The 16 April 2011 EF3 Tornado in Greene County, Eastern North Carolina

THOMAS M. RICKENBACH
East Carolina University

This paper presents a case study of an EF3 tornado that adversely impacted Greene and Pitt Counties in eastern North Carolina on 16 April 2011. This was one of the most damaging and longest-lived of the multiple tornados that occurred across central and eastern North Carolina that day, the most extensive outbreak in North Carolina since 1984. This event occurred during the month (April 2011) with the largest number of tornadoes on record in the United States. The focus of this case study was to examine the relationship between the mesocyclone evolution and the location and intensity of surface damage associated with the EF3 tornado. Results indicated that the initial contraction and spin up of the mesocyclone circulation preceded EF3 damage by about 20 minutes. At the time of mesocyclone intensification, the damage swath and tornado were situated much closer to the mesocyclone center than in the formative and dissipating stages. The weakened mesocyclone passed directly over a meteorological station at East Carolina University's West Research Campus, providing a rare opportunity for surface measurements associated with a weakening tornadic mesocyclone.

Este trabajo presenta un estudio de caso de un tornado EF3 que impactó negativamente los condados de Greene y Pitt en el este de Carolina del Norte el 16 de abril de 2011. Este fue uno de los más dañinos y de más larga duración de los múltiples tornados que se produjeron en el centro y el este de Carolina del Norte ese mismo día, el brote más extenso en Carolina del Norte desde 1984. Este evento tuvo lugar durante el mes (abril de 2011) con el mayor número de tornados en el registro en los Estados Unidos. El objetivo de este estudio fue examinar la relación entre la evolución del mesociclón y la ubicación e intensidad de los daños en la superficie asociados con el tornado EF3. Los resultados indicaron que la contracción inicial y el giro de la circulación del mesociclón precedió los daños del EF3 por unos 20 minutos. Al momento de intensificación del mesociclón, la franja de daños y el tornado se encontraban mucho más cerca del centro del mesociclón que en las etapas de formación y disipación. El mesocicón debilitado pasó directamente sobre una estación meteorológica del West Research Campus de East Carolina University, proporcionando una oportunidad única para las mediciones de la superficie asociada con un debilitamiento del mesociclón de tornados.

KEY WORDS: severe weather, North Carolina, radar, tornado

PALABRAS CLAVES: mal tiempo, Carolina del Norte, radar, tornado

INTRODUCTION

On the afternoon and early evening of 16 April 2011, a significant tornado outbreak affected much of central and eastern North Carolina, producing fatalities as

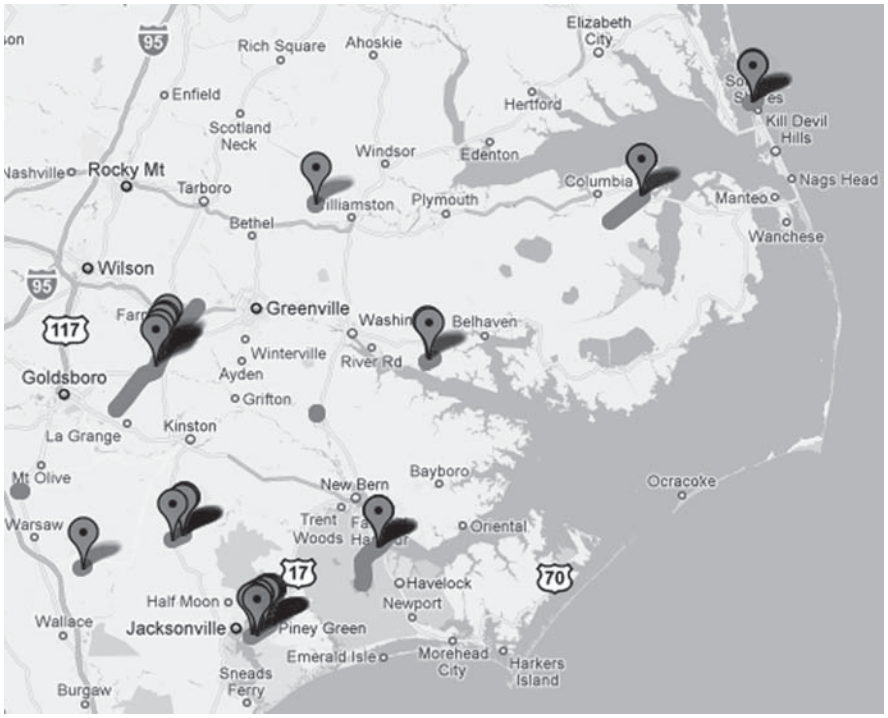

Figure 1. Location and tracks of confirmed tornadoes on 16 April 2011 within the NWS Newport/Morehead City Office warning area (from NWSFO 2011).

