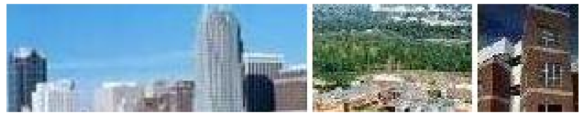
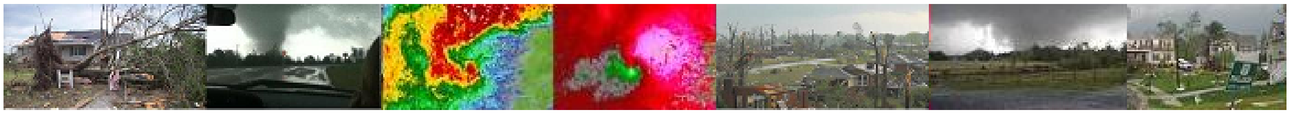
Event Summary
National Weather Service, Raleigh NC



April 16, 2011 North Carolina Tornado Outbreak

Note that this is a PDF version of the event summary and that some links, media or resources may not be avaiable in this format.



Event Headlines -
...Thirty confirmed tornadoes occurred in North Carolina on 16 April 2011, the greatest one-day total for North Carolina on record...
...A total of 24 individuals lost their lives in North Carolina with thirteen tornadoes classified as strong, some hitting highly-populated areas...
...Nine tornadoes occurred in the National Weather Service (NWS) Raleigh (RAH) County Warning Area (CWA). Among the nine, there were two EF-3 tornadoes, four EF-2 tornadoes and three EF-1 tornadoes...
...There were 8 fatalities in the RAH CWA, the most in April on record in central North Carolina (official tornado database begins in 1950) and second only to the 28 March 1984 outbreak...
...There were a total of 304 injuries reported in central North Carolina but the actual number is likely much higher. Two tornadoes, the Sanford-Raleigh Tornado and the Fayetteville-Smithfield Tornado had more than 100 injuries each...
...Total structural damage in central North Carolina was estimated at $328,610,000. The Sanford-Raleigh Tornado produced $172,075,000 in damage alone and the Fayetteville-Smithfield Tornado produced $116,100,000 in damage...

Case Study Highlights -
- Several detailed interactive maps that contain a total of 466 separate pieces of information are available including tornado tracks, tornado summaries, damage locations, fatality information, photos, and videos across central North Carolina.
- A discussion of several aspects of the outbreak that made it such a historic and unique event including the rarity of the number, strength, and longevity of the tornadoes as well as the multiple long track tornadoes, the issuance of a "High Risk" severe weather outlook, the first use of the “Tornado Emergency” wording by the NWS Raleigh in a Tornado Warning, and the track of the Sanford-Raleigh tornado that came within 1.75 miles of the NWS Raleigh office.
- A summary of how meteorologist at the NWS Raleigh forecasted the event.
- Several interesting science topics including the atypical evolution of a squall line that breaks up into multiple discrete supercells and the use of high resolution convection allowing models.
- Multiple radar images and loops as well as discussions of NSSL's Rotational Track Product and MESH Hail Swath Product.
- An audio recording of the Central Carolina SKYWARN amateur radio transmissions on 16 April.

Event Overview -
A well forecast, recording breaking tornado outbreak occurred across central North Carolina (NC) during the afternoon of 16 April, 2011. Thirty confirmed tornadoes occurred in North Carolina on 16 April 2011, the greatest one-day total for North Carolina on record. A total of 24 individuals lost their lives in North Carolina with more than 400 injuries.

The North Carolina NC Department of Crime Control & Public Safety reported that over 900 homes and businesses were destroyed and more than 6,400 were damaged across the state. Across central North Carolina in the National Weather Service (NWS) Raleigh (RAH) County Warning Area (CWA), total structural damage was estimated at nearly a third of a billion dollars, $328,610,000. The Sanford-Raleigh Tornado produced $172,075,000 in damage alone and the Fayetteville-Smithfield Tornado produced $116,100,000 in damage.

Nine tornadoes occurred in the Raleigh CWA. Among the nine, there were two EF-3 tornadoes, four EF-2 tornadoes and three EF-1 tornadoes. The nine tornadoes in the RAH CWA were produced by four supercell thunderstorms, with each supercell producing at least two tornadoes. The Sanford-Raleigh tornado and the Fayetteville-Smithfield tornado were long tracked and were on the ground for more than 55 miles each. The 9 tornadoes in central North Carolina were on the ground for a total of 196.4 miles. The tornadoes in central North Carolina touched down between 200 and 500 PM local time which is a little earlier than the climatological peak hours of tornado touchdown of 500 to 700 PM as noted in a Severe Weather Climatology for the Raleigh, NC County Warning Area (Locklear 2008).

There were 8 fatalities in the RAH CWA, the most in April on record in central North Carolina (official tornado database begins in 1950) and second only to the 28 March 1984 outbreak. Seven fatalities occurred in mobile homes and the other in a vehicle. Tornado fatalities occurred in the communities of Sanford, Lemon Springs, Raleigh, Linden and Dunn. All of the tornado fatalities occurred within the boundaries of tornado watches and were preceded by tornado warnings. The mean lead time for tornado warnings covering fatalities was 28 minutes and the mean lead time for all tornado warnings issued was 26 minutes.

There were a total of 304 injuries reported in central North Carolina but the actual number is likely much higher. Two tornadoes, the Sanford-Raleigh Tornado and the Fayetteville-Smithfield Tornado had more than 100 injuries each.

One tornado came within 1.75 miles (2.8 km) of the NWS Weather Forecast Office Raleigh and the staff executed a phased evacuation from the operations area which is on the third floor of a three story building. WFO Blacksburg, VA backed up the Raleigh office for around 6 or 7 minutes. As the storm drew closer, the power went out but there was no damage to the building or in the immediate area. The staff noted a strong odor of pine in the air after returning to the operations area.

The threat of severe weather on Saturday, 16 April 2011, was first mentioned during the morning of the Tuesday, 12 April Area Forecast Discussion (AFD) and the Hazardous Weather Outlook (HWO). On the morning of 13 April, forecasters became even more concerned as noted in the AFD with confidence increasing on 14 April. By the afternoon of 15 April, forecasters expressed a growing confidence of a significant tornado outbreak in the AFD. On Saturday morning, forecasters at WFO Raleigh and the Storm Prediction Center (SPC) issued statements and alerts that emphasized the unique and serious dangers presented by this particular weather pattern. WFO RAH issued 31 Tornado Warnings during the event with a probability of detection of 97%, false alarm rate of 48%, and an event average lead time of 19.5 minutes.

Synoptic and Mesoscale Summary-

The upper air pattern on the morning of 16 April 2011 featured an impressive eastward advancing upper level trough extending from the western Great Lakes into the lower Mississippi Valley. The 500 hPa trough at 00 UTC had moved eastward and became negatively tilted at 12 UTC with significant height falls of more than 120m noted across the Ohio and Tennessee Valleys. A 90 kt mid-level jet was rounding the base of the 500 hPa trough at 12 UTC across northeast Alabama, northwest Georgia, and far southeast Tennessee with a diffluent pattern noted across Georgia and the Carolinas. At 300 hPa, a strong jet core of 110 kts was located across northern Mississippi, northern Alabama, and southeastern Tennessee.

At 850 hPa, a closed low was analyzed over the western Great Lakes with a trough axis extending south along and near the Mississippi River. Another trough axis was located near and just west of the Southern Appalachians in eastern Kentucky, eastern Tennessee, and northwestern Georgia. Ahead of this trough, a region of enhanced south-southwesterly to southerly winds of 50 kts or more was analyzed across the western Carolinas, West Virginia, and western Virginia. A thermal ridge at 850 hPa extended into the Carolinas with dew points ranging into the 9 to 11 degree C range. A strong southeasterly flow at 925 hPa was noted with winds of 35 to 45 kts across central North Carolina.

At the surface, a cold front was analyzed near or just west of the Appalachians, extending from eastern Kentucky south across far western North Carolina into Georgia and the Florida panhandle. A warm front noting the leading edge of a warmer, more moist and unstable surface air mass extended west to east across southern North Carolina to the northeastern North Carolina Coast. North of the warm front, surface dew points were generally in the mid to upper 50s with temperatures in the upper 50s to lower 60s. South of the front, dew points climbed into the lower to mid 60s. The setup of synoptic scale features with this event was somewhat similar to the composite map of major synoptic scale features typically associated with severe weather outbreaks provided by Barnes and Newton (1983). The regional composite radar at 1158 UTC showed some scattered light to moderate rain showers across the Piedmont and Foothills of North Carolina with some convection developing south of the warm front across South Carolina and Georgia.

The air mass across central North Carolina at 12 UTC was stable with little or no surface based or mixed layer CAPE. The 60 degree isodrosotherm marking the leading edge of 60+ dew points was located near the North Carolina-South Carolina border. The strong low level flow resulted in strong, deep layer shear with bulk shear values around 50 to 60 kts. SPC analyzed 0-3km storm relative helicity values were extreme, ranging between 500-800 m2/s2.

Showers and thunderstorms developed along and just ahead of the cold front in western North Carolina between 1300 UTC and 1500 UTC. By 1500 UTC, the warm front had advanced into central and northern North Carolina. The 60 degree isodrosotherm extended into the northern Piedmont, very close to the North Carolina-Virginia border with dew points approaching the mid 60s in far southern North Carolina.

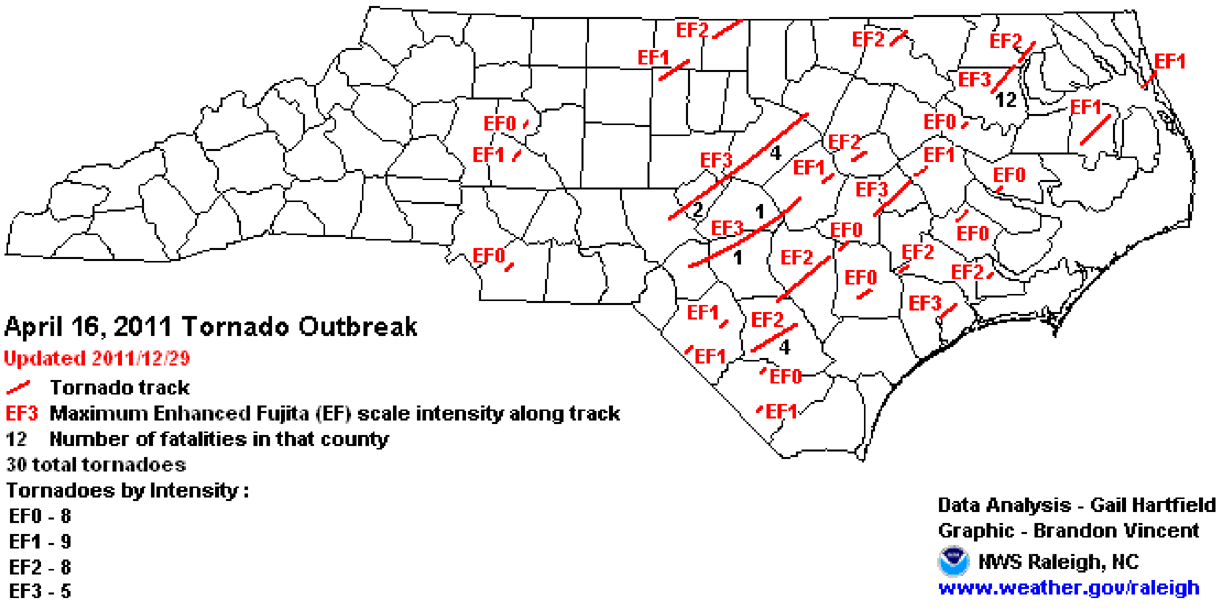
The convection across western North Carolina intensified and grew into a squall line between 1500 UTC and 1700 UTC. The squall line moved quickly east, advancing off of, and out ahead of the slow moving cold front. There was very little convection ahead of the squall line and the limited amount of convection that developed ahead of the squall line was weak and dissipated fairly quickly. One thought is that the strong vertical wind shear had a detrimental effect on the convection that tried to develop ahead of the squall line. The developing updrafts essentially tilted and ripped the immature convection apart. Further west, the large scale forcing at the mid and upper levels and the surface cold front were sufficient to initiate and sustain the convection in the highly sheared environment.

By 1800 UTC, the cold front was located across the Foothills of North Carolina. The warm front reached the Virginia border and dew points were well into the lower to middle 60s across central North Carolina. During the previous 6 hours, the surface based CAPE had increased dramatically during the late morning and afternoon hours. It is worth noting that the increase in the surface instability was dramatic and only preceded the squall line by just a few hours. The surface flow increased and backed more, resulting in incredible hodographs. The convection had intensified into a well-developed line of thunderstorms, and was able to race ahead of the cold front and survive in the strongly sheared environment as it reached the western Piedmont. The outflow behind the squall line was not especially cold, and there was also very little trailing stratiform precipitation behind the squall line, both suggesting that the environment was not supportive of long lived linear convection.

During the next few hours, the well-developed pre-frontal squall line fractured into multiple, discrete, long lived tornadic supercells. The large vertical wind shear, strongly curved clockwise hodographs, and minimal low-level line-normal shear appeared to strongly favor the development and maintenance of discrete supercells.

Severe Weather Reports

Map of tornado tracks and strength across North Carolina on 16 April 2011 -
The map below highlights the tornado tracks across the entire state of North Carolina with the maximum EF scale rating for each tornado shown in red. The number of fatalities for each tornado is shown in black. There were 30 total tornadoes including five EF-3 tornadoes, eight EF-2 tornadoes, and nine EF-1 tornadoes.



Interactive map of tornado tracks and tornado statistics across central North Carolina from 16 April 2011 -
The interactive map below includes summary information on each tornado (available via the blue balloon) and high resolution tornado track information shown in red.

View Overview Map - April 16, 2011 Central NC Tornado Outbreak in a larger map

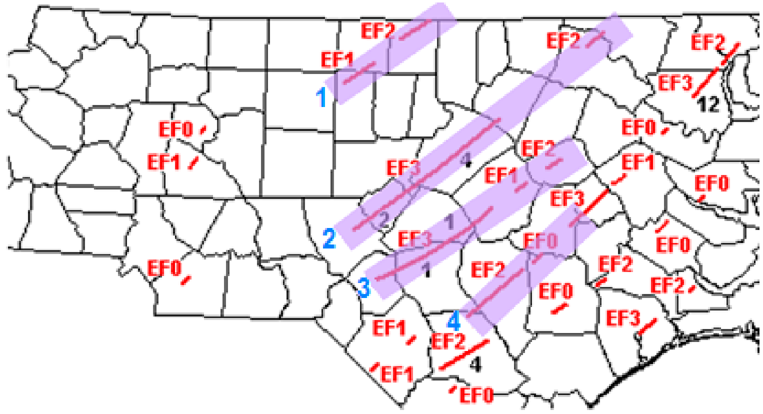
Links to additional detailed interactive maps of tornado information across central North Carolina from 16 April 2011 -
The maps below were produced from a painstaking analysis of damage reports, photographs, and videos of the 16 April event. The information used the these maps was provided by countless contributors including county and city emergency management officials, law enforcement and public safety personnel, media, military, storm spotters and the general public. **These maps contain 466 separate pieces of information** including 110 damage photographs and 285 individual specific reports of tornado damage or tornado touchdown locations.

Complete information including tracks, summaries, damage locations, fatalities, photos and videos - Google Map (kml file)
Tornado tracks with a summary for each tornado - Google Map (kml file)
Damage locations with tornado tracks - Google Map (kml file)
Fatality location and information with tornado tracks - Google Map (kml file)
Selected photos with tornado tracks - Google Map (kml file)
Selected videos with tornado tracks - Google Map (kml file)
Tornado Warnings with tornado tracks - Google Map (kml file)

Four Supercells Produced Nine Tornadoes in the RAH CWA

Nine tornadoes occurred in the Raleigh CWA on 16 April 2011 including two EF-3 tornadoes, four EF-2 tornadoes and three EF-1 tornadoes. The nine tornadoes in the RAH CWA were produced by four supercell thunderstorms, with each supercell producing at least two tornadoes. These four supercells were actually responsible for as many as 17 of the 30 total tornadoes across North Carolina on 16 April. The tornado tracks are shown in red in the map to the right and the path of each of the tornadic supercells is shown with the purple highlighting. A number identifying each supercell that moved through central North Carolina is shown in blue. A table summarizing the various statistics for each tornado along with the supercell ID is shown in the chart below.

