE 16 APRIL 2011 OUTBREAK

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1. INTRODUCTION

Thirty confirmed tornadoes occurred in North Carolina on 16 April 2011, the greatest one-day total for North Carolina on record. Thirteen of the 30 tornadoes were significant (EF2 or greater), and several of these tornadoes hit highly populated areas, including the cities of Raleigh and Fayetteville (Fig. 1). The tornado outbreak extended from South Carolina northward into Pennsylvania; in this paper, we focus on central North Carolina, especially the NOAA/NWS-RAH (Raleigh) county warning area (CWA). Nine tornadoes occurred in the RAH CWA, including two EF3 tornadoes, four EF2 tornadoes, and three EF1 tornadoes. Both of the EF3 tornadoes had path lengths greater than 50 miles (80 km), and the event set the record for summed path length both in the state of NC and for the Raleigh CWA.

Here we address a number of interesting aspects of the outbreak, including the environmental ingredients and the unique evolution of the predominant convective mode (from a squall line to discrete supercells).

2. ENVIRONMENTAL INGREDIENTS

On the morning of 16 April 2011 a deep upper tropospheric trough was progressing through the Great Lakes region (Fig. 2), with the primary surface cyclone well to the northwest of North Carolina throughout the episode. As of 1200 UTC central NC was on the poleward side of a warm front (Figs. 2 and 3), with widespread overcast and stratiform rain associated with warm advection. Both frontal upglide and low-level vertical wind shear were enhanced by the strong southerly winds present at 850 hPa over the threat area (Fig. 2).

As the upper tropospheric jet streak and vorticity maximum moved toward the northeastern United States, surface pressures fell across the mid-Atlantic states, in response to which the surface warm front moved northward through North Carolina and a cold front began to approach from the west (Fig. 2). Deep convection was triggered along the cold front shortly after 1200 UTC, and was widespread by mid-afternoon (Fig. 3).

The outbreak was well anticipated, with the 12Z NAM model from the previous day (15 April 2011) forecasting CAPE values and 0-6 km shear vector magnitudes that would easily support supercells, as well as long, strongly curved hodographs with very large values of 0-1 km and 0-3 km storm-relative helicity. The Storm Prediction Center recognized the threat and by 1630 UTC they had issued a High Risk that included 30% tornado probabilities for much of east central NC. The mid-day 1600 UTC sounding from Greensboro, NC (Fig. 4), revealed observed wind profiles that were even more favorable for supercells and tornadoes than what models had forecast, although thermodynamic instability was somewhat limited owing to the overcast and stratiform precipitation during the morning hours.

During subsequent hours, the warm front passed through NC. Within the warm sector breaks in the overcast, along with continuing warm and moist advection, led to surface temperature increases of 5-6°C and surface dewpoint increases of 4-5°C. As a result, by 1800 UTC a RUC analysis sounding for Raleigh, NC indicated a CAPE value > 1000 J kg^{-1}, with a hodograph continuing to resemble the earlier Greensboro observation. By mid-afternoon, large CAPE values and long, strongly-curved hodographs were analyzed over

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the majority of central and eastern North Carolina (Fig. 5).

3. CONVECTIVE EVOLUTION

A squall line formed along the cold front that was crossing western North Carolina; this squall line accounted for several reports of weak tornadoes in western North Carolina (Fig. 1). Over time this squall line appeared to have moved ahead of the initial cold front's position (Fig. 3), with surface observations suggesting that it was subsequently maintained by the convectively-generated outflow boundary. Between 1700 and 1900 UTC, this squall line broke apart into discrete supercells (Fig. 6), which moved into the high-CAPE warm sector and began to produce the stronger, longer-lived tornadoes that constituted the bulk of the outbreak in central North Carolina (Fig. 1).

Three supercells accounted for the majority of the tornadoes (and all of the long-track tornadoes) in the Raleigh CWA (indicated by arrows in Fig. 6). Once the discrete supercells emerged, the threat was well-handled by regional NOAA/NWS offices, with probability of detection of 97% and average lead time of 19.5 minutes at NOAA/NWS-Raleigh. However, the convective evolution earlier in the day was considered somewhat surprising. It is widely presumed that the strong slabular lifting associated with a squall line's cold pool would tend to make evolution into discrete storms unlikely. Instead, it was generally thought that the greater tornado threat would emerge from a handful of more isolated cells that were initiated ahead of the existing squall line (several such weak cells can be seen in the left hand panel of Fig. 6). However, none of these pre-line echoes survived to become long-lived supercells.