well as extensive damage to structures and buildings across the region. This was the most damaging and widespread tornado outbreak since the 28 March 1984 event in central North Carolina, where such occurrences are much less frequent than in the Midwestern U.S. (Fujita and Steigler 1985; Gyakum and Barker 1988). The 16 April 2011 tornadoes in North Carolina were part of a larger-scale outbreak across the southeastern United States that resulted in 875 tornadoes for the month of April, the largest monthly total in the United States on record (Hoerling 2011). In particular the 25–28 April outbreak across several southeastern states, which included the Tuscaloosa, Alabama EF5 tornado, was the costliest tornado outbreak in the United States, with approximately 321 deaths and over $10 billion in damage (NOAA Extreme Weather summary 2011).

Twelve tornadoes were confirmed within the National Weather Service Newport/Morehead City office warning area on 16 April 2011 in eastern North Carolina, with additional tornadoes near Raleigh (NWSFO 2011). The tornado outbreak in eastern North Carolina occurred within a 230 km long swath extending southwest to northeast from Mt. Olive in Duplin County to Duck in Dare County along the Outer Banks (Figure 1). The most significant of these in terms of damage and duration occurred in Greene County near the town of

Snow Hill (between Goldsboro and Greenville), with an enhanced Fujita scale (EF) intensity rating (McDonald 2002) of EF3. This tornado destroyed several businesses and homes, and severely damaged several schools in Greene County as it traversed a 29 km path of up to 300 m in width. The National Weather Service (NWSFO 2011) estimated that maximum wind speeds associated with the Snow Hill tornado inferred from structural damage reached 67–72 m s^{-1} (150–160 miles hr^{-1}). Approximately one hour following the damage in Greene County, the same supercell thunderstorm produced another tornado that resulted in twelve confirmed deaths north of Williamston (Figure 1), about 65 km northeast of Snow Hill (NWS Tornado Damage Survey 2011).

The challenge in tornado forecasting generally is that not all mesocyclones, the parent circulation within most tornadic supercell thunderstorms, produce tornadoes (Donaldson and Desrochers 1990; Burgess et al. 1993). Trapp et al. (2005) found that only 26 percent of mesocyclones in their sample, objectively identified with the NEXt-generation RADar (NEXRAD), were tornadic. About half of the subset of mesocyclones that are strong and long-lived fail to produce tornadoes, underscoring the unresolved forecast problem of unambiguously inferring the presence of a tornado from the NEXRAD-observed mesocyclone (Brooks et al. 1994; Trapp 1999). Moreover, the intensity of the mesocyclone circulation seen by the NEXRADs is not a unique surrogate for the presence, strength, or precise location of an embedded tornado circulation (Wakimoto et al. 2003). It is therefore important to examine those characteristics of NEXRAD-observed mesocyclones that are linked to verified tornado sightings with known damage attributes. This is particularly important for this case because EF3 tornadoes are much less common in eastern North Carolina compared to the well-studied Great Plains of the United States (Rasmussen et al. 1994; Trapp et al. 2005).

This paper presents a case study of the 16 April 2011 EF3 tornado near Snow Hill, North Carolina. The radar reflectivity and radial velocity data from the Morehead City NEXRAD is described first, which forms the basis for the analysis. Next an overview is given of the large-scale meteorological conditions on the day of the outbreak. Results are then presented from an analysis of the radar-observed mesocyclone evolution in the context of the location of verified tornado sightings and damage, prior to, during, and following the tornado event. The study connects damage reports and photographic observations of the weakening EF3 tornado to the evolving radar reflectivity and radial velocity structure of the parent mesocyclone in Greene and Pitt counties, North Carolina on 16 April 2011. Finally, surface meteorological observations at the East Carolina University (ECU) West Research Campus (WRC) provide a rare opportunity to document the weakening stage of the tornadic mesocyclone, which passed very near the WRC site.