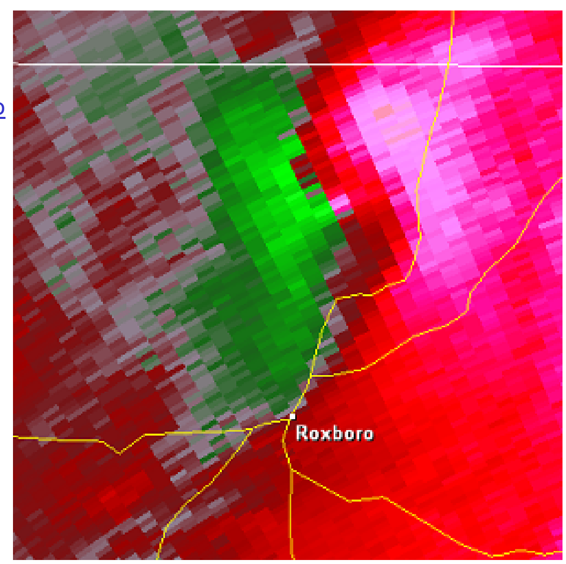
An overview of the event with KRAX reflectivity imagery from every volume scan between 1603 UTC and 0058 UTC on 16 and 17 April 2011 is available in this **java loop** which includes 114 frames.



Tornado	Supercell	Counties	Max EFScale	Max Wind	Fatalities	Injuries	Damage	Max Width	Path Length
Alamance County	1	Alamance	EF-1	110 MPH	0	0	$580,000	75 yards	7.4 miles
Person County	1	Person	EF-2	125 MPH	0	2	$400,000	300 yards	9.8 miles
Sanford-Raleigh	2	Moore, Lee, Chatham, Wake, Franklin	EF-3	160 MPH	6	103	$172,075,000	500 yards	66.8 miles
Roanoke Rapids	2	Halifax	EF-2	120 MPH	0	0	$1,200,000	250 yards	4.9 miles
Fayetteville-Smithfield	3	Hoke, Cumberland, Harnett, Johnston	EF-3	140 MPH	2	109	$116,100,000	~ 1700 yards	58.5 miles
Micro	3	Johnston	EF-1	90 MPH	0	67	$25,000,000	100 yards	8.7 miles
Wilson	3	Wilson	EF-2	120 MPH	0	10	$3,000,000	200 yards	9 miles
Cumberland-Sampson	4	Cumberland, Sampson	EF-2	120 MPH	0	13	$10,250,000	800 yards	28.5 miles
Wayne County	4	Wayne	EF-0	80 MPH	0	0	$5,000	400 yards	2.8 miles
Total					8	304	$328,610,000		196.4 miles

Alamance and Person County Tornadic Supercell

Summary



The thunderstorm that would eventually produce the Alamance County Tornado and the Person County Tornado initially developed at around 1015 AM about 20 miles northwest of Spartanburg, South Carolina. During the next hour, this thunderstorm along with other storms across the western Carolinas would grow into an organized line of convection. As the low level instability increased, the thunderstorms became more intense by around 1200 PM. The broken line of thunderstorms continued to intensify and move east with embedded thunderstorms developing into supercells with persistent rotating updrafts. Tornadoes were reported in Davie and Rowan Counties at around 1245 PM.

The same complex cluster of thunderstorms that produced the tornadoes in Davie and Rowan Counties weakened slightly as they moved across Davidson and Guilford Counties between around 100 PM and 145 PM. The weak low-level rotation across eastern Guilford County at 150 PM quickly strengthened as the storm moved into northwestern Alamance County at 204 PM when a tornado touched down around 6 miles northwest of Graham. The tornado moved across northwestern Alamance County with the storm relative velocity imagery becoming very impressive at 213 PM. The tornado remained on the ground for another few minutes before exiting Alamance County at around 216 PM and entering Caswell County.

The tornado remained on the ground for another few miles in Caswell County before dissipating. The parent supercell weakened slightly but still maintained a broad area of rotation as it moved across eastern Caswell County. As the supercell moved into western Person County, the rotation strengthened while the reflectivity structure improved. At around 240 PM, the Person County Tornado touched down with an impressive radar signature at 245 PM (storm relative velocity image) & reflectivity image). The tornado remained on the ground for 10 minutes and nearly 10 miles before the storm weakened and moved into Virginia.

Initial Alamance County Tornado Storm Survey Summary
Initial Person County Tornado Storm Survey Summary

Radar Imagery

Reflectivity loop for the tornado in Alamance County
Storm relative velocity loop for the tornado in Alamance County

[Reflectivity loop for the tornado in Person County](#)
[Storm relative velocity loop for the tornado in Person County](#)

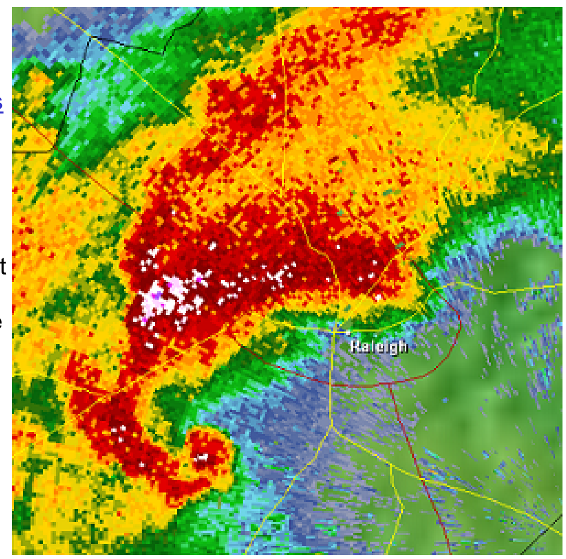
Damage Photos

Sanford-Raleigh and Roanoke Rapids Tornadic Supercell

Summary

The thunderstorm that would eventually produce the Sanford-Raleigh Tornado and the Roanoke Rapids Tornado initially developed to the southeast of Lancaster, South Carolina just after 115 PM. The thunderstorm intensified as it moved into North Carolina and approached Wadesboro. The storm then became a supercell as it developed a persistent rotating updraft as it moved into Moore County just after 230 PM. At 253 PM the storm produced a tornado in northeastern Moore County. The tornado strengthened as it moved across southeastern Sanford (reflectivity image & storm relative velocity image). The circulation in the storm remained intense as the storm moved across Chatham County into Wake County (reflectivity image & storm relative velocity image). The rotation within the storm weakened as it moved through Holly Springs with EF-0 to EF-1 damage observed from Holly Springs to southern Raleigh (reflectivity image & storm relative velocity image). The storm weakened a bit as it moved through downtown Raleigh before intensifying as it moved across northeastern parts of the city. A persistent path of EF-2 damage was noted in Raleigh from Stony Brook Drive (reflectivity image & storm relative velocity image) to Buffalo Road and Forestville Drive. The tornado began to weaken as it moved across far northeastern Wake County with damage becoming sporadic and isolated as it moved into Franklin County (reflectivity image & storm relative velocity image).



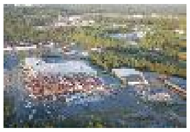
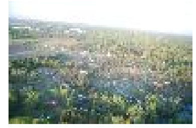
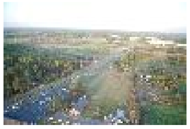
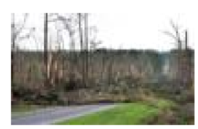
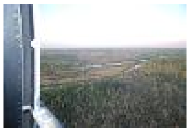
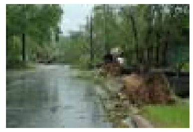
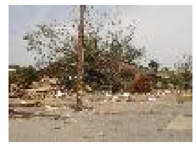
The thunderstorm associated with Sanford-Raleigh Tornado weakened somewhat as it moved across Franklin County but it remained strong as it moved through Warren County into southern Halifax County with no confirmed tornado damage. The supercell possessed an impressive reflectivity structure and broad rotation at 508 PM (reflectivity image & storm relative velocity image). The storm intensified markedly during the next few minutes and by the next volume scan the storm relative velocity imagery was indicating a new and intensifying area of rotation with an impressive reflectivity pattern. At 517 PM, both the storm relative velocity imagery and the reflectivity imagery had become even more alarming with a strong velocity couplet approaching Roanoke Rapids. Just a few minutes later, an EF-2 tornado touched down in the city. The tornado moved across the Roanoke River and dissipated in a few minutes (reflectivity image & storm relative velocity image) after moving into Northampton County.

Initial Sanford-Raleigh Tornado Storm Survey Summary
Initial Roanoke Rapids Tornado Storm Survey Summary

Radar Imagery

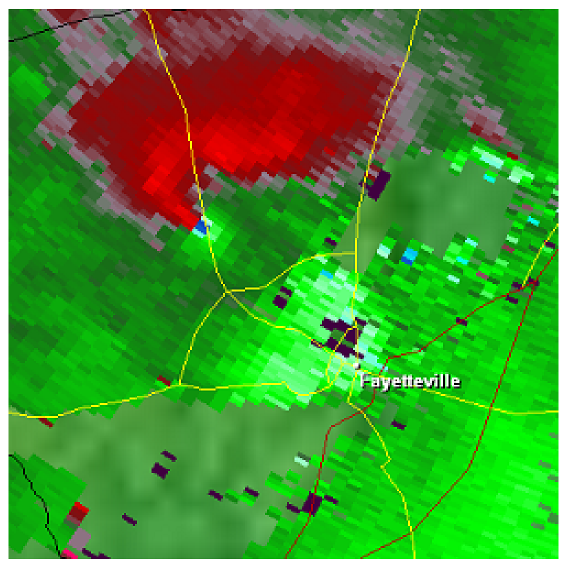
Reflectivity loop for the tornado in Moore, Lee and Chatham Counties
Storm relative velocity loop for the tornado in Moore, Lee and Chatham Counties
Reflectivity loop for the tornado in Wake County
Storm relative velocity loop for the tornado in Wake County
Reflectivity loop for the tornado in Halifax County
Storm relative velocity loop for the tornado in Halifax County

Damage Photos

Fayetteville-Smithfield, Micro, and Wilson Tornadic Supercell

Summary



The thunderstorm that would eventually grow into the Fayetteville-Smithfield, Micro, and Wilson tornadic supercell can be traced back to convection that developed around 25 miles west of Columbia, South Carolina at around 1230 PM. This thunderstorm was rather strong as it moved northeast across northern and northeastern South Carolina exhibiting periods of strong radar signatures with reports of damaging winds and hail. As the thunderstorm moved into far southern North Carolina near Cheraw at around 245 PM, it began to strengthen. The thunderstorm exhibited broad rotation across central Hoke County at 331 PM with a fairly impressive reflectivity signature. The first tornado that this supercell would produce touched down near the Wayside and Johnson Mills communities at around 340 PM. The reflectivity image and storm relative velocity image was very impressive and well defined at 345 PM. The tornado remained on the ground and tracked northeast across northern Cumberland County maintaining a strong radar signature at 404 PM (reflectivity image & storm relative velocity image). As the tornado approached and crossed Interstate 95, the tornadic circulation became separated from the main updraft at 417 PM (reflectivity image & storm relative velocity image). The storm maintained an impressive structure as it moved south of interstate 95 in the 427 PM reflectivity image and storm relative velocity image. As the tornado crossed interstate 95 for the second time and approached Smithfield, a secondary area of rotation developed near U.S. 70, around 3 to 4 miles southeast of the main circulation center (reflectivity image & storm relative velocity image). After the tornado went through Smithfield, it abruptly dissipated as a new tornado was forming to the southeast.

The Fayetteville-Smithfield, Micro, and Wilson tornadic supercell developed a new updraft just as the first tornado was approaching Smithfield. The 450 PM radar imagery not only shows a new updraft developing to the northeast of Smithfield but also a new low level circulation developing to the east of the weakening circulation associated with the first tornado. This is a remarkable image that shows both the weakening circulation from the first tornado and an intensifying circulation associated with the second tornado. The Micro Tornado was relatively short lived and the most impressive radar signature associated with the storm occurs at around 454 PM when the tornado touches down (reflectivity image & storm relative velocity image). The low level circulation weakened a few minutes later and the tornado dissipated after being on the ground for around 3 miles.

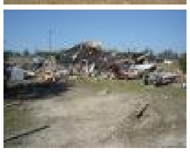
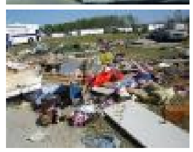
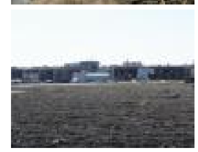
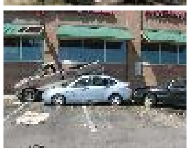
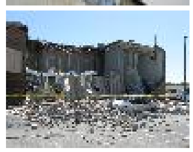
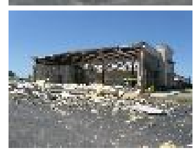
Around 10 minutes after the Micro Tornado dissipates, the same supercell featured broad low level rotation and a modest reflectivity pattern. As the supercell approached Wilson, a small but tightening low level circulation developed at 513 PM with a reflectivity appendage. The tornado touched down southwest of Wilson and then moved through western Wilson (reflectivity image & storm relative velocity image) before dissipating just north of town.

Initial Fayetteville-Smithfield, Micro, and Wilson Tornado Storm Survey Summary

Radar Imagery

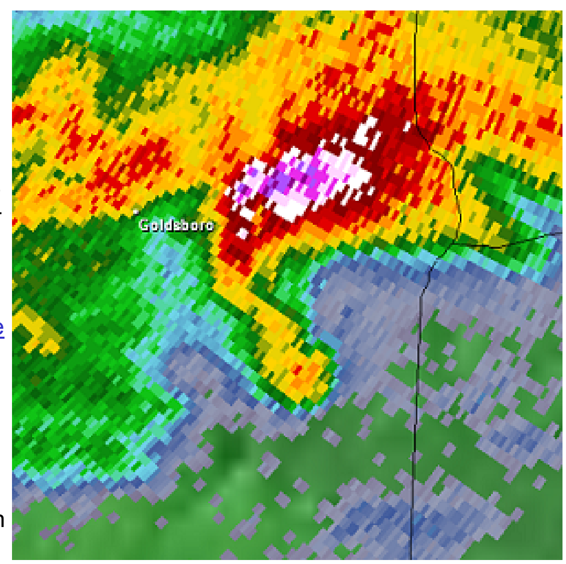
Reflectivity loop for the tornado in Hoke, Cumberland, and Harnett Counties
Storm relative velocity loop for the tornado in Hoke, Cumberland, and Harnett Counties
Reflectivity loop for the tornado in Harnett, Johnston, and Wilson Counties
Storm relative velocity loop for the tornado in Harnett, Johnston, and Wilson Counties

Damage Photos

Cumberland-Sampson and Wayne County Tornadic Supercell

Summary



The thunderstorm that would eventually produce the Cumberland-Sampson and Wayne County Tornadic Supercell can be traced back to convection that developed around 25 miles southwest of Columbia, South Carolina at around 1230 PM. This thunderstorm intensified after it moved east of Columbia and approached Darlington and Florence. The thunderstorm intensified further into a supercell as it moved into northeastern South Carolina and produced an EF-1 tornado near Little Rock in Dillion County, South Carolina. After crossing into North Carolina, the same supercell produced an EF-1 tornado near Rowland in Robeson County and another EF-1 tornado near Barker Ten Mile.

This supercell moved into southern Cumberland County and a tornado touched down just north of the Bladen-Cumberland County line at 433 PM (reflectivity image & storm relative velocity image). The tornado moved northeast crossing into southwestern Sampson County and weakened slightly. As the storm moved to the north of Clinton, the circulation strengthened while the reflectivity pattern remained impressive. The circulation subsequently weakened and the tornado dissipated at around 500 PM.

The same supercell continued to move northeast across Sampson County and then produced a relatively brief tornado as it moved across northern Duplin County near Faison. As the supercell moved into and across southern Wayne County, the storm relative velocity signature was generally convergent while the reflectivity pattern showed a developing appendage. Just before the storm was about to exit Wayne County, the storm relative velocity and especially the reflectivity pattern became more impressive on radar. An EF-0 tornado touched down near Parkstown and was on the ground for a mile before exiting Wayne County and moving into Greene County.