We hypothesize that several primary factors controlled the observed evolution. First, even though the squall line appeared to be cold pool-driven, the temperature deficits within the post-squall outflow were not especially cold (only 5-6°C colder than the ambient environment; Fig. 3). This relatively weak outflow may have been attributable to the relatively moist boundary layer (Figs. 3 and 4) and the relative absence of trailing stratiform precipitation behind the squall line (e.g. Fig. 6). When the weak cold pool was combined with low-level shear vectors that were largely parallel to the squall line (Figs. 4 and 5), this would have tended to produce somewhat weak vertical lifting at the outflow boundary, which may have lessened the tendency for continued linear retriggering of convection, permitting more isolated storms to emerge. Finally, the sharply curved clockwise-turning hodographs (Figs. 4 and 5) would have strongly favored dynamical lifting on the right flanks of active cells, tending to lead toward predominant right-moving supercells over time. The large vertical wind shear values within the environment may also have acted to suppress the pre-squall convective cells through enhanced entrainment and mixing; perhaps only in the zones of persistent mesoscale ascent (i.e. the outflow boundary) was long-lived convection able to be sustained.

4. IDEALIZED SIMULATION

In the preceding section we hypothesized that the evolution from linear to supercellular structures could be explained in terms of ingredients within the prevailing environment. As a very simple test for these hypotheses, we simulated the 16 April 2011 event in a highly idealized setting (details are in the caption for Fig. 7). Interestingly, in a homogeneous model environment representing the 16 April warm sector, an artificially triggered squall line spontaneously breaks apart into supercells (Fig. 7). The simulated squall line produces a weak cold pool that is comparable to the observed case, and the squall line evolves into discrete cells on a similar timescale to what was observed. Although this pilot simulation is primarily meant as a simple demonstration of the influence of the base state upon the convective mode, future research on the essential dynamics of this squall line-to-supercell evolution would be of interest.

5. DISCUSSION

The 16 April 2011 outbreak set new records for number of tornadoes and integrated tornado path length. The ingredients for supercells and tornadoes were clearly present across the region, although the superposition of large CAPE with such favorable hodographs occurred only a few hours prior to the outbreak across central North Carolina, as surface temperatures and dewpoints rapidly increased. A surprising aspect of the outbreak was the evolution of deep convection from a predominantly linear structure (initiated along the synoptic cold front) to discrete tornadic supercells.

It is interesting to compare the 16 April 2011 outbreak to the famous 28 March 1984 tornado outbreak (which produced 22 total tornadoes in the Carolinas, including four F4s and a total of 57 fatalities). An elevated mixed layer was found to be an important ingredient in the 1984 event, and has since become a commonly used "warning flag" for eastern U.S. tornado outbreaks. Although dry air was noted above 500 hPa in the 1600 UTC Greensboro sounding on 4/16/2011 (Figure 4), it was not evident in other regional soundings, and it also did not seem to be accompanied by the steep lapse rates that are commonly associated with most elevated mixed layers. It is unclear whether dry air aloft, or an elevated mixed layer in general, is an important independent ingredient or whether it merely implies a high likelihood that substantial CAPE can be generated.

In many respects, the hodographs were almost identical for the 1984 and 2011 outbreaks. A casual review of past events, along with anecdotal evidence from regional experts, suggests that the long, strongly-curved low-level hodographs for these events are not commonly found to coincide with substantial warm sector CAPE in North Carolina. This may partly be because backed low-level winds imply flow from off of the Atlantic Ocean, which is typically a source region for much lower values of θ_e than is the Gulf of Mexico (i.e. a limited CAPE scenario). In turn, the more common situation for substantial CAPE typically requires the higher θ_e Gulf parcels, which in turn implies a veered low-level wind component and straight-line hodographs (i.e. a limited helicity scenario). More research into the potentially complicated interplay between stability and low-level shear in this region could be quite beneficial.