DATA AND METHODS

This work is based primarily on analysis of radar reflectivity and radial velocity data from the NEXRAD radar located in Morehead City, North Carolina (station identifier KMHX) approximately 100 km southeast of the Greene County tornado on 16 April 2011. At the time of the tornado, the KMHX NEXRAD was collecting data at 17 elevation angles every five minutes with a resolution of 0.5° in azimuth and 0.25 km along each radial (in super-resolution mode, Torres and Curtis 2007). For this study, level II NEXRAD data were ingested, visualized and analyzed using the National Climatic Data Center's Weather and Climate Toolkit (NCDC WCT; Ansari et al. 2009). The radar data was exported from the NCDC WCT to ArcGIS (Geographic Information Systems) format, which allowed for a more detailed visualization of structural features of the supercell and mesocyclone with respect to the location of road networks, structures, and towns. From 2116 to 2214 UTC (1716 to 1814 local time), thirteen radar volume scans separated in time by approximately five minutes sampled the tornadic supercell as it moved from near Goldsboro in Wayne County to just west of Greenville in Pitt County, a distance of about 50 km.

The supercell and mesocyclone structure was examined from each radar volume scan at the lowest elevation angle (0.48°, or about 1.7 km above the surface based on the nominal range of the supercell from the radar). For each scan, the following attributes of the supercell and mesocyclone structure were determined: maximum reflectivity in the supercell, qualitative structure features of the supercell reflectivity pattern, the location, speed, and direction of mesocyclone center, strongest radial velocity values in the mesocyclone, and the mesocyclone diameter. Storm-relative maxima in the mesocyclone radial velocity were determined by first dealiasing (unfolding) the velocity values exceeding the Nyquist interval of 29.65 m s^{-1} (57.6 kt), and then subtracting the component of storm motion along the radar beam from each velocity maximum. Storm motion was estimated by tracking the center of the mesocyclone circulation as indicated in the radial velocity field at the lowest elevation angle. The diameter of the mesocyclone was defined as the horizontal distance between the velocity maxima through the mesocyclone center.

The NWS issued a preliminary assessment of the tornado track and EF rating along with a general description of the damage extent and location across Greene and Pitt counties (NWSFO 2011). A detailed map indicating the Greene County tax parcels with tornado damage was obtained from the Greene County Tax Office following their independent damage assessment (http://www.co.greene.nc.us). Guided by these reports, the author conducted an informal damage survey to ascertain the start and end points of the damage swath from northern Wayne County near Goldsboro to southern Pitt County west of Greenville. This information was integrated to form the basis for the damage locations and EF ratings discussed later in the paper. Photographic evidence of the EF3 tornado in the town of Snow Hill came from video taken by an emergency medical technician from outside the Greene County Emergency Services Building. The video was shot from a vantage point approximately 1 km east-southeast of the tornado at the time it produced the most extensive damage associated with the entire event.

The Department of Geography at East Carolina University (ECU) maintains an automated weather station at the ECU West Research Campus in central Pitt County. The station provides wind measurements on a 10 m tower located in an unobstructed open field, as well as other standard surface

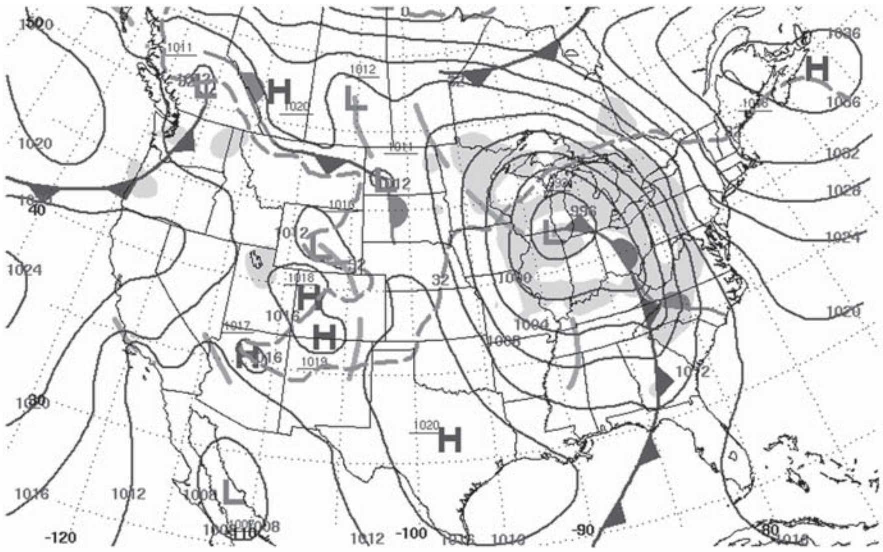

Figure 2. National Weather Service surface analysis on 16 April 2011 1200 UTC, the morning of the tornado event. Surface map shows pressure (mb, solid lines) and frontal locations. Source: http://www.hpc.ncep.noaa.gov/dailywxmap/index.html.