Initial Cumberland-Sampson and Wayne County Tornado Storm Survey Summary

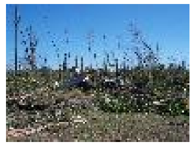
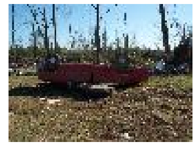
Radar Imagery

Reflectivity loop for the tornado in Cumberland and Sampson Counties

[Storm relative velocity loop for the tornado in Cumberland and Sampson Counties](#)
[Reflectivity loop for the tornado in Wayne County](#)
[Storm relative velocity loop for the tornado in Wayne County](#)

Damage Photos







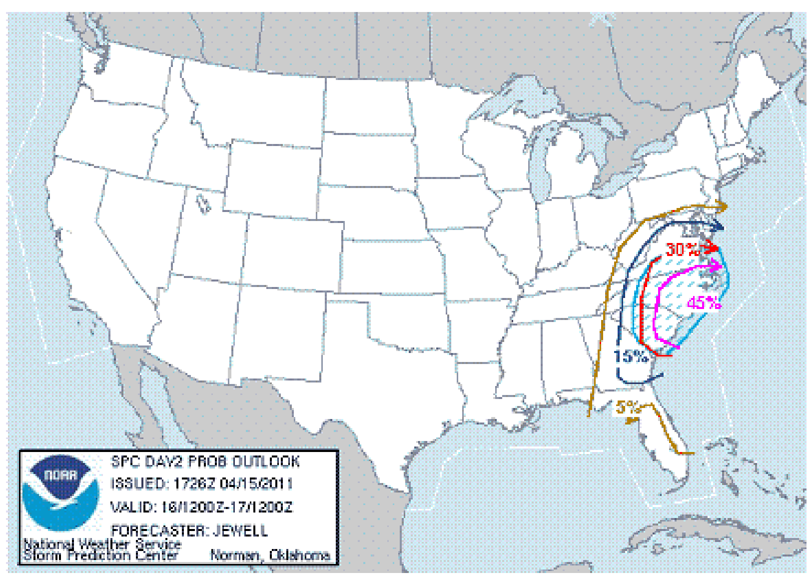
Forecasting the 16 April Tornadoes

The threat of severe weather on Saturday, 16 April 2011, was first mentioned by WFO RAH on Tuesday, 12 April in the Hazardous Weather Outlook (HWO) and the Area Forecast Discussion (AFD): "THE SEVERE THREAT SHOULD AGAIN BE BASED ON TIMING OF THE SURFACE FRONT. IF THE FRONT ARRIVES DURING THE MORNING INTO THE EARLY AFTERNOON... THE BOUNDARY LAYER INSTABILITY WOULD NOT BE AS GREAT... ESPECIALLY IN THE WESTERN AREAS. THE EASTERN ZONES MAY HAVE THE GREATER SEVERE THREAT (IF THE CURRENT INDICATIONS VERIFY AND THE FRONT ARRIVES IN THE AFTERNOON THERE)."

Beginning several days before the event and leading into 16 April, computer models showed a large scale flow pattern that indicated a potential significant weather event. The Storm Prediction Center (SPC) highlighted the possibility of strong storms in longer range outlooks, and they began offering more specified outlooks starting with the Day 3 forecast, issued the preceding Wednesday night. The text from the day 3 outlook noted: "LOW-LEVEL SHEAR WILL BE QUITE STRONG DUE TO A WELL-DEVELOPED LOW-LEVEL JET. THIS WILL MAKE TORNADOES A POSSIBILITY ESPECIALLY IF THE STORMS CAN REMAIN DISCRETE OR IF THERE ARE BREAKS WITHIN THE LINE FOR ANY LENGTH OF TIME DURING THE AFTERNOON. AN ENHANCED WIND DAMAGE THREAT OR TORNADO THREAT COULD EXIST BUT TOO MUCH UNCERTAINTY EXISTS TO FORECAST AN ENHANCED THREAT AREA."

The GFS model's 60-hr 500 hPa forecast, valid at 12 UTC (8 AM EDT) 16 April, depicted a powerful, negatively-tilted trough approaching from the west. In addition, the GFS indicated a strong 100 kt jet at 300 hPa extending across the Deep South. Finally, the GFS depicted a strong, warm southerly flow, including a 50+ kt low level jet at 850 hPa.

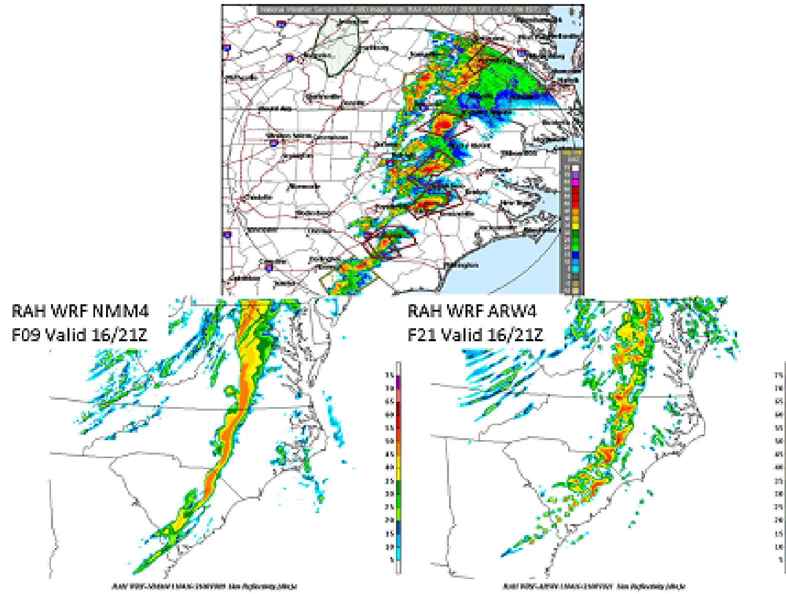
Throughout the week, forecasters knew that if the models were correct in showing all of these mechanisms coming together during the daytime, when heating would likely provide the instability needed for intense storms, a significant outbreak of severe weather was possible. The early morning AFD on Wednesday, 13 April noted the increasing concern: "MODELS HAVE SLOWED ARRIVAL TIME OF THE CONVECTIVE LINE BY 6-12 HOURS...MORE TOWARD THE DAYTIME HOURS SATURDAY. THIS MAY SPELL A GREATER SEVERE THREAT AS MODEST DESTABILIZATION WILL BE POSSIBLE VIA DAYTIME HEATING AND A SURGE OF 60F+ DEWPOINT AIR FROM THE SOUTH. AS THE UPPER TROUGH BECOMES NEGATIVELY TILTED...DEEP LAYER SHEAR IN EXCESS OF 50KT AND LOW LEVEL VEERING PROFILE/HODOGRAPH SIGNATURES ARE A BIT CONCERNING."



SPC's Day 2 outlook, issued the Thursday night before the event, increased the threat for severe storms, including a 30 percent chance of severe thunderstorms over central and eastern NC on 16 April. This threat was raised to 45 percent by early Friday afternoon. As confidence in a potential major severe weather event increased, WFO Raleigh forecasters offered strongly-worded statements and discussions providing more specifics on the most likely storm threat (tornadoes) as well as the location and timing of the severe weather. The first detailed online weather briefing, focused on alerting the public, emergency managers, and other officials, was prepared and posted on our web page the morning of Friday 15, April.

By Friday afternoon, forecasters expressed their growing confidence in a significant tornado outbreak in the AFD: "SHEAR WILL SUPPORT DISCRETE CELLS DEVELOPING AHEAD OF A DANGEROUS SQUALL LINE... THE DANGEROUS COMBINATION OF HIGH SHEAR... MODERATE CAPE AND LOW LCLS WILL BE SUPPORTIVE OF DISCRETE SUPERCELLS CAPABLE

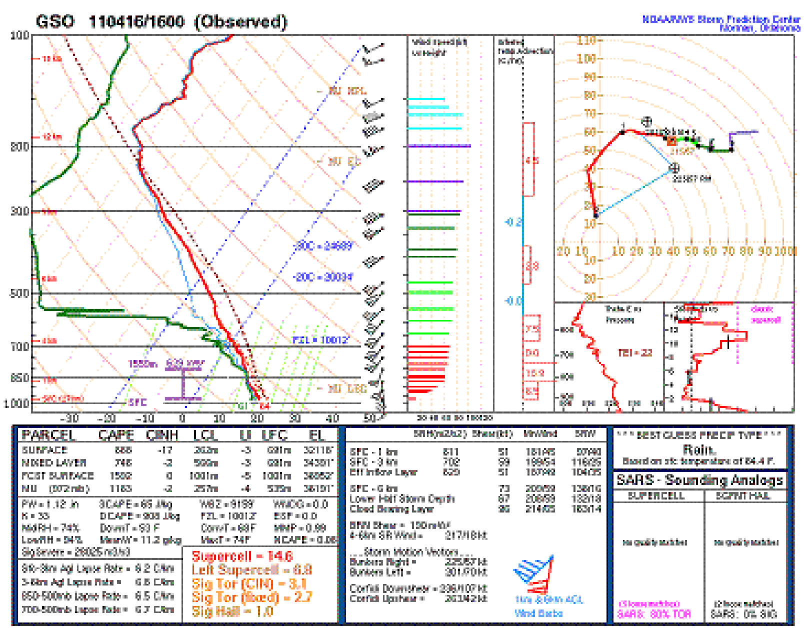
OF PRODUCING TORNADOES AHEAD OF A MAIN SQUALL LINE CAPABLE OF WIDESPREAD DAMAGING WIND AND ADDITIONAL TORNADOES. A FEW INTENSELY ROTATING SUPERCELLS WITH A THREAT OF TORNADOES WILL LIKELY EXIST."



High resolution Numerical Weather Prediction (NWP) models have been widely used in recent years to help with short range forecasting and warning operations. Recent advances in NWP and in computational efficiency have resulted in an improvement in and the availability of high resolution model forecasts on the convective scale. An example of the opportunities that high resolution NWP can provide is shown in the image to the right (click on the image to enlarge). This image is a comparison of the observed KRAX reflectivity at 2058 UTC and the simulated (forecast) reflectivity valid at nearly the same time from the 9 hour forecast of the RAH WRF NMM4 and the 21 hour forecast of the RAH WRF ARW4 model. Both of the RAH WRF forecasts show a line of intense convection across central North Carolina with the ARW version showing more cellular convective features while the NMM version is much more linear. A comparison image of reflectivity forecasts from both the RAH NMM and the RAH ARW valid at 18 UTC, 20 UTC, and 22 UTC also shows a tendency for the ARW version showing more cellular features while the NMM version is much more linear. A similar pattern and timing was noted in the NCEP High Resolution Window (HiResWindow) Weather Research and Forecasting (WRF) simulations as seen in the 21 hour forecast from the 00 UTC 16 April initialization of the NMM forecast and ARW forecast. The capability of high resolution NWP in the very short term was also apparent in the High Resolution Rapid Refresh (HRRR) 8 hour reflectivity forecast from the 12 UTC 16 April initialization when compared to the radar observations.

A major tornadic outbreak was becoming a near certainty. On Saturday morning, forecasters at WFO Raleigh and SPC issued statements and alerts that emphasized the unique and serious dangers presented by this particular weather pattern. The WFO Raleigh Hazardous Weather Outlook issued early Saturday morning noted: "THOSE WITH OUTDOOR PLANS AND ACTIVITIES SATURDAY AFTERNOON SHOULD CONSIDER ALTERNATIVE PLANS. EVERYONE ACROSS CENTRAL NORTH CAROLINA SHOULD CLOSELY MONITOR FORECASTS AND BE ALERT FOR FUTURE WATCHES AND WARNINGS. STORMS COULD POTENTIALLY BE MOVING IN EXCESS OF 55 MPH... ALLOWING LITTLE TIME TO REACT ONCE THE THREAT IS NEAR. KNOW WHERE THE SAFEST LOCATION IN ANY BUILDING YOU OCCUPY IS LOCATED. RESIDENTS OF MOBILE HOMES SHOULD CONSIDER ALTERNATES TO REMAINING HOME THIS AFTERNOON."

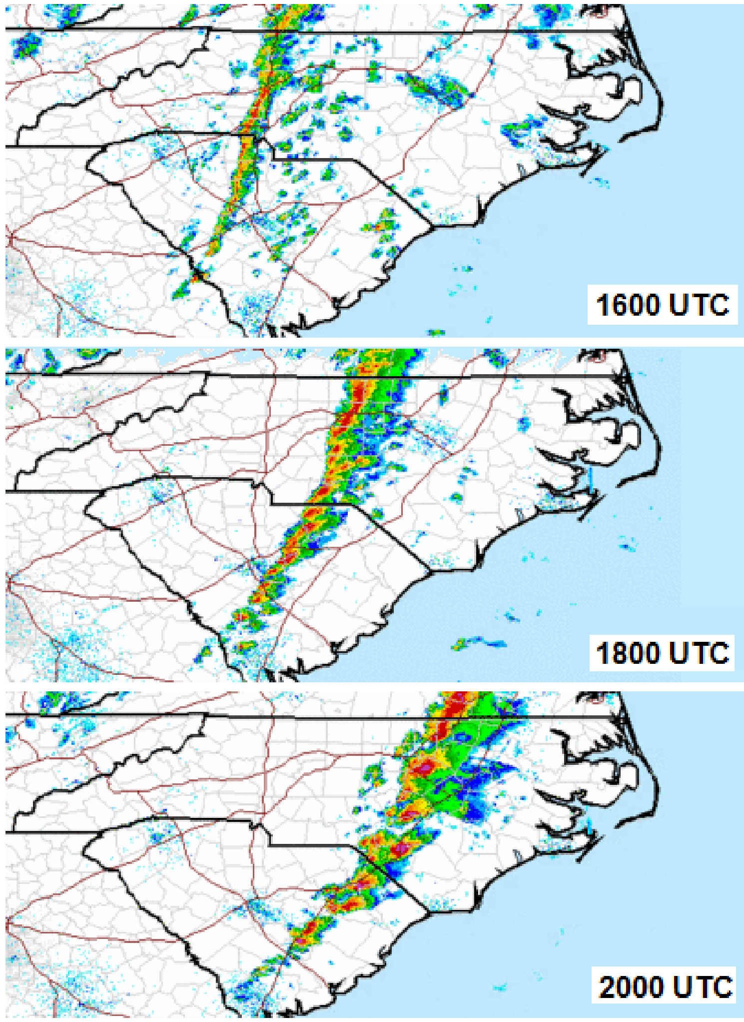
By mid-morning Saturday, forecasters recognized that the atmosphere was becoming increasingly favorable for deadly tornadoes, just as the computer models and observational data leading into the event had indicated. In particular, in the hours before storms developed and moved into central NC, low level instability was increasing rapidly, low level shear was very strong, and lifted condensation levels were low, a little more than one half kilometer which is a condition which research has shown is supportive of the development and maintenance of significant tornadoes. By midday, SPC had placed central and eastern North Carolina in an unusual "high" risk for severe thunderstorms, with a very high risk of major tornadoes.



The mid-morning AFD from Saturday noted the impending danger: "LOOKING OVER RECENT TRENDS AND 12Z SOUNDINGS EVERYTHING REMAINS PRIMED FOR A SIGNIFICANT SEVERE WEATHER OUTBREAK ACROSS CENTRAL NC FROM NOON THROUGH 7 PM TODAY." "LOW LCLS AND HIGH SHEAR FROM THE LOW TO MID LEVELS IS ALREADY IN PLACE. AS THE INSTABILITY INCREASES AND THE DYNAMICS AND UPDRAFT VELOCITIES INCREASE AS THE UPPER LOW APPROACHES FROM THE WEST THE DANGER OF SEVERE WEATHER WILL INCREASE GREATLY."

A special sounding at Greensboro (KGSO) from 1600 UTC (1200 PM EDT) revealed a destabilizing environment with an intense wind field and impressive shear. This sounding combined with other observations and analysis from the early afternoon hours on 16 April confirmed that the environment that was predicted for several days had materialized and that a significant severe weather event would soon be underway.