6. EXTENDED ANALYSIS

A much more detailed analysis than what was possible in this preprint has been completed by the Raleigh NOAA/NWS office. Interested readers may access their extended discussion at:

http://www4.ncsu.edu/~nwsfo/storage/cases/20110416/

REFERENCES

Please contact the corresponding author for a full list of related literature.

ACKNOWLEDGMENTS

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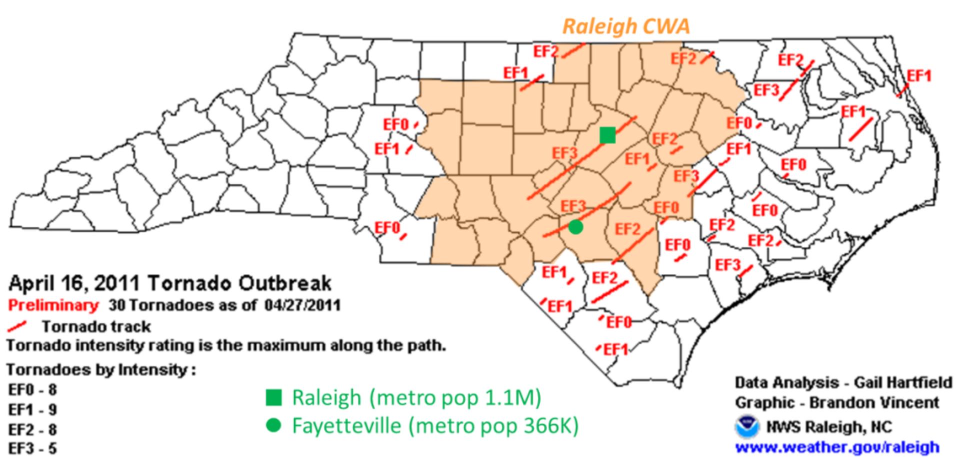


Figure 1: Map of tornado tracks from April 16th, 2011. Positions of Raleigh and Fayetteville, NC are indicated in green, and the extent of the Raleigh National Weather Service County Warning Area is shaded in orange.