meteorological parameters such as pressure, temperature, precipitation, relative humidity, and solar radiation. All parameters were sampled at 0.1 Hz and averaged over a five-minute period. The mesocyclone center passed within 1 km of the WRC station about 5 minutes following the last observed EF0 damage associated with the tornado. These data will be discussed in Section 6.

SYNOPTIC SETTING

On 16 April 2011 the eastern third of the United States was under the influence of a large extratropical cyclone. The surface and upper air situation on the morning of the tornado event is presented in Figures 2 and 3. At 1200 UTC a low pressure center $<$ 996 mb was located over the Great Lakes with a strong cold front extending south through Ohio, the Virginias and Carolinas and down through Georgia and the Florida panhandle. A warm front extended eastward from a developing region of low pressure in western Virginia, extending across North Carolina and moving slowly northward. The 1200 UTC upper air chart representing the height of the 500 mb pressure surface showed a deep trough extending southward along the Mississippi Valley to the west of North Carolina. The 17 April 0000 UTC sounding at Morehead City (Figure 4), during the tornado outbreak, indicated 28 m s^{-1} (55 kt) shear between the surface and 2 km with southerly winds veering to southwesterly in that layer. The sounding indicated an environment of strong instability with values of convective available potential en-

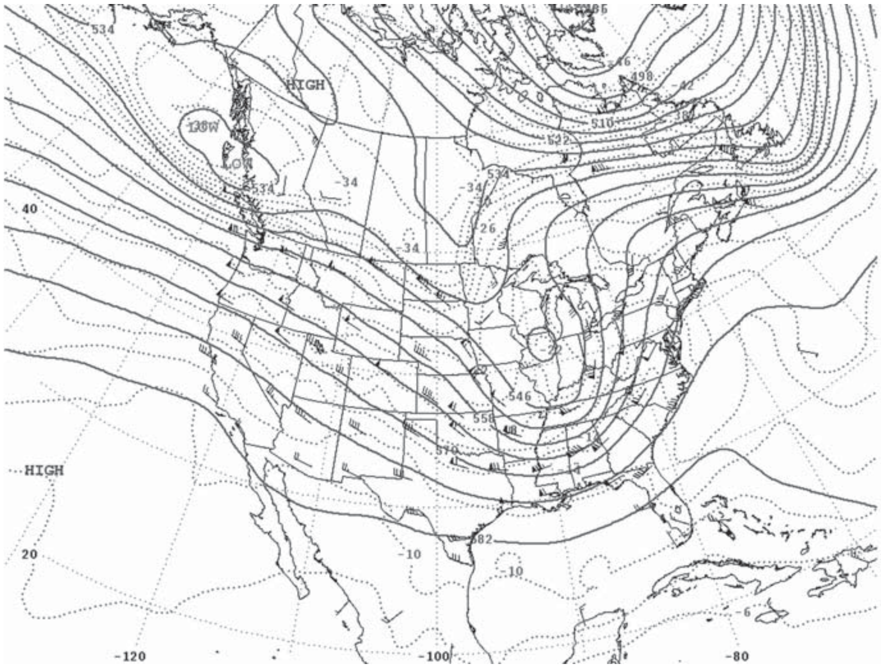

Figure 3. National Weather Service 500 mb upper air analysis on 16 April 2011 1200 UTC, the morning of the tornado event. Map gives 500 mb height (0.1 x m, solid lines), wind vectors, and temperature (oC, dotted lines). Source: http://www.hpc.ncep.noaa.gov/dailywxmap/index.html.

ergy (CAPE) in excess of 2300 J kg^{-1}. Taken together, the large-scale environment was conducive to the formation of potentially tornadic supercell thunderstorms across central and eastern North Carolina.