Evolution from a Squall Line to Discrete Supercells



The evolution of the convective mode from a long linear structure to multiple discrete supercells on 16 April was unusual. Often times, convection will grow upscale from individual cells, to multicells, and then into a line of convection or squall line as the convectively induced cold pools merge and interact. This event was rather remarkable in that no discrete supercells developed ahead of the line, rather the squall line fractured into several discrete long lived tornadic supercells.

Showers and thunderstorms developed along and just ahead of a cold front in western North Carolina between 1300 UTC and 1500 UTC. The convection intensified and grew into a squall line between 1500 UTC and 1700 UTC. The squall line moved quickly east, advancing off of and out ahead of the slow moving cold front.

The outflow behind the squall line was not especially cold; outflow temperature deficits ranged around 5 degrees C, which is common in environments with high relative humidity in the boundary layer. Anecdotal experience of forecasters at the NWS Raleigh is that some of the most significant tornado events, including those with long track tornadoes, (November 1988 Raleigh tornado, November 1992 tornadoes, and the March 1984 tornadoes), occur with rich boundary layer moisture, often at night when the lack of convective mixing keeps the boundary layer moist.

Radar imagery indicated very little trailing stratiform precipitation behind the squall line. This suggests that the support or maintenance of the cold pool was limited, and that the squall line was potentially missing a component to sustaining itself.

It is interesting to note that very little if any intense convection developed ahead of the squall line. The limited amount of convection that did develop ahead of the squall line was weak and dissipated fairly quickly. One thought is that the strong vertical wind shear had a detrimental effect on the developing updrafts and essentially tilted and ripped the immature convection apart. This helps to explain why the few showers that developed ahead of the line failed to intensify and fell apart. It could be argued that the larger scale forcing at the mid and upper levels and the surface cold front were sufficient to initiate and intensify the convection in a region of potentially hostile shear. Once the convection matured, it was able to race ahead of the cold front and survive in the strongly sheared environment.

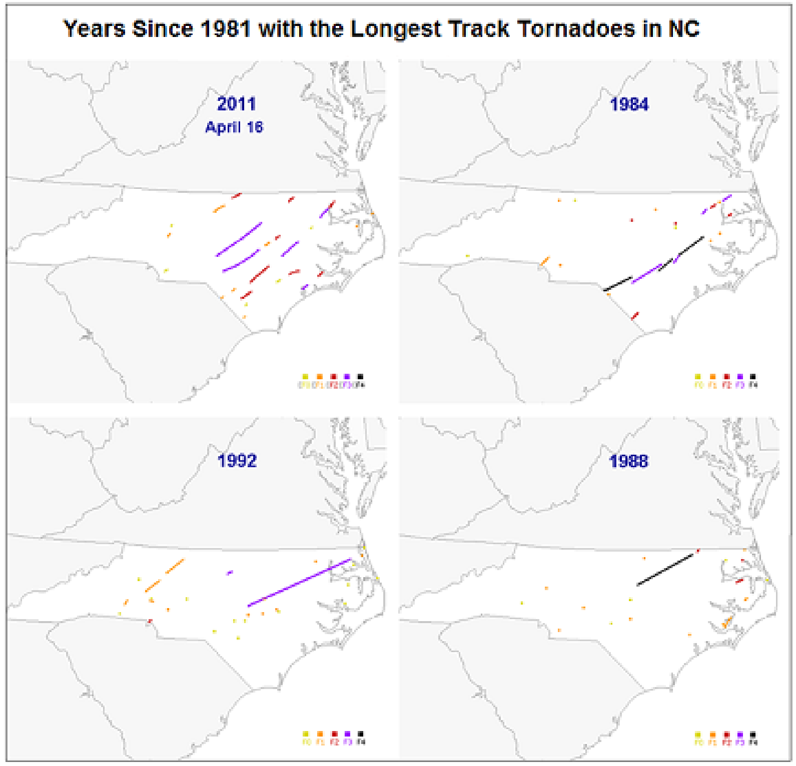
It has been shown that the component of the 0-3 km low-level environmental shear oriented perpendicular to a squall line is one of the most important factors in the line's evolution. Long-lived squall lines can be expected when the wind shear is perpendicular to the line while squall lines with little or no line-normal shear will likely be shorter-lived and promote more discrete cells. The low-level shear vectors during this event were largely parallel to the squall line. The large vertical wind shear, strongly curved clockwise hodographs, and minimal low-level line-normal shear appeared to strongly favor discrete supercells. It can be argued that the environmental shear played a significant role in the evolution of the convection. As the squall line pushed east, the line began to fracture and discrete supercells emerged.

A Historic and Unique Event

Tornado events of this magnitude are very rare in North Carolina. The 16 April 2011 outbreak was comprised of 30 tornadoes including five EF-3 and eight EF-2 tornadoes and resulted in 24 fatalities. The 28 March 1984 Tornado Outbreak is the only precedent during the 20th or 21st century of an event of this size, intensity, destruction, and fatalities. The March 1984 outbreak produced 14 tornadoes, including four F-4's and resulted in approximately 801 injuries and 42 deaths in North Carolina. The March 1984 tornado outbreak impacted around 20 counties in eastern North Carolina whereas the 2011 outbreak impacted 37 counties across central and eastern North Carolina.

The Raleigh tornado which touched down on 28 November 1988 was rated an F-4. It was the only tornado that night but it killed 4 people and injured 157 residents. The 5 May 1989 tornado outbreak produced only 11 tornadoes, but they were generally more intense, including three F-4 tornadoes and they resulted in 5 fatalities in North Carolina. An outbreak on 15 April 1996 produced 18 tornadoes, all of them were F-2 or weaker and there were no deaths in the state. More recently, an outbreak on 7 May 1998 produced 20 tornadoes in

North Carolina, including one F-4 and one F-3, but the other tornadoes during that event were considerably weaker and short-lived and no fatalities were reported. Finally, [Hurricane Floyd's landfall on 15 September 1999] resulted in 17 tornadoes, all of them were F-2 or weaker, and there were no fatalities.



Adapted from Chris Broyles SPC

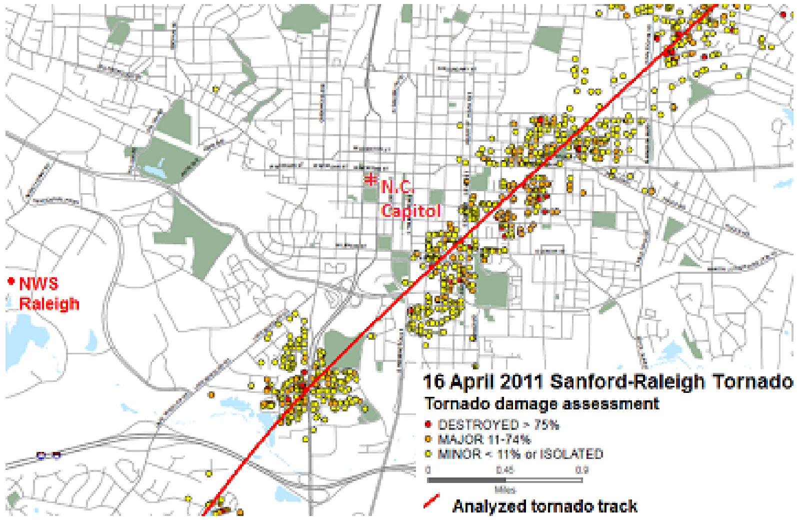
Chris Broyles from the Storm Prediction Center put together an image (click here to open) that shows the years with the longest tornado tracks since 1980. The longest track tornadoes in North Carolina during this period are from 2011, 1992, 1988, and 1984. On 16 April 2011, two tornadoes were long tracked and were on the ground for more than 55 miles each. The Sanford-Raleigh Tornado was on the ground for 67 miles and the Fayetteville-Smithfield Tornado was on the ground for nearly 59 miles. A tornado on 22 November 1992 tracked from Harnett County to Pasquotank County, a total of 160 miles which set a North Carolina record. The 28 November 1988 Raleigh Tornado was on the ground for 84 miles and eventually reached Northampton County. The 28 March 1984 Tornado Outbreak included 4 tornadoes which were on the ground for more than 20 miles, including two tornadoes that were on the ground for 40 miles each.

The Storm Prediction Center (SPC) upgraded the Day 1 Severe Weather Outlook to a "High Risk" for much of central and eastern North Carolina at 1230 PM EDT and mentioned the possibility of strong tornadoes. The "High Risk" designation is a very unusual occurrence (there have been only 44 "high risk" outlooks issued across the country for the 10 year period of 2002-2011 with only 5 "High Risk" outlooks issued in 2011). Information provided by Andy Dean at the SPC indicated that a portion of the RAH CWA (as currently defined) has been in the SPC "High Risk" severe weather outlooks just four times since March 1984. The dates are 28 March 1984, 3 May 1984, 29 March 1991, and 16 April 2011. There have been several occasions since March 1984 when some portion of the state of North Carolina has been in a high risk, most recently a small part of NC was in a High Risk on the 0100Z November 11, 2002 outlook.

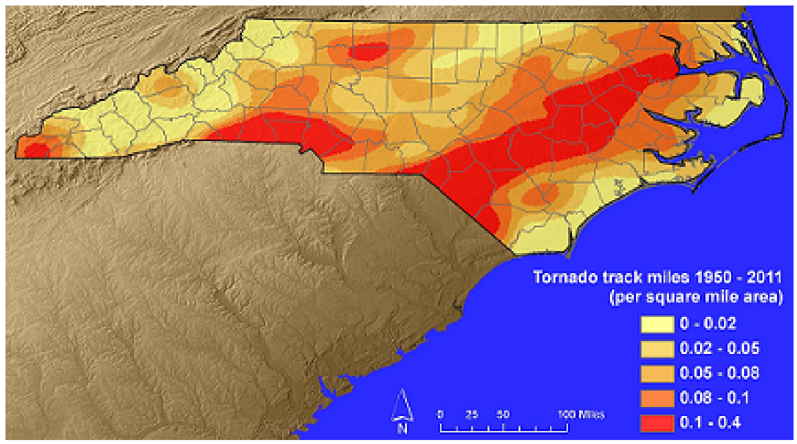
For the first time, the NWS Raleigh issued a tornado warning with “Tornado Emergency” wording. Four separate Tornado Warnings, including the Tornado Warning for Wake County including the city of Raleigh and especially downtown Raleigh were issued with “Tornado Emergency” wording. In addition, numerous Severe Weather Statements used to update the Tornado Warnings included the “Tornado Emergency” wording as well. While the “Tornado Emergency” wording was used in 3 Severe Weather Statements during the 28 March 2010 Tornado Outbreak, this event marked the first time it was used in such a significant way with 19 different products including the “Tornado Emergency” wording. Tornado Emergencies were issued for every area in which fatalities occurred in central North Carolina with the exception of Sanford which was the first large tornado of the day. Tornado Emergencies were issued for the storms which crossed Raleigh as well as Linden, Dunn, Micro, Clinton and Wilson.

During times of extreme severe weather, normal communication means can be hampered. The use of SKYWARN spotters, amateur radio operators and the more recent additions of NWSChat, POP, and CoCoRaHS were extremely important to in severe weather operations. This was the first significant event in which some of the new communication technologies were used and their utility was apparent. Two Central Carolina SKYWARN amateur radio operators were staffed at the NWS Raleigh during event and they collected 96 reports from 57 different spotters during the event (listen to audio of the Central Carolina SKYWARN amateur radio transmissions on 16 April - caution, large file >95 MB). Many of the reports were first hand observations by trained spotters with additional reports relays of Public Safety transmissions heard on a scanner. Many of the initial reports of severe damage near Sanford were relayed by SKYWARN spotters listening to 911 traffic via scanners. NWSChat users provided 14 separate reports of damage or severe weather. The Public Observation Program (POP), which allows the public to call and leave reports of severe weather on a computer system, provided 28 separate reports of hail, funnel clouds, or tornadoes. CoCoRaHS observers provided 10 real time reports of heavy rain, hail, or tornado debris.

The Sanford-Raleigh tornado came within 1.75 miles (2.85 km) of the NWS Raleigh office which is located on the Centennial Campus of N.C. State University. The NWS Raleigh operations area is located on the third floor of a three story building with a large bank of windows looking north. The tornado moved just to the southeast of the office and was not visible out the windows. The threat of a potential tornado strike on the office was noted more than 30 minutes in advance and multiple coordination calls were made with our backup office in Blacksburg Virginia. As the tornado approached, the staff executed a phased evacuation from the operations area. The Blacksburg office backed up the Raleigh office for around 6 or 7 minutes as Raleigh staff members took shelter in the stairwell tornado shelter. As the tornado drew closer, the power went out and the staff was huddled in the dark. After a few minutes, the staff returned to the operations area and noted very little damage, the tornado had tracked less than 2 miles to the southeast of the office. Some small branches and debris was noted out the window and the staff noted a strong odor of pine in the air.

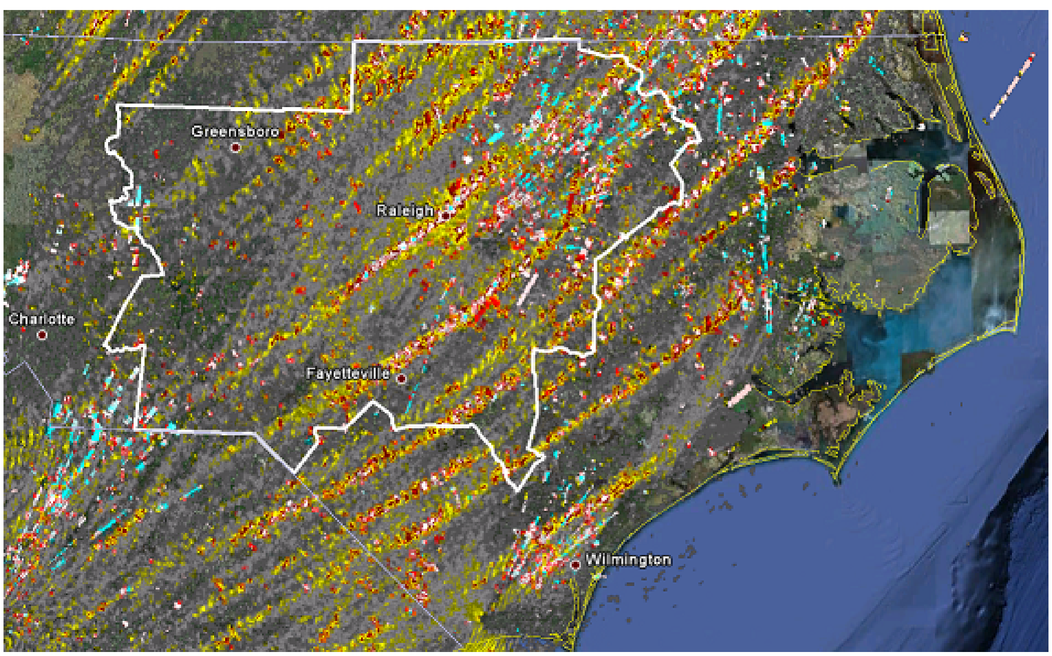


The NWS Raleigh has provided senior undergraduate and graduate meteorology students at N.C. State University internship opportunities since the late 1990s. On 16 April, one of the student interns, Carl Barnes, was scheduled to work a shadow extended range forecast shift. Carl didn't practice an extended range forecast that day, but instead, for over 8 hours, Carl sat alongside NWS meteorologists as they issued lifesaving tornado warnings, evacuated to the tornado shelter as a tornado moved through Raleigh, and heard the reports of devastation and casualties. Carl's first person summary of the event is available here.