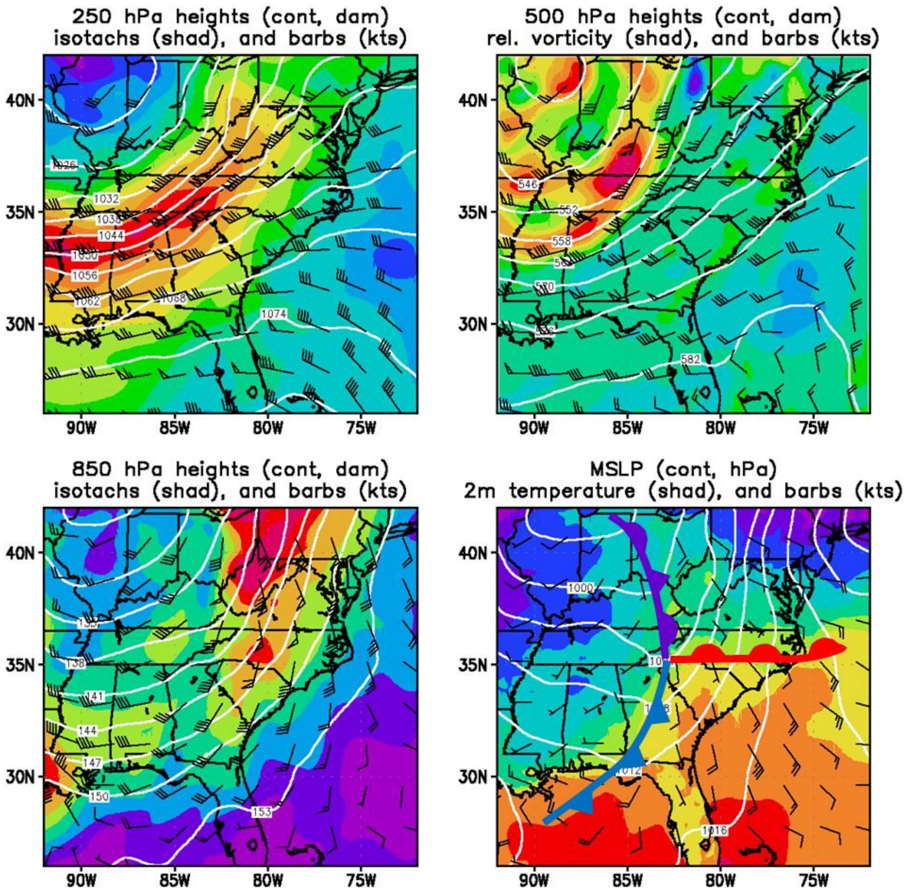


Figure 2: Four panel RUC analysis synoptic overview chart valid at 1200 UTC the morning of the April 16th 2011 outbreak. Fields and units are as labeled on each panel. Subjectively analyzed fronts are indicated on the surface panel.

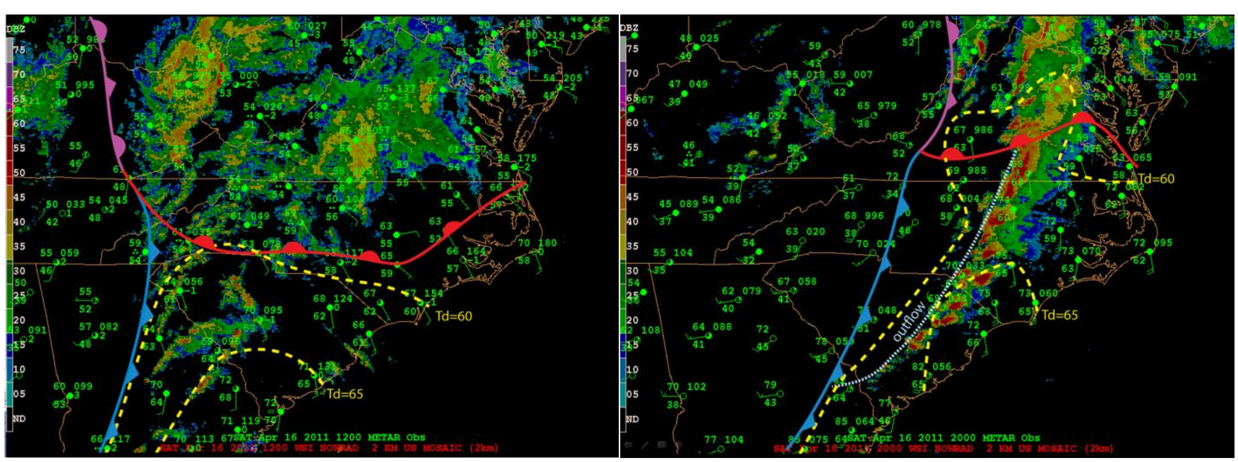
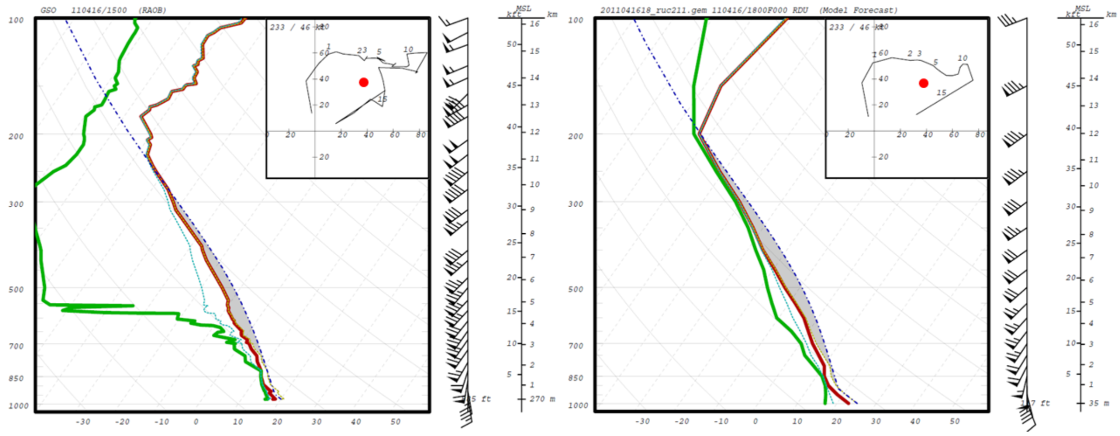


Figure 3: Regional surface analysis at 1200 UTC and 2000 UTC on April 16th 2011. Surface observations are plotted as station models (temperature in F, winds in kts, MSLP in tenths of hPa) with composite radar reflectivity and subjectively analyzed fronts and isodrosotherms superimposed.