Accordingly, at 1600 UTC on 16 April 2011 The National Weather Service Storm Prediction Center placed the eastern two-thirds of North Carolina, southern Virginia, and eastern South Carolina under a tornado watch, emphasizing the potential for EF2 or greater tornadoes in that region. By 1930 UTC, radar indicated a northeast to southwest oriented line of 4–5 supercell thunderstorms across central North Carolina (Figure 5) moving eastward ahead of the advancing cold front.

SUPERCELL EVOLUTION AND DAMAGE SWATH

This section outlines the evolving radar reflectivity and radial velocity structure of the supercell thunderstorm that produced the EF3 tornado in central Greene County, eastern North Carolina. The analysis covers the period from 2126 UTC to 2214 UTC during which time the supercell exited eastern Wayne County, traversed Greene County, and entered southwestern Pitt County. This analysis emphasizes the

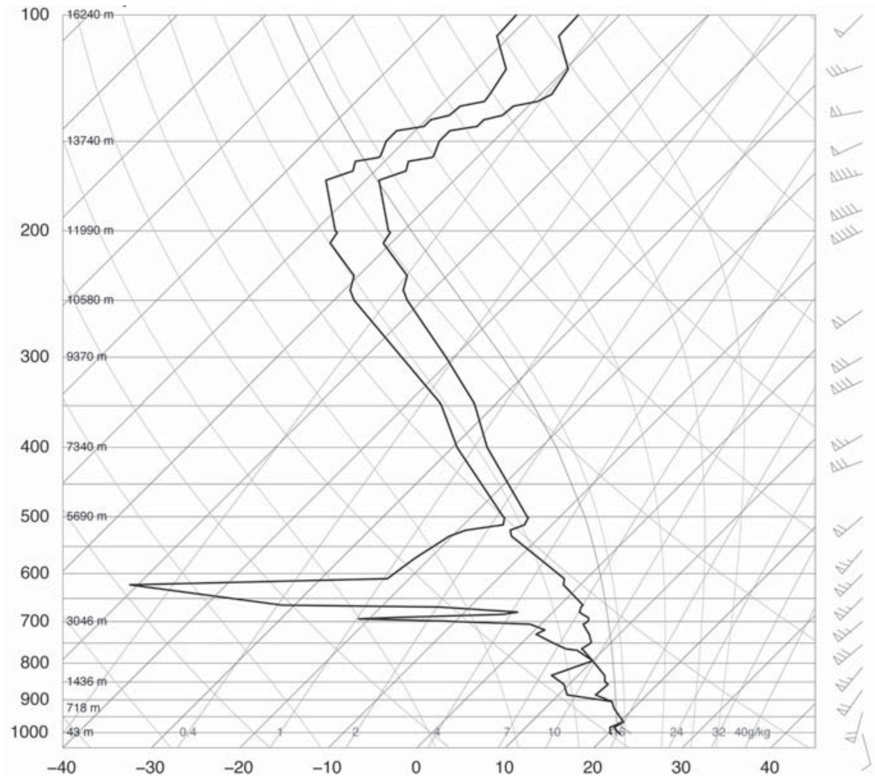

Figure 4. Sounding from Morehead City, North Carolina on 17 April 2011 0000 UTC, about 125 km southeast of and two hours following the tornado event in Snow Hill. Source: University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html).

irculation and central position of the mesocyclone and the supercell reflectivity structure from the lowest tilt angle of the radar scan (nominally 1.6–1.9 km above ground level at the range of the supercell). The supercell and mesocyclone structure is also placed in context with the location and intensity of the damage swath from the tornado.

At 2126 UTC the KMHX NEXRAD indicated a supercell thunderstorm in the vicinity of Goldsboro in central Wayne County approaching the town of Elroy (Figures 6 and 7). A mesocyclone was centered 2 km south of the reflectivity core, within a well-defined weak echo region. Over the next five minutes the supercell moved northeastward at about 22 m s^{-1} (50 mi hr^{-1}), crossed U.S. Highway 70 and passed 4 km northwest of the town of LaGrange (Figures 8 and 9). By 2135 UTC the enhanced reflectivity on the southern edge of the weak echo region had expanded and had nearly detached from the supercell core (Figure 10). At this time the mesocyclone center was located within the now bounded weak echo region