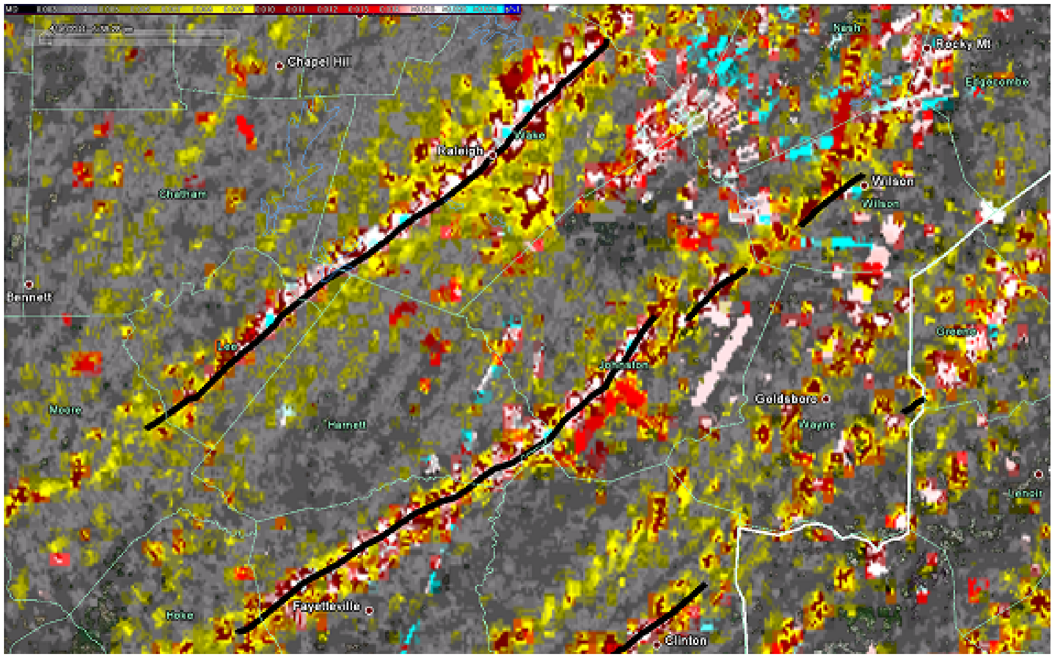
Dr Tom Allen from the East Carolina University Department of Geography created a tornado track density map for North Carolina. The map includes data from the Storm Prediction Center (SPC) SVRGIS dataset (1950-2010) and additional data for 2011. The map shows the tornado track density (per square mile area) during the period using a 5 class (quartile classification). The analysis uses tornado tracks on the ground in North Carolina including tracks within ~40 miles of the North Carolina border. An axis of higher tornado track density extends across the southern Piedmont, eastern Sandhills, and the Coastal Plain. These results show a similar signal to a study by Michael Frates entitled "Demystifying Colloquial Tornado Alley" which examined the frequency of long-track F-3 to F-5 tornadoes. The results in the Frates study identified and labeled a "Carolina Alley" which extends from the southern Piedmont, across the Sandhills region and northward across the Coastal Plain of North Carolina. Finally, a study by Dixon et al. (2011) Tornado Risk Analysis: Is Dixie Alley an Extension of Tornado Alley showed a similar but less significant increase in the density of average annual tornadoes within 25 miles of any point across southern and eastern North Carolina.

NSSL's Rotational Track Product



NOAA's National Severe Storms Laboratory (NSSL) has developed a gridded dataset that contains rotational shear from single and multiple radars that is accumulated over time providing tracks of radar detected rotation. The basic process for creating these products is initiated when velocity data from each radar is run through a Linear Least Squares Derivative (LLSD) filter creating an azimuthal shear field. The azimuthal shear fields in a 0-3 km layer from each radar across the CONUS are then combined and the maximum value at each 250 m² grid point is plotted over the time period providing the graphic.

The process was further improved when the WDSS-II (Warning Decision Support System - Integrated Information) group at NSSL made the "Rotational Tracks" data available for display in Google Earth. Using Google Earth with an overlay of near real-time "rotational tracks" allows forecasters to estimate where a storm's low-altitude circulation was most intense and to determine locations of possible damage. The satellite images and high density maps in Google Earth often make it possible to determine the location of enhanced rotation down to the neighborhood scale. This simplifies the verification process by reducing the amount of time that is spent searching for reports. This data has been used for numerous events across central North Carolina during the past few years including the 27 October 2010 Tornado Event, the 25 April 2010 Tornado Event, the 27 March 2009 Tornado Event, and the 15 November 2008 Outbreak.

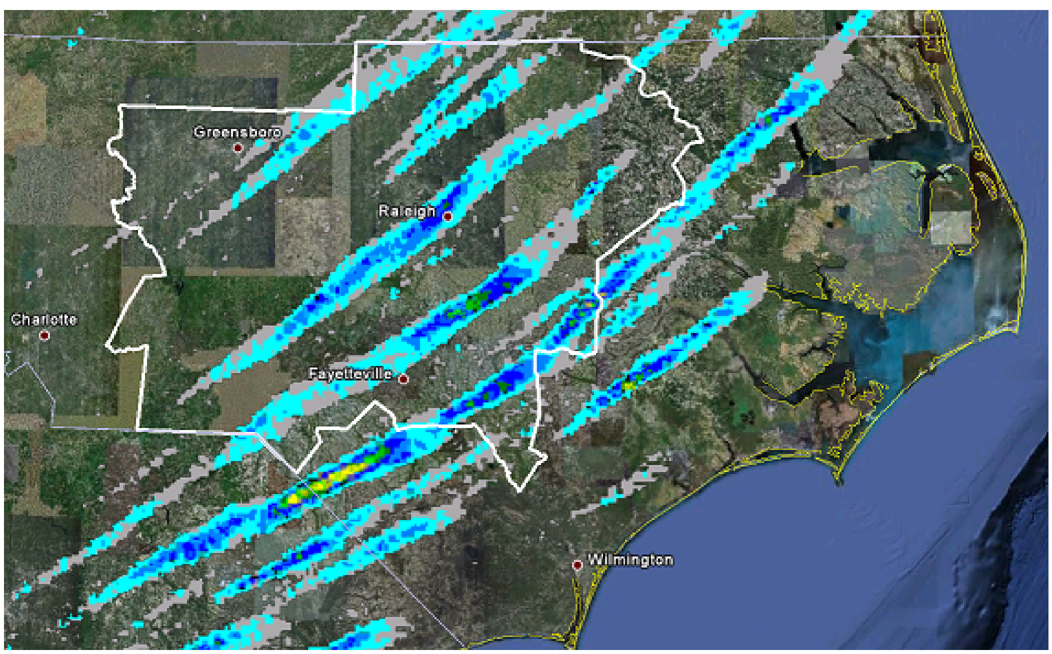


The rotational track product for this event from 1200 to 2358 UTC on 16 April 2011 is shown above and to the right (click on it to enlarge). The product shows numerous corridors of enhanced rotation across central and eastern North Carolina which are associated with the many supercell thunderstorms that moved across the region that afternoon and evening. The northeast storm motion is easy to see as is the longevity of the rotating thunderstorms with some of the tracks extending more than 100 miles (160 km). The two long track tornadoes (the Sanford-Raleigh Tornado and the Fayetteville-Smithfield Tornado) can be identified in the rotational track product.

The image to the right is a zoomed in view of the rotational track product across central and eastern portions of the RAH CWA with the tracks of the tornadoes that occurred in the RAH CWA shown in black (click on it to enlarge). While the tornado tracks show a general northeast motion, the tracks are nonlinear and wobble somewhat as the storm structure evolves and as the tornado vortex interacts with the varied terrain and land uses. Note that the rotational track product uses radar data in the lowest 3km of the atmosphere that is blended from multiple radar sites. Because of this and with fast moving, tilted thunderstorms, the rotational track product will not match the tornado track exactly. Despite these limitations, the rotational track product does a good job highlighting the storm's low-altitude circulation and likely tornado track.

NSSL rotational track product from 1200 to 2358 UTC on 16 April 2011 for viewing in Google Earth.

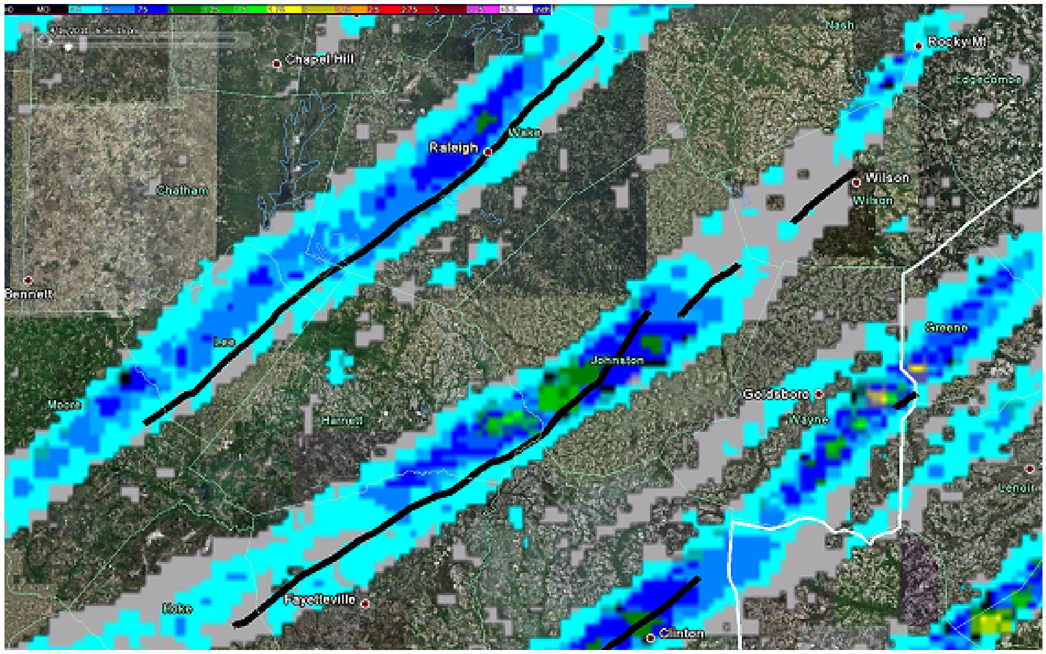
NSSL MESH Hail Swath Product



NOAA's National Severe Storms Laboratory (NSSL) has been developing techniques for getting popular WSR-88D cell-based hail information from the Hail Detection Algorithm (HDA) into formats that users can more effectively use. Some of the cell-based hail information has been incorporated into high-resolution gridded products that allow users to diagnose which portions of storms contain large hail. One such product is the "Hail Swath" product which accumulates hail size data over a period of time to provide hail swath maps, estimating both maximum hail size by location, and hail damage potential (a combination of hail size and how long the hail has been falling).

More specifically, the "Hail Swath" product is a derivative of the MESH (Maximum Expected Size of Hail) output from the HDA. Reflectivity data from all of the CONUS NEXRAD radars are merged into a three dimensional (latitude/longitude/height) grid. A modified version of the NSSL HDA is then run on this grid producing a MESH grid at 60 second intervals. The maximum MESH value at each 1 square kilometer grid point is plotted over a chosen time period in order to create the areal "swaths" of MESH.

The NSSL Hail Swath product valid from 1200 to 2358 UTC on 16 April 2011 is shown above and to the right (click on it to enlarge). The track of several hail producing supercells that moved across central and eastern North Carolina is clearly visible. The color scale on the image indicates the maximum expected hail size during the period with the light blue area indicating hail estimated at around a half inch in diameter, the darker blue area indicating hail greater than an inch in diameter, and the lighter green area indicating hail potentially larger than an inch and a half. In the RAH CWA, the hail swath product highlighted eastern Harnett and Johnston Counties as locations with potentially the largest hail and there were numerous reports of golf ball size hail (1.75 inch diameter) to 2 inch diameter hail across Johnston County. The hail swath product also highlighted small portions of Sampson County where 2 inch diameter hail was reported and Wake County where 1.75 inch diameter was observed.



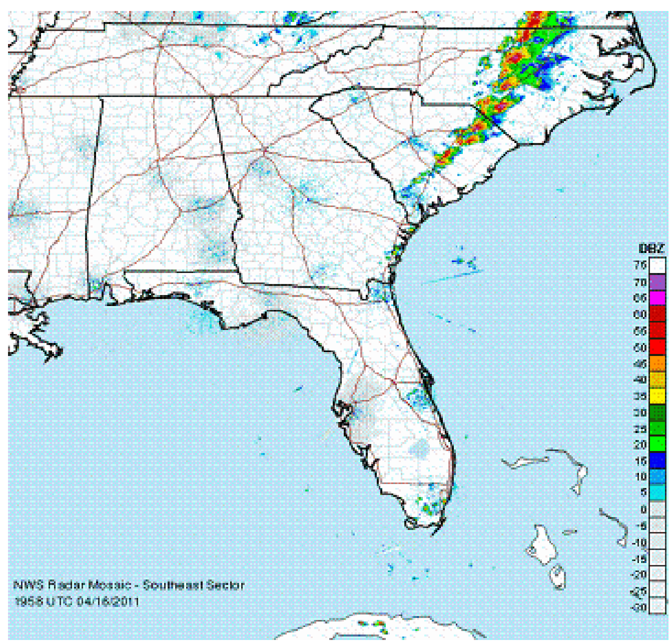
The image above and to the right is a zoomed in view of the hail swath product across central and eastern portions of the RAH CWA with the tracks of the tornadoes that occurred in central North Carolina shown in black (click on it to enlarge). In general, the radar estimated hail swaths were located to the north and west of tornado track which is consistent with a conceptual model of a tornado producing supercell thunderstorm.

NSSL Hail Swath product from 1200 to 2358 UTC on 16 April 2011 for viewing in Google Earth.

More information on the MESH is available from the *Verification of multi-sensor, multi-radar hail diagnosis techniques* by Kiel L. Ortega, Travis M. Smith, and Gregory J. Stumpf.

Regional Radar Loop

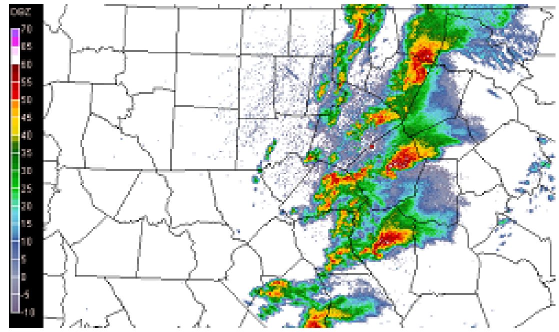
A regional radar loop of the southeastern United States shows the evolution of the 16 April 2011 tornado event. A fairly large area of showers moved through western portions of central North Carolina just prior to and around the time of daybreak. The widely scattered showers and a few thunderstorms that developed and moved across central and eastern North Carolina between 1330 and 1600 UTC generally weakened as they moved northeast. During the same period, a narrow line of thunderstorms developed in western Carolinas and reached the I-77 corridor in North Carolina by around 1600 UTC. The thunderstorms continued to intensify between 1600 and 1730 UTC and grew into a fairly continuous convective line. Note that the isolated thunderstorms ahead of the line in northeastern South Carolina and south-central North Carolina developed quickly and then rapidly weakened leaving little in the way of discrete convection ahead of the line. Between 1730 and 2000 UTC the line fractured and several discrete supercells emerged. These discrete thunderstorms would be responsible for the majority of the tornadoes on 16 April.

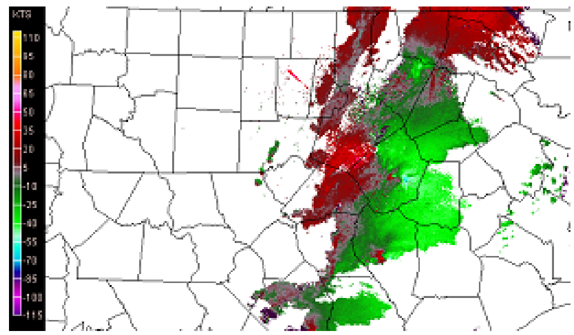


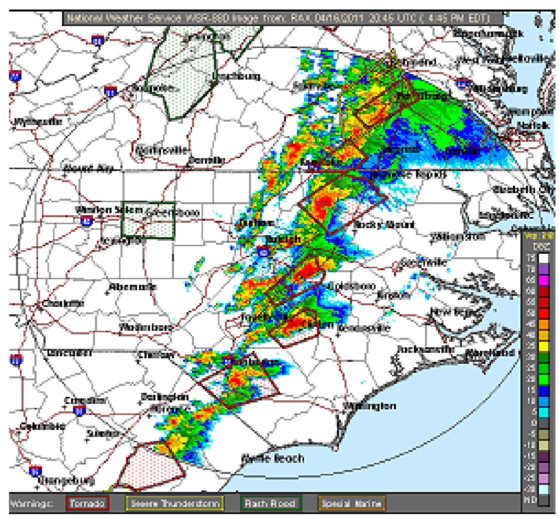
The regional reflectivity image to the right (click to on this link to enlarge) is from 1958 UTC on 16 April 2011 and shows several supercells moving across central and eastern North Carolina.