(modified with observed cell motion) | *(modified with observed sfc T, sfc Td, cell motion)*

	GSO (left)		RDU (right)
CAPE:	668 J/kg	CAPE:	1043 J/kg
CIN:	-10 J/kg	CIN:	0 J/kg
0-6 km shear:	28 m/s	0-6 km shear:	30 m/s
0-3 km SRH:	807 m^2/s^2	0-3 km SRH:	804 m^2/s^2
LCL height:	264 m AGL	LCL height:	763 m AGL

Figure 4: Soundings and wind profiles typifying central North Carolina on April 16th 2011: 1600 UTC observed sounding from Greensboro, NC (GSO, left) and 1800 UTC RUC Analysis sounding for Raleigh, NC (RDU, right).

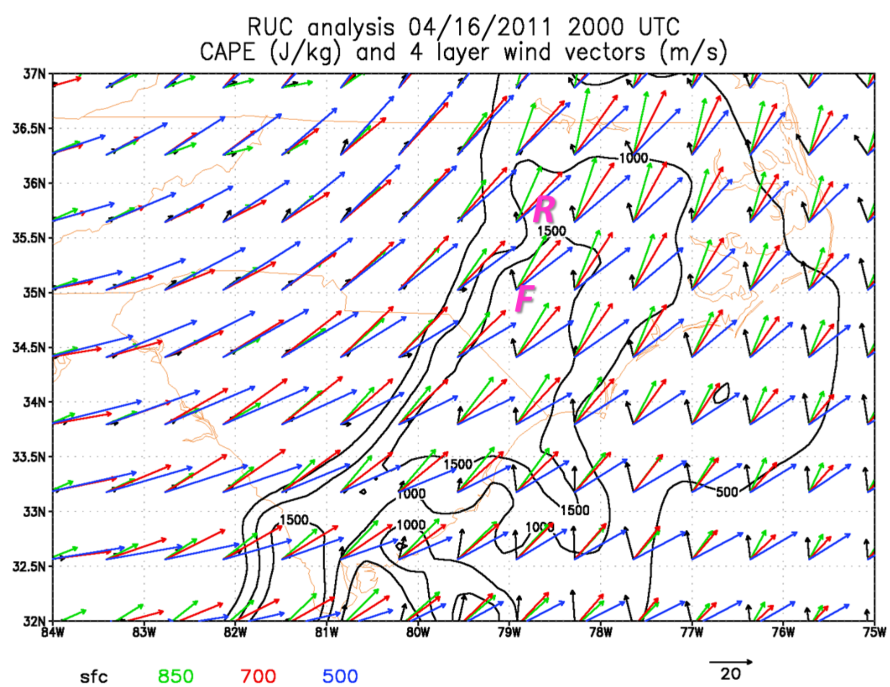


Figure 5: RUC analysis of surface-based CAPE (contoured in J/kg) and wind vectors (m/s) at the surface and three standard isobaric levels, valid 2000 UTC on April 16th 2011. The locations of Raleigh ("R") and Fayetteville ("F") are indicated.