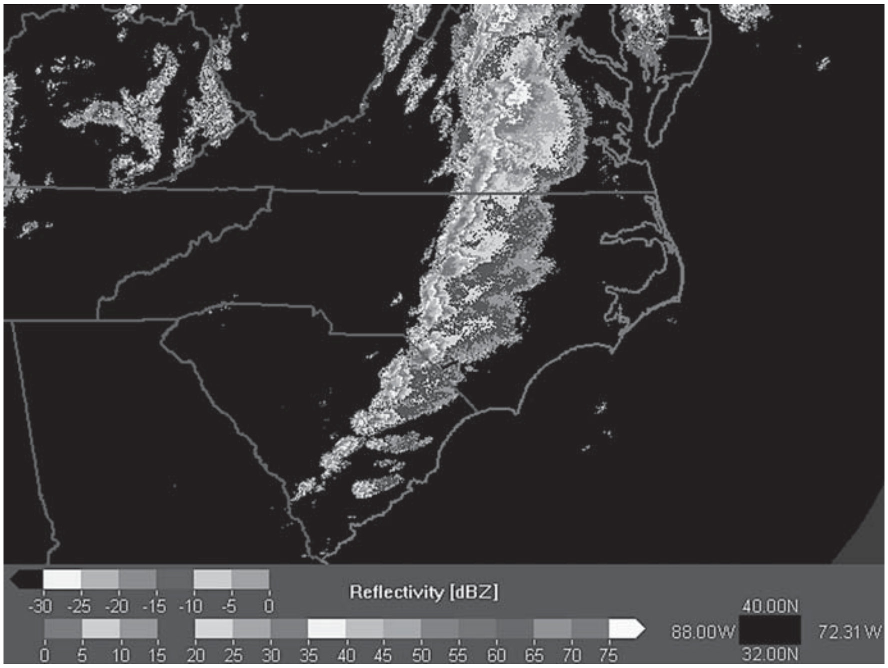

Figure 5. Regional radar composite for 16 April 2011 at 1930 UTC. (Source: http://nmq.ou.edu).

(BWER), suggesting the establishment of a strong coherent updraft (Browning and Foote 1976; Knupp et al. 1998). At this location, near the intersection of Wayne, Lenoir and Greene counties just southwest of the community of Jason, several snapped pine trees and minor roof damage to a small house were noted by the author several days after the event. Based on the damage, the National Weather Service (NWS Newport/Morehead City Public Information Statement issued 19 April 2011) estimated the surface wind speed at this location to be about 36 m s^{-1} (80 mi hr^{-1}), corresponding to an EF0 tornado (the location of EF0 damage is indicated on Figure 10 and similar figures). There were no confirmed visual sightings of a tornado at that time and location. The mesocyclone center was located about 1 km northwest of the surface damage and continued to move northeast along North Carolina Highway 903 (between Highway 13 and Highway 258) toward Snow Hill.

The next ten minutes saw significant changes to the mesocyclone and reflectivity structure of the storm. From 2135 UTC to 2145 UTC, the BWER filled in nearly completely (Figures 10–15), while a low reflectivity notch cut into the southwestern portion of the supercell south of the core (visible at 2145 UTC, Figure 14). Such features are often associated with the descent of the rear-flank downdraft, which is thought to be an important precursor to tornado genesis by tilting horizontal vorticity downward into the boundary layer