KRAX Radar Loops

The KRAX reflectivity, storm relative velocity, and reflectivity with warning polygon images to the right are from 2045 UTC on 16 April 2011 when four supercell thunderstorms were moving across central and eastern North Carolina. The 3 different images to the right correspond to the 3 different types of imagery available in the various loops below.







Note the clear hook signature on the thunderstorms near Clinton and northwest of Goldsboro. Three of the supercells were located in the WFO RAH CWA at this time, with one supercell producing an EF-2 tornado in Sampson County at the time of this radar image. Another supercell which produced the Fayetteville-Smithfield tornado would produce a second tornado near Micro about 10 minutes after this radar image was generated. The supercell that had produced the Sanford-Raleigh tornado was located over northeastern Franklin and southern Warren Counties at the time of this radar image. This same supercell would produce the Roanoke Rapids tornado about 25 minutes after this radar image was produced.

Overview of the event with KRAX reflectivity imagery from every volume scan between 1603 UTC and 2154 UTC on 16 April 2011 is available in this **Java loop**. Note - this loop includes 78 frames

Overview of the event with KRAX storm relative velocity imagery from every volume scan between 1603 UTC and 2154 UTC on 16 April 2011 is available in this **Java loop**. Note - this loop includes 78 frames

Overview of the event with KRAX reflectivity imagery from every volume scan and warning polygons between 1603 UTC and 0058 UTC on 16 and 17 April 2011 is available in this **Java loop**. Note - this loop includes 114 frames

Overview of the event with KRAX reflectivity imagery from every 15 minutes and warning polygons between 1603 UTC and 0058 UTC on 16 and 17 April, 2011 is available in this **Java loop**. Note - this loop includes 37 frames

Mesoscale Data

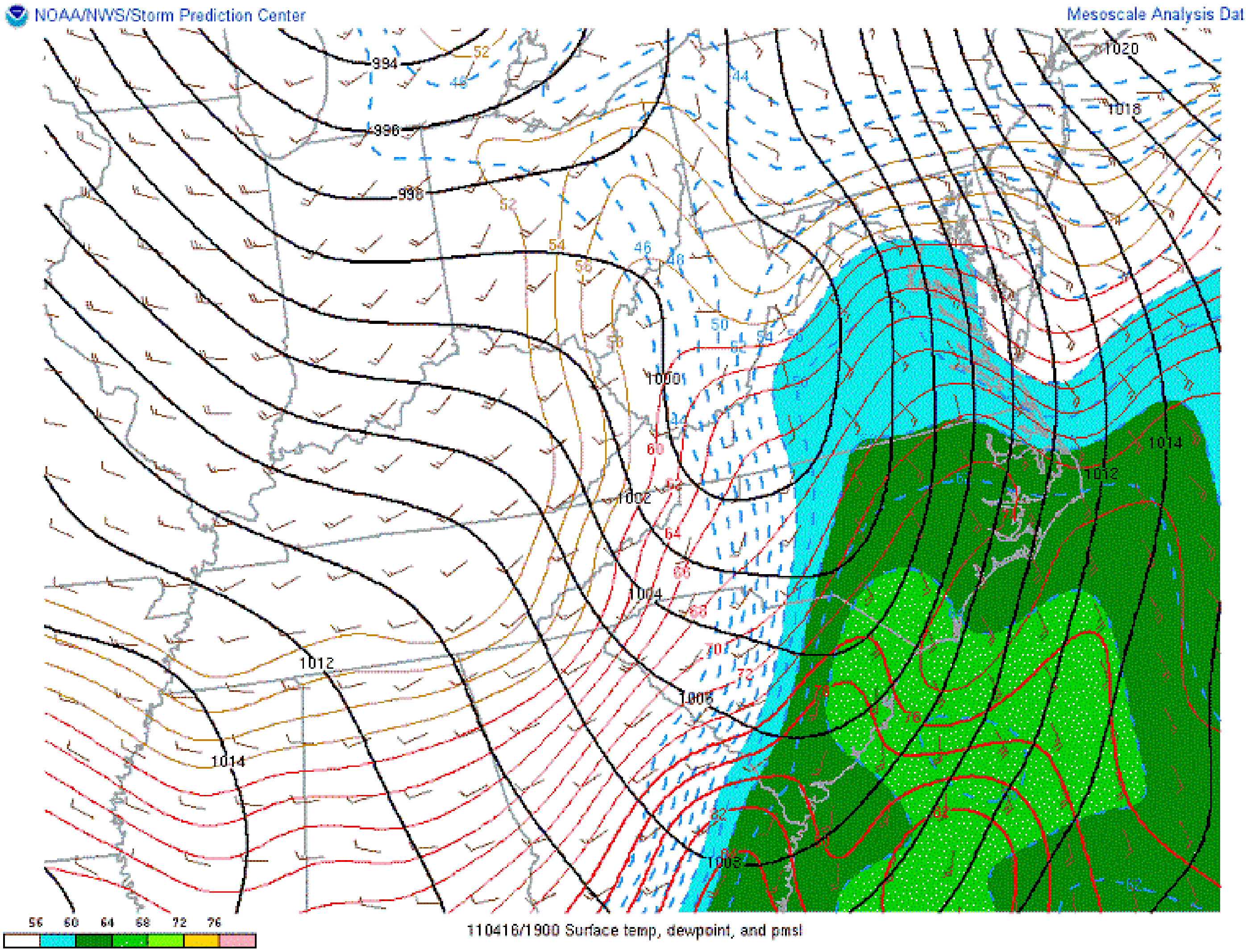
Forecasters at the NWS Raleigh, NC routinely use the SPC meso-analysis products during severe weather operations. During this event, the SPC meso-analysis products were consulted frequently to monitor the evolving environment, and locate the region of the greatest tornado threat. The images and discussion below highlight several of the SPC meso-analysis products that provide insight into the evolution of the severe weather event.

It should be noted that the SPC meso-analysis products are based on a combination of observed fields and RUC forecasts (which are used for the background field and upper-air data for the analysis). Each grid point of the analysis is then inputted into "NSHARP" to calculate the analysis fields. While these analysis products provide a great tool, it is important to note that the analysis can include errors, especially when evaluating fields in the storm scale.

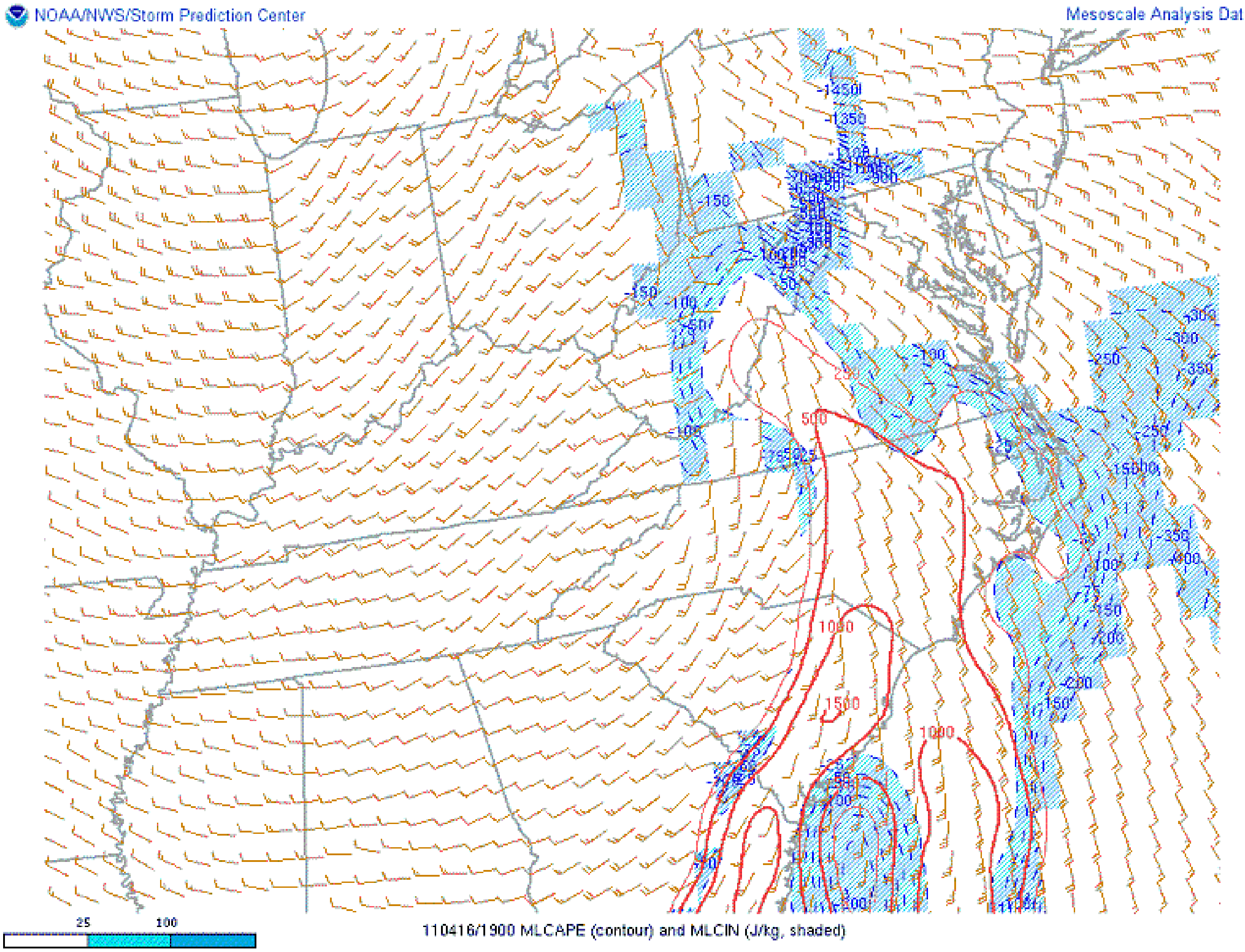
Analyzed MSLP (black) surface temperatures (red), dew points (blue) and shaded, and wind barbs from SPC at 1900 UTC 16 April 2011

The surface analysis showed a low pressure system over the northern Great Lakes with a strong cold front extending southward into the western Piedmont of the Carolinas. The cold front marked the leading edge of a cooler and much drier air mass with dew points falling into the 40s across the Foothills of North Carolina. A warm front extended from the cold front eastward along the Virginia-North Carolina border marking the leading edge of a more unstable air mass. A strong south-southeasterly surface flow was noted, likely enhanced by 2-3mb/2hr pressure falls along and ahead of the front.

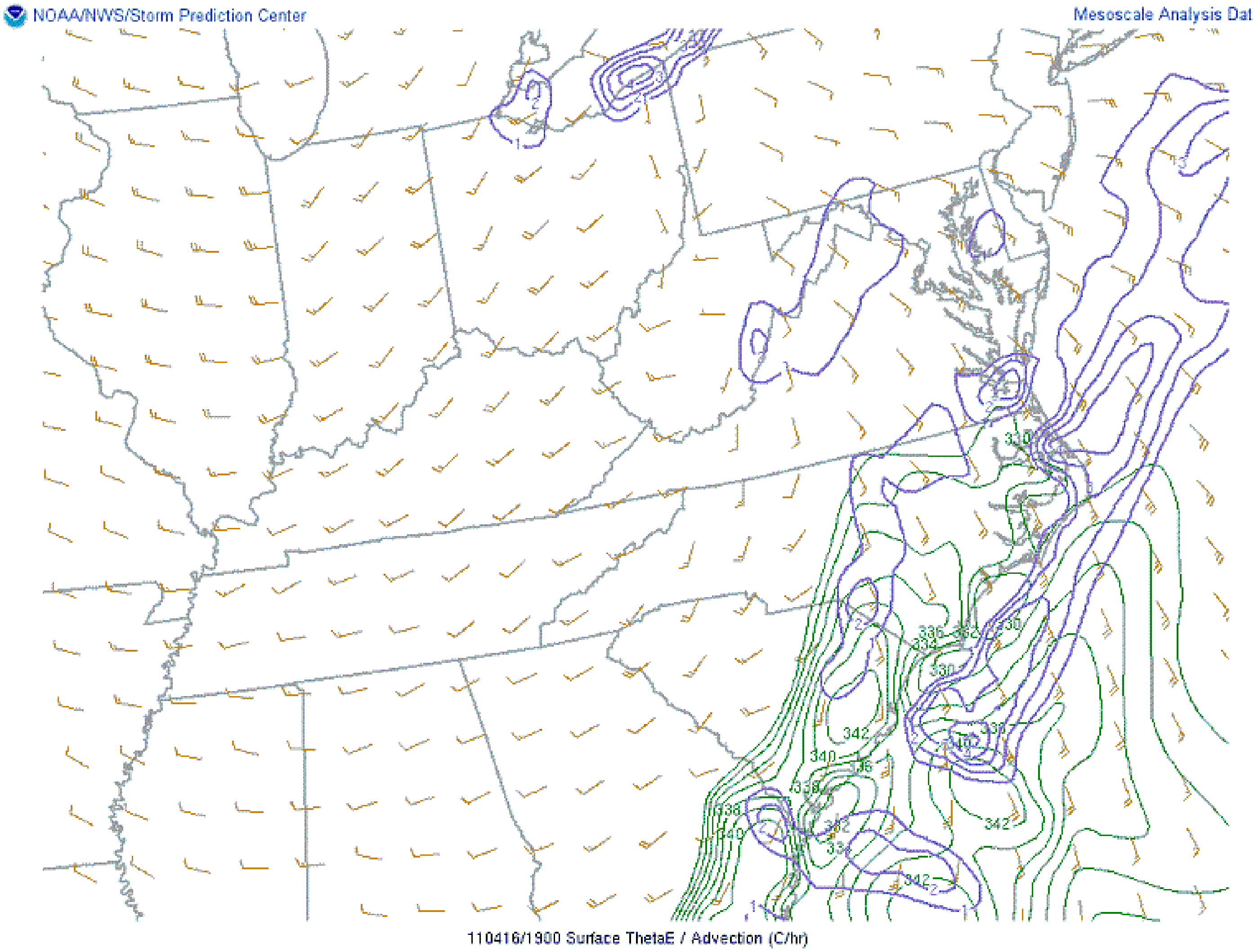
(Click on the image below to enlarge)