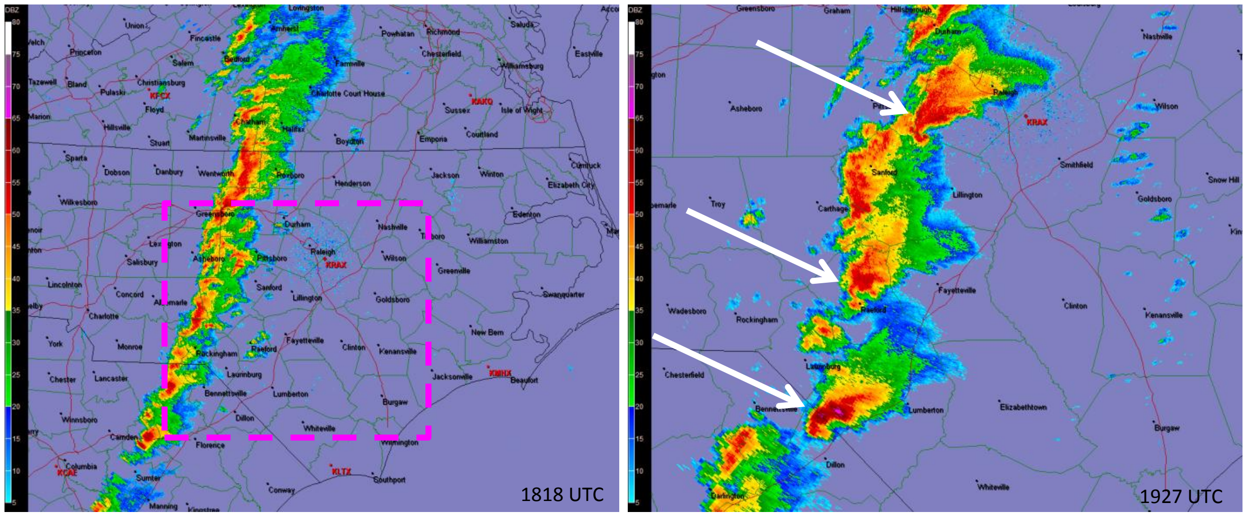


Figure 6: Base scan radar reflectivity from Raleigh, NC (KRAX) at 1818 and 1927 UTC. The zoomed area depicted in the right hand panel is indicated by the dashed box in the left-hand panel. Three supercells of note are indicated by arrows in the right hand panel.

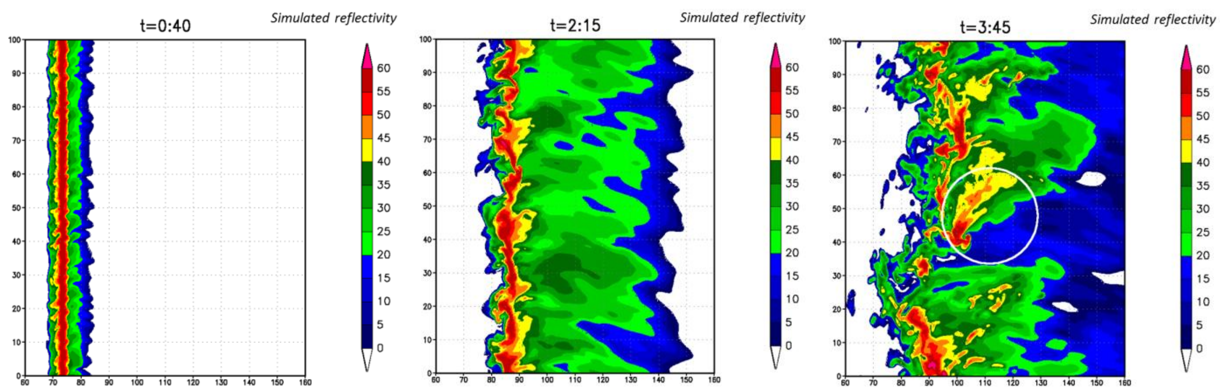


Figure 7: Simulated radar reflectivity at three times from an idealized simulation of the April 16th 2011 event. The initial condition was the 1800 UTC RUC analysis sounding for Raleigh (Figure 4), with a linear initial thermal trigger and a periodic north-south boundary condition. In the right-hand panel, the circle indicates a supercell that emerges after 3 hours, 45 minutes of simulated time. The model environment was homogeneous, and the simulation used the Thompson microphysical parameterization, with no parameterization of surface fluxes, radiation, or boundary layer processes. The horizontal grid spacing was 250 m and the vertical grid was stretched from a spacing of 100 m at the surface to 250 m aloft. For further details, contact the corresponding author.