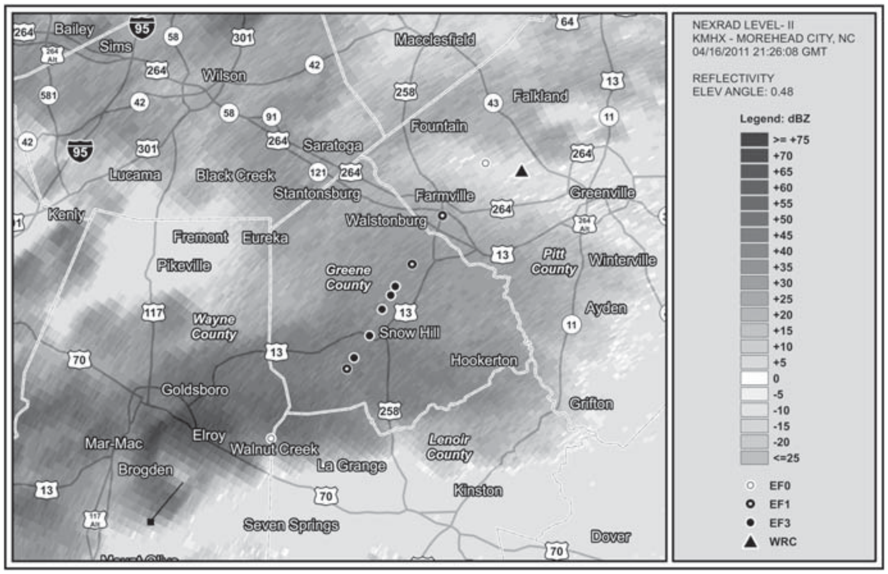

Figure 6. Regional map of radar reflectivity (dBZ) from the KMHX NEXRAD on 16 April 2011 centered on Snow Hill, Greene County, North Carolina for 2126 UTC. The radar is located 115 km (70 miles) southeast of Snow Hill. For scale, line segment is approximately 5 km.

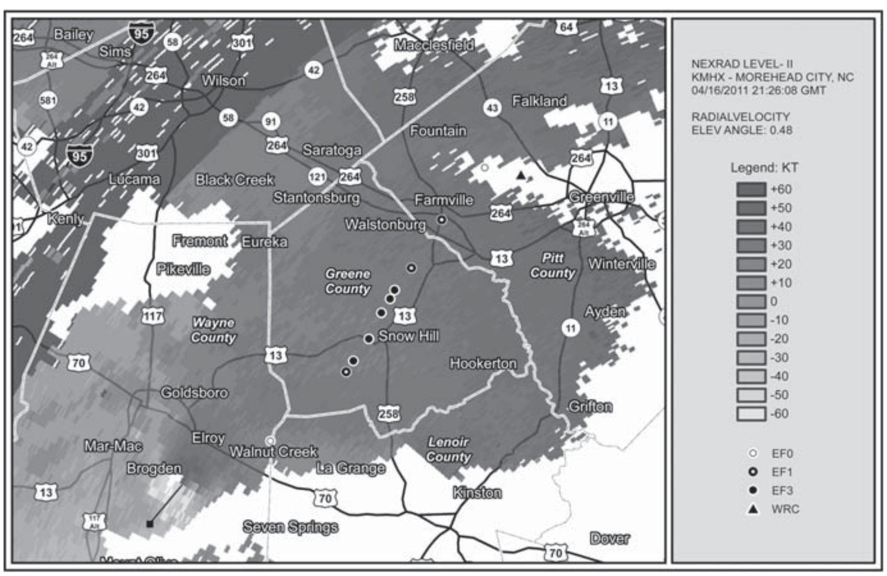

Figure 7. Regional map of ground-relative radial velocity (knots) from the KMHX NEXRAD on 16 April 2011 centered on Snow Hill, Greene County, North Carolina for 2126 UTC. The radar is located 115 km (70 miles) southeast of Snow Hill. For scale, line segment is approximately 5 km.

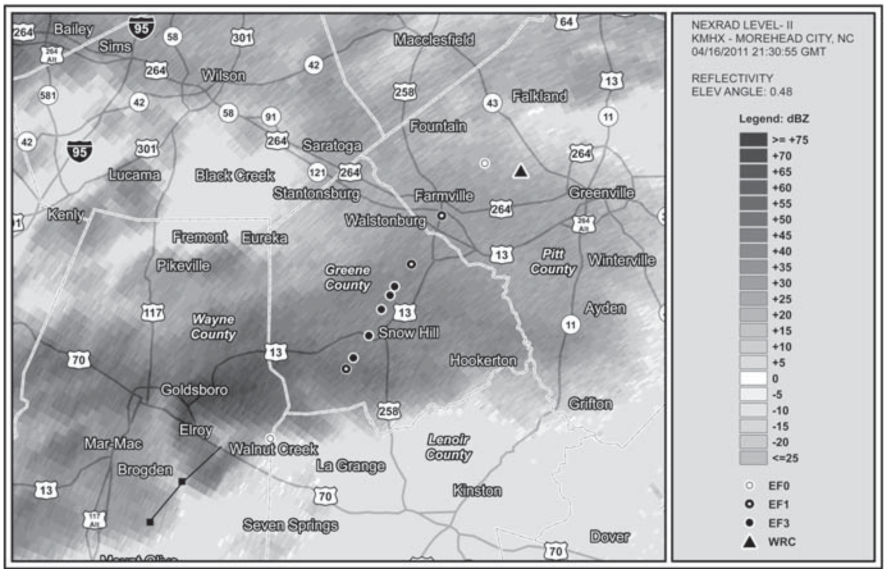

Figure 8. Regional map of radar reflectivity (dBZ) as in Figure 6, but for 21:30 UTC. The mesocyclone center is located at the open end of the line segment indicating the northeastward motion of the center. Black squares indicating the location in five-minute intervals prior to the current image.