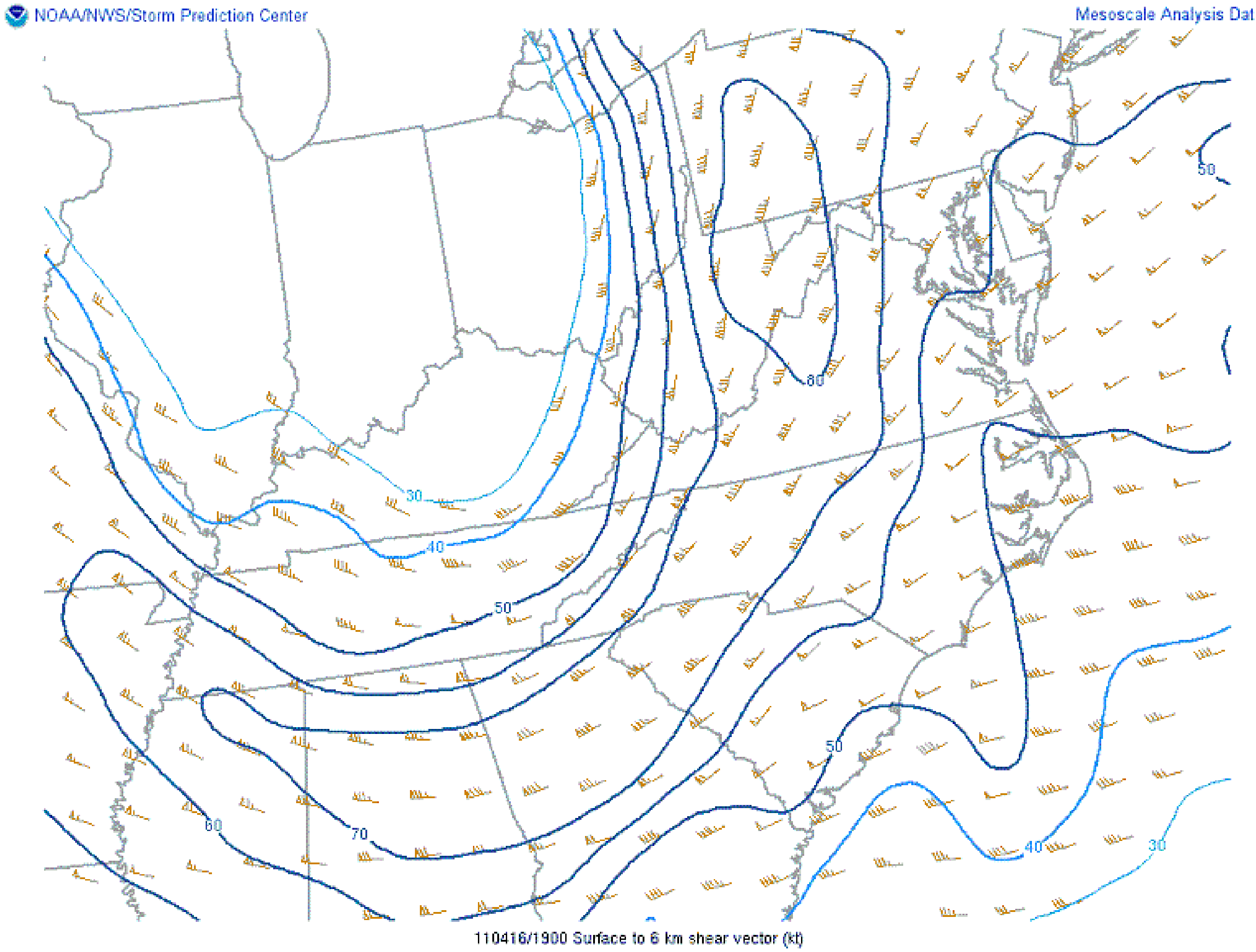
Analyzed Mixed Layer CAPE (red contours), and Mixed Layer CIN (shaded) from SPC at 1900 UTC 16 April 2011
By 1900 UTC, the atmosphere had become more unstable across central North Carolina. The Mixed Layer CAPE analysis indicated MLCAPE values ranging between 500 J/kg and 1000 J/kg across the eastern Piedmont, Coastal Plain, and Sandhills region. Just four hours earlier, MLCAPE values analyzed at 1500 UTC were less than 250 J/kg across most of the same region with just a small area of MLCAPE greater than 250 J/kg noted across the southern Piedmont. The analyzed 3-hour MLCAPE change product indicated that the MLCAPE values had increased between 200 J/kg and 400 J/kg during the 3-hour period ending at 1900 UTC.
(Click on the image below to enlarge)



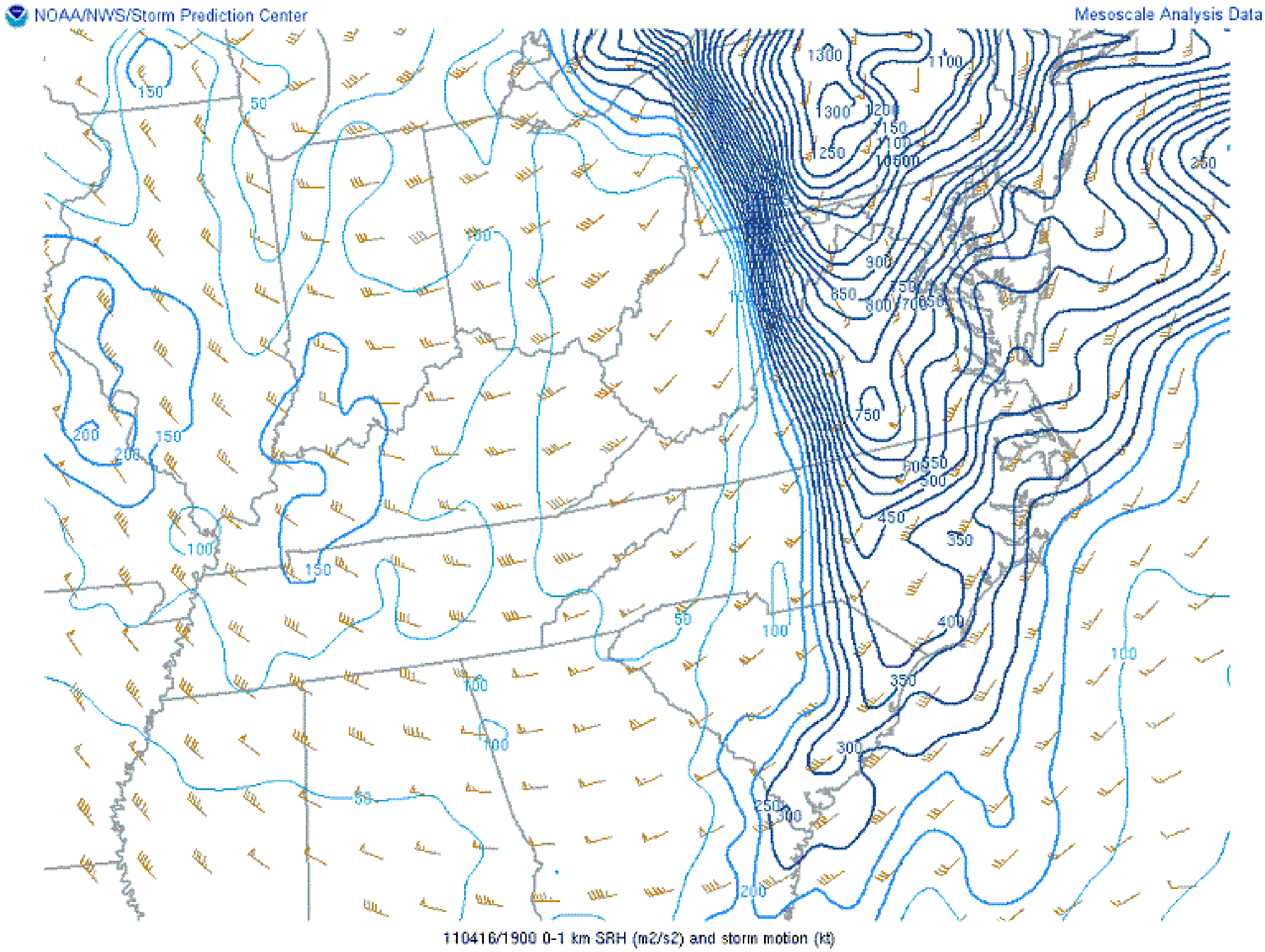
Analyzed surface Theta-e (green contours), Theta-e convergence (purple contours) and wind barbs from SPC at 1900 UTC 16 April 2011
At 1900 UTC, theta-e values ranged between 332-336 degrees K across the eastern Piedmont, Coastal Plain, and Sandhills region. The axis of greatest theta-e extended northward along and just ahead of the intensifying convection as shown in the 1858 UTC regional radar image.
(Click on the image below to enlarge)



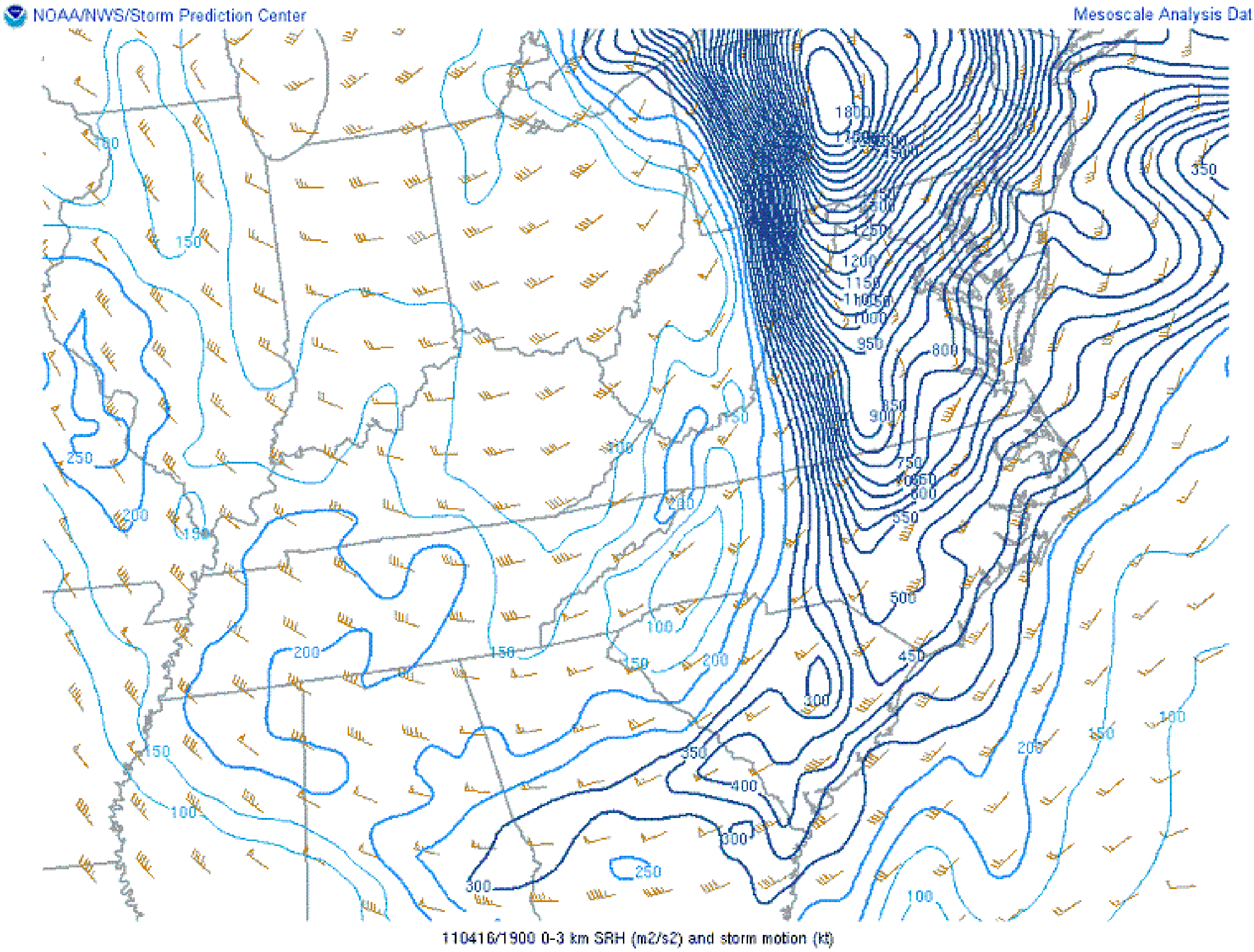
Analyzed surface to 6km Bulk Shear vectors from SPC at 1900 UTC 16 April 2011
The 0-6 km bulk shear values ranged between 50 and 70 kts across the eastern Piedmont, Coastal Plain, and Sandhills region. Given sufficient instability, thunderstorms tend to become more organized and persistent as vertical shear increases. Supercells are commonly associated with vertical shear values of 35 to 40 kts in this depth and the analysis at 1900 UTC supports the potential of supercells. It is interesting to note that when the convection developed a few hours earlier at 1600 UTC, it was more linear despite being in a region of similar bulk shear.
(Click on the image below to enlarge)



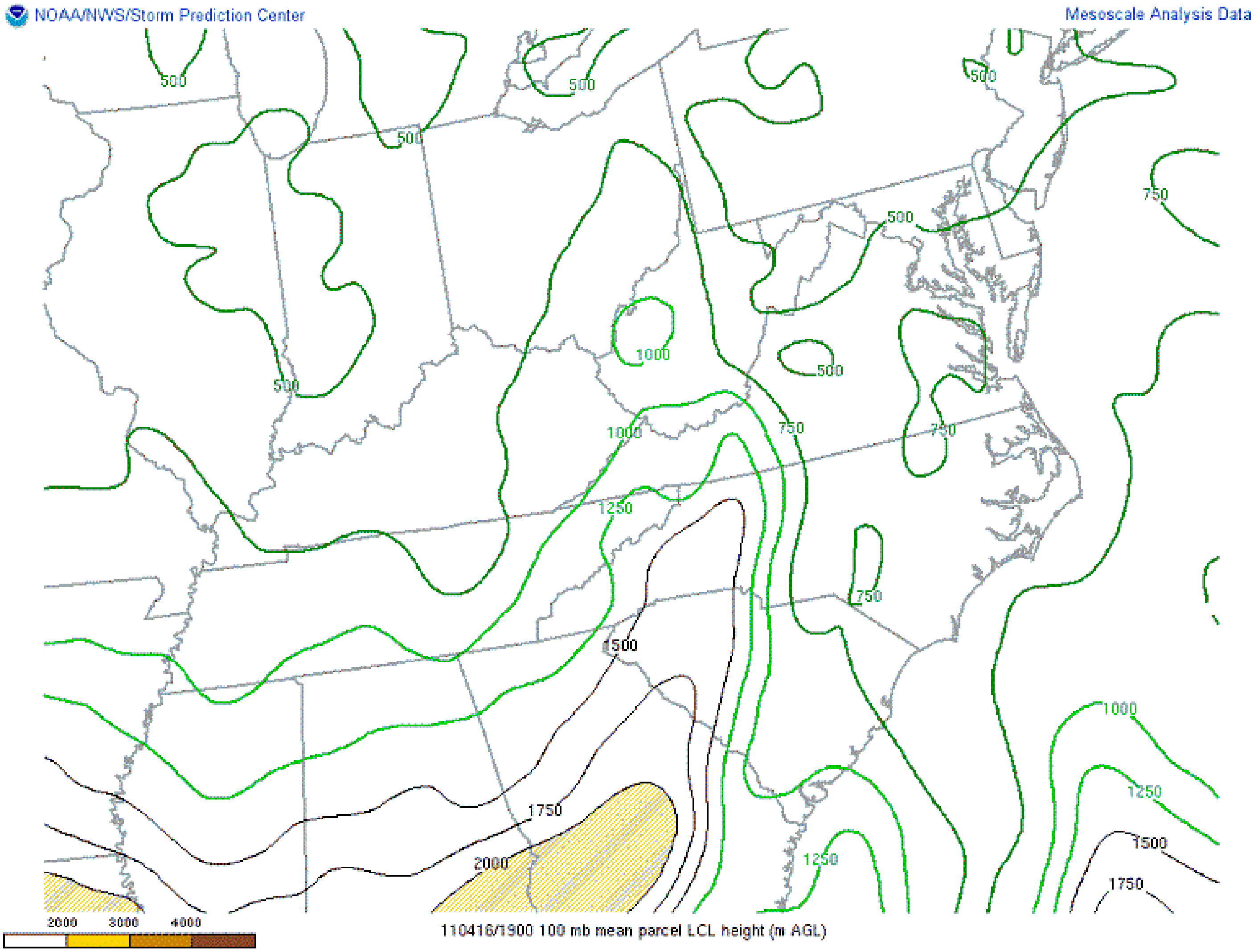
0-1 km Storm Relative Helicity (blue) and storm motion (brown) from SPC at 1900 UTC 16 April 2011
The 0-1 km Storm Relative Helicity (SRH) analysis was extreme with the axis of greatest SRH extending along and ahead of the cold front. The 0-1 km SRH values ranged from around 400 m^2/s^2 to 600 m^2/s^2. The SRH is a measure of the potential for cyclonic updraft rotation in right-moving supercells. Studies have shown that larger values of 0-1 km SRH, greater than 100 m^2/s^2, suggests an increased threat of tornadoes and that very large values of 0-1 km SRH (perhaps greater than 200 to 300 m^2/s^2) are indicative of significant tornado potential. Examining the storm motion after the event revealed a mean motion of near 230 degrees at 45 kts which was faster than the SPC analysis estimate and suggests that the 0-1 SRH values could be underdone by 200-400 m^2/s^2.
(Click on the image below to enlarge)



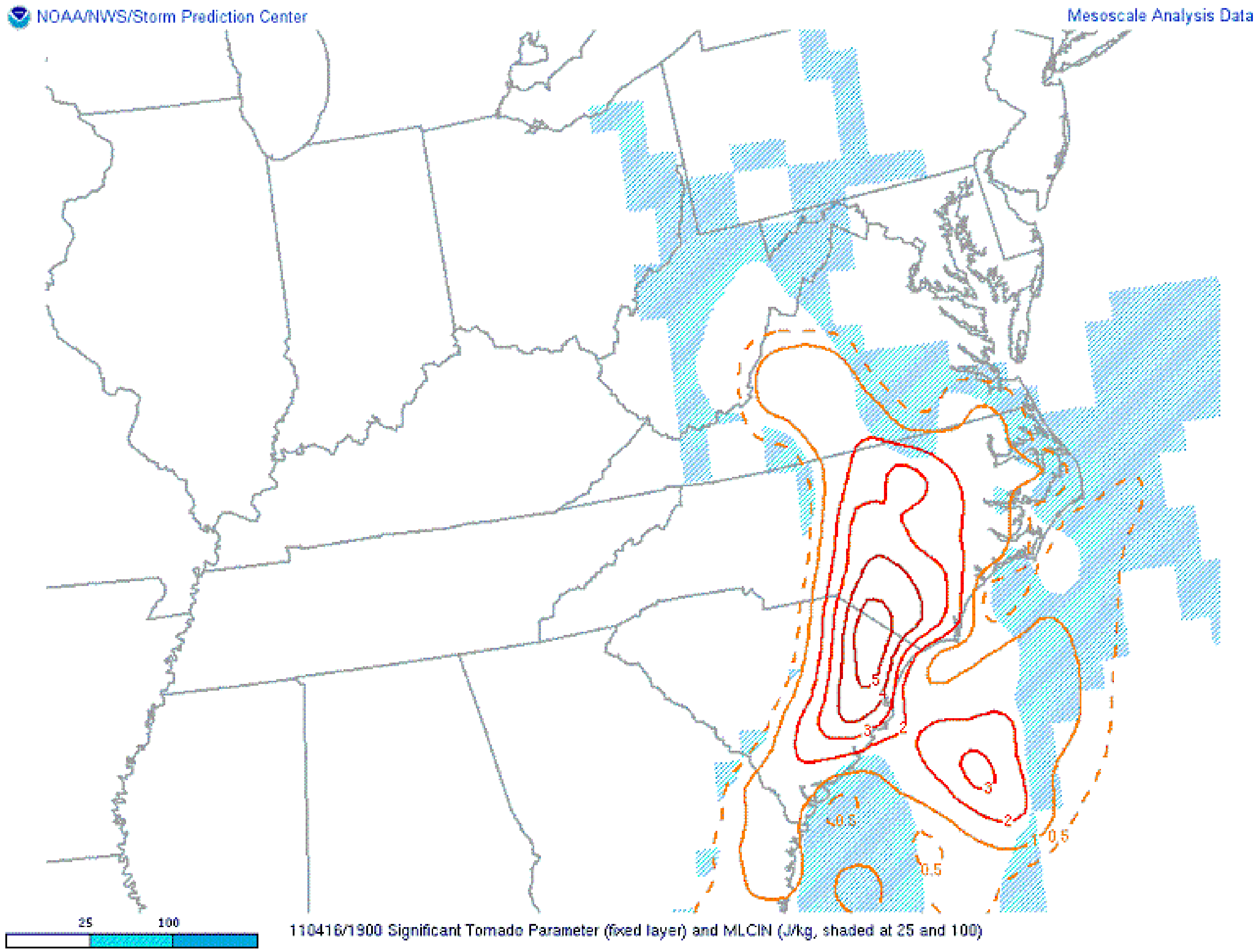
0-3 km Storm Relative Helicity (SRH) (shown in blue) and storm motion (brown) from SPC at 1900 UTC 16 April 2011
The 0-3 km Storm Relative Helicity (SRH) analysis was extreme with SRH values ranging between 500-800 m^2/s^2 across the eastern Piedmont, Coastal Plain, and Sandhills region. The SRH is a measure of the potential for cyclonic updraft rotation in right-moving supercells. Larger values of 0-3 km SRH (greater than 250 m^2/s^2) suggest an increased threat of supercells and tornadoes. Some studies suggest that the 0-3 km SRH is a better indicator of storm rotation, which is related to tornadoes, but not directly the potential for tornadoes themselves.
(Click on the image below to enlarge)



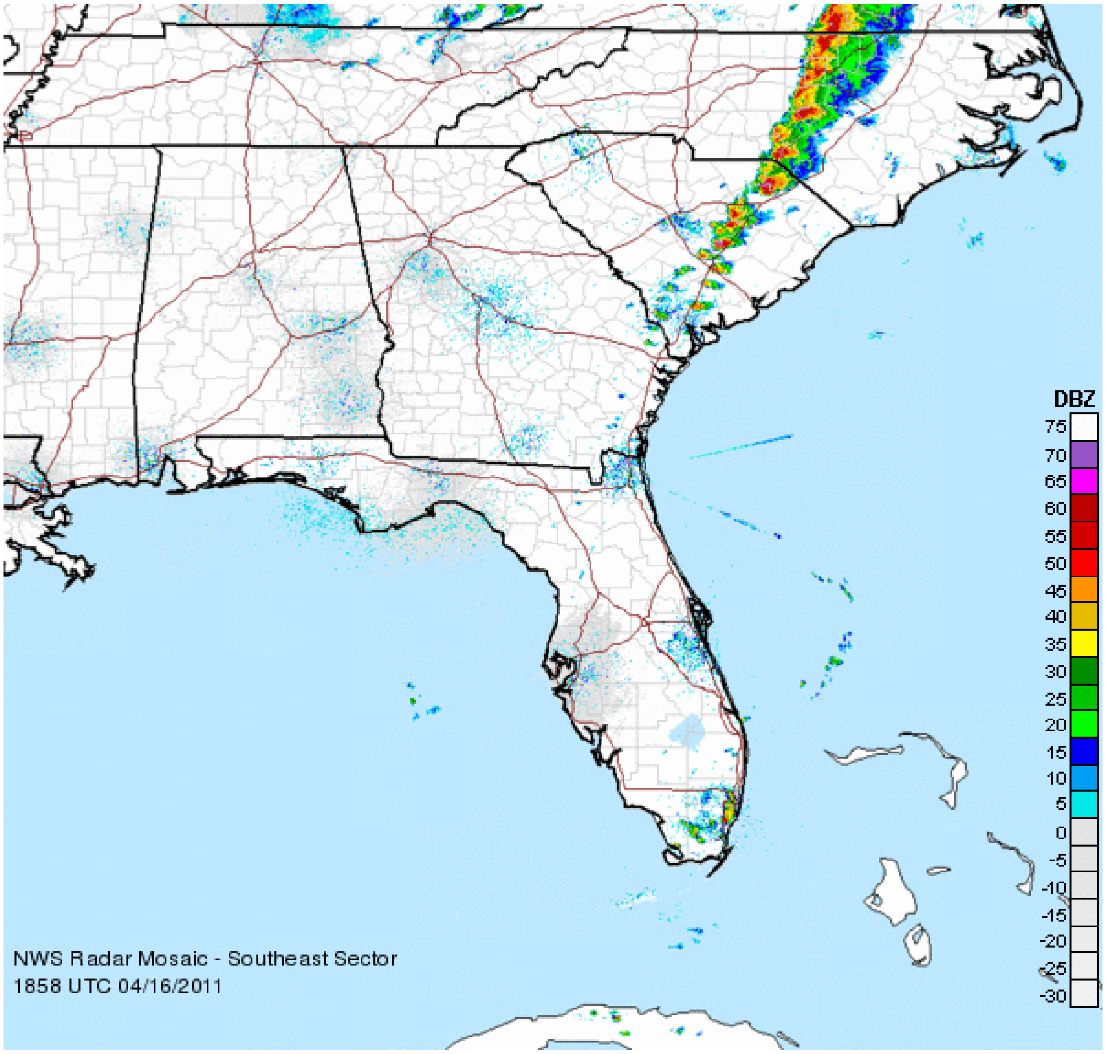
Analyzed Lifting Condensation Level (red, blue, and green) from SPC at 1900 UTC 16 April 2011
The LCL values across central and eastern North Carolina ranged between 750 and 1,000 meters at 1900 UTC. The LCL height is the height at which a parcel becomes saturated when lifted dry adiabatically. The importance of the LCL height is thought to relate to sub-cloud evaporation and the potential for outflow dominance. Low LCL heights imply less evaporational cooling from precipitation and less potential for a strong outflow that would likely inhibit low-level mesocyclone development. Thunderstorms that produce significant tornadoes generally have a lower LCL height with LCL heights less than 1,000 meters typically favoring the development of significant tornadoes.
(Click on the image below to enlarge)



Significant Tornado Parameter (red) with Mixed Layer CIN (shaded) from SPC at 1900 UTC 16 April 2011
The Significant Tornado Parameter (STP) is designed to highlight areas favoring right-moving tornadic supercells. The STP is a multiple ingredient, composite index that includes effective bulk wind difference (EBWD), effective storm-relative helicity (ESRH), 100-mb mean parcel CAPE (MLCAPE), 100-mb mean parcel CIN (MLCIN), and 100-mb mean parcel LCL height (MLLCL). Analyzed STP values across the eastern Piedmont, Coastal Plain, and Sandhills region ranged between 2 and 5 units with a max of more than 4 across the southern Coastal Plain and the eastern Sandhills. A majority of significant tornadoes (EF-2 or greater damage) have been associated with STP values greater than 1, while most non-tornadic supercells have been associated with values less than 1 in a large sample of RUC analysis proximity soundings. Additional details on the Analyzed Significant Tornado Parameter (STP) is available in this reference.
(Click on the image below to enlarge)



NWS composite radar reflectivity imagery from 1858 UTC 16 April 2011
The regional composite reflectivity imagery is from the approximate time in which the analysis imagery above is valid.



Archived Text Data from the Severe Weather Event

Select the desired product along with the date and click "Get Archive Data."
Date and time should be selected based on issuance time in GMT (Greenwich Mean Time which equals EST time + 4 hours).

Product ID information for the most frequently used products...

RDUAFDRAH - Area Forecast Discussion
RDUZFPRAH - Zone Forecast Products
RDUAFMRAH - Area Forecast Matrices
RDUPFMRAH - Point Forecast Matrices
RDUHWORAH - Hazardous Weather Outlook
RDUNOWRAH - Short Term Forecast
RDUSPSRAH - Special Weather Statement
RDULSRRAH - Local Storm Reports (reports of severe weather)
RDUSVRRAH - Severe Thunderstorm Warning
RDUSVSRAH - Severe Weather Statement
RDUTORRAH - Tornado Warning

* Scroll down for list from April 16 2011

Get Archive Data

Lessons Learned and Final Thoughts

Tornado events of this magnitude are very rare in North Carolina. The 16 April 2011 outbreak was comprised of 30 tornadoes including five EF-3 and eight EF-2 tornadoes and resulted in 24 fatalities. The 28 March 1984 Tornado Outbreak is the only precedent during the 20th or 21st century of an event of this size, intensity, destruction, and fatalities.

The threat of severe weather on Saturday was well advertised for several days in advance.
- First AFD to mention the potential for severe thunderstorms was 315 AM Tuesday, 12 April.
- First HWO to mention the potential for strong thunderstorms was 601 AM Tuesday, 12 April.
- First HWO to mention the potential for severe thunderstorms was 417 AM Wednesday, 13 April.
- First AFD to mention the potential for a tornado was 255 PM Wednesday, 13 April.
- First HWO to mention the threat of tornadoes was 308 PM Thursday, 14 April.

Staffing was planned out well in advance, and a preliminary discussion of likely operational roles the day prior to the event, helped with a rapid spin-up on Saturday morning. The work load was generally divided as noted below:
- Three radar operators who all sat next to each other
- One storm coordinator that evolved into two storm coordinators during the height of the event
- One public gridded forecast database / aviation forecaster
- Three verification / phone communication staff members who focused on intelligence gathering. Of these three, one staff member assisted with the forecast databases and radar interrogation while another staff member monitored hydrologic conditions
- Two SKYWARN radio operators helped out with storm reports

This event provided some interesting examples of the recent advances in meteorology while illustrating some new opportunities for additional research. First, high resolution (NWP) provided excellent forecasts indicating the timing and location of the squall line, the absence of discrete cells ahead of the squall line, and then the evolution of the squall line into discrete cells. Forecasters made very good use of pattern recognition ahead of the event along with storm scale conceptual models and warning polygon strategies. Future work can further examine the uniqueness of the event noting the importance of low level moisture and shear in the processes which allowed a squall line to fragment in to multiple discrete supercells and examine total lightning trends with the long track tornadoes. This event will also be included in a comprehensive climatology of modern day tornadoes in central North Carolina.

The Blacksburg NWS office provided quick-response backup for the Raleigh office for around 6 or 7 minutes as Raleigh staff members took shelter in the stairwell tornado shelter. Blacksburg provided excellent service.

In situations with long lived supercells, a strategy of each radar operator following a particular supercell for the duration of its life cycle in central North Carolina once again proved to be effective. This strategy has also been employed successfully in previous tornadic events.

Relaying information to customers, particularly the media through the use of NWSChat was highly effective in this event. We were able to communicate reasons for issuing or continuing warnings and share preliminary damage reports before all of the details were resolved and an LSR was sent. We also received numerous reports from the media and emergency management. Monitoring local television stations from both Greensboro and Raleigh during the event revealed that in numerous instances, our information sent via chat was being delivered in some form by the media on-air.

During times of extreme severe weather, normal communication means can be hampered. The use of SKYWARN spotters, amateur radio operators and the more recent additions of NWSChat, POP, and CoCoRaHS were extremely important to in severe weather operations. Two Central Carolina SKYWARN amateur radio operators were staffed at the NWS Raleigh during event and collected 96 reports from 57 different spotters during the event. NWSChat users provided 14 separate reports of damage or severe weather. The Public Observation Program (POP), which allows the public to call and leave reports of severe weather on a computer system, provided 28 separate reports of hail, funnel clouds, or tornadoes. CoCoRaHS observers provided 10 real time reports of heavy rain, hail, or tornado debris.

Numerous staff members were needed to conduct storm surveys or cover shifts for those conducting the surveys during the days following the event. Staffing was already stretched thin to support operations during the day of the severe weather and fatigue was a concern for the days following the event. Storm surveys were conducted or augmented by neighboring offices including the NWS Blacksburg and Wilmington offices as well as the NWS Eastern Region Headquarters. This team worked well together to provide good post-event information out to our customers.

Recent advances in Numerical Weather Prediction (NWP) and in computational efficiency have resulted in an improvement in and the availability of high resolution model forecasts on the convective scale. These products did a good job in this event noting that the linear convective structure would evolve into discrete cells and that there would be very few discrete cells developing ahead of the line.

All of the fatalities in central North Carolina occurred in mobile homes or in a vehicle. There were no fatalities in permanent homes or structures despite the significant damage produced by the storm.

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Acknowledgements

Many of the images and graphics used in this review were provided by parties outside of the NWS Raleigh. The surface analysis graphics were obtained from the Hydrometeorological Prediction Center. The SPC meso-analysis graphics provided by the Storm Prediction Center. NSSL's Rotational Track product and the Hail Swath Product were provided by the WDSS-II (Warning Decision Support System - Integrated Information) group at NSSL. Local storm reports and warning polygons KMZ data provided by the National Climatic Data Center. Long track tornado maps and high risk outlook information provided by the SPC. Dr Tom Allen from East Carolina University provided a tornado track density map. Tornado emergency television snapshot provided by WTVD. Google Earth map imagery used under license. Archived HRRR imagery provided by Stan Benjamin. The city of Raleigh provided high resolution damage assessment imagery. Dr Matt Parker from North Carolina State University provided the regional radar and surface analysis images.

Case Study Team

Nearly every NWS Raleigh staff member contributed to this event summary in some way either through participating in the storm surveys, providing input on lessons learned, archiving the data or otherwise. More significant contributions to the summary were provided by several staff members including:
Terry Click
Darin Figurskey
Gail Hartfield
Bradley McLamb
Jeff Orrock
Scott Sharp
Barrett Smith
Brandon Vincent
Jonathan Blaes
In addition, two N.C. State student volunteers, Rachel Wrenn and Lindsey Andersen contributed to the summary.