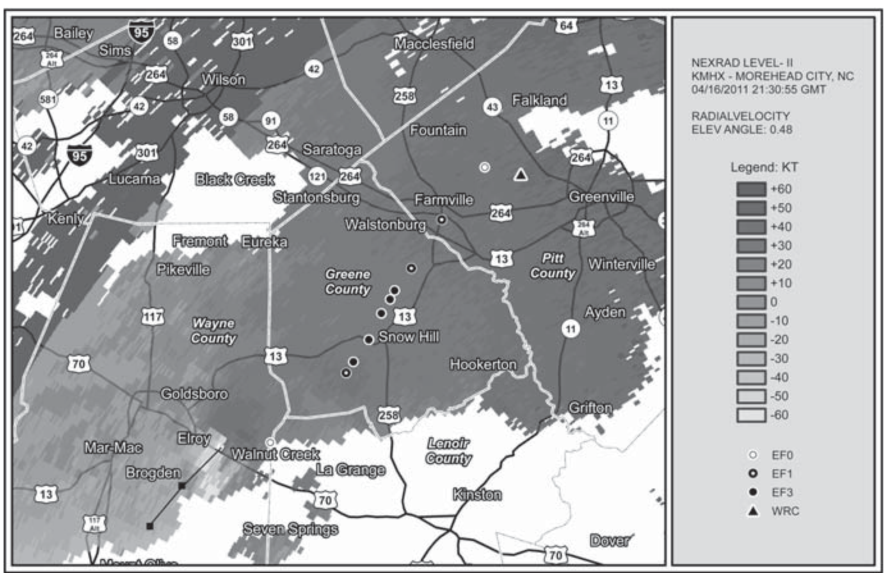

Figure 9. Regional map of ground-relative radial velocity (knots) as in Figure 7, but for 21:30 UTC. The mesocyclone center is located at the open end of the line segment indicating the northeastward motion of the center. Black squares indicating the location in five-minute intervals prior to the current image.

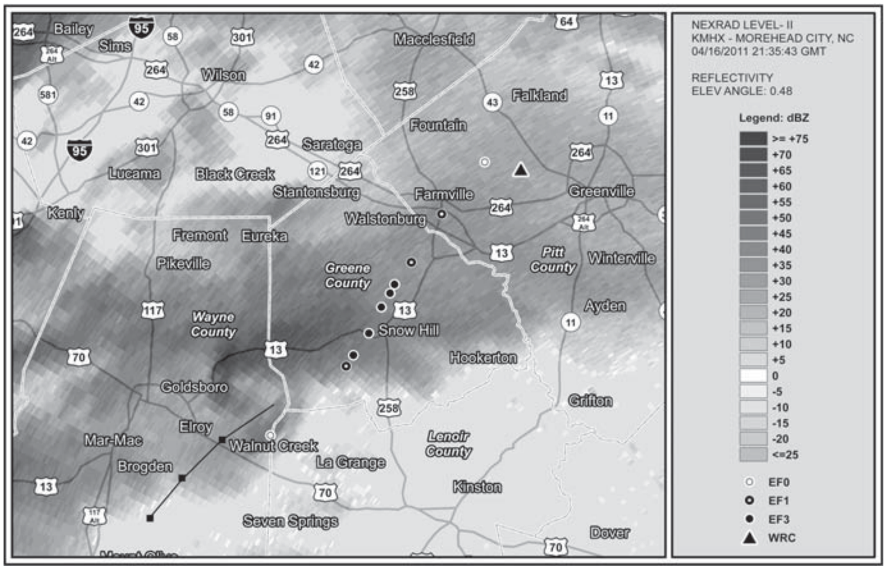

Figure 10. As in Figure 6 and Figure 8, but for 21:35 UTC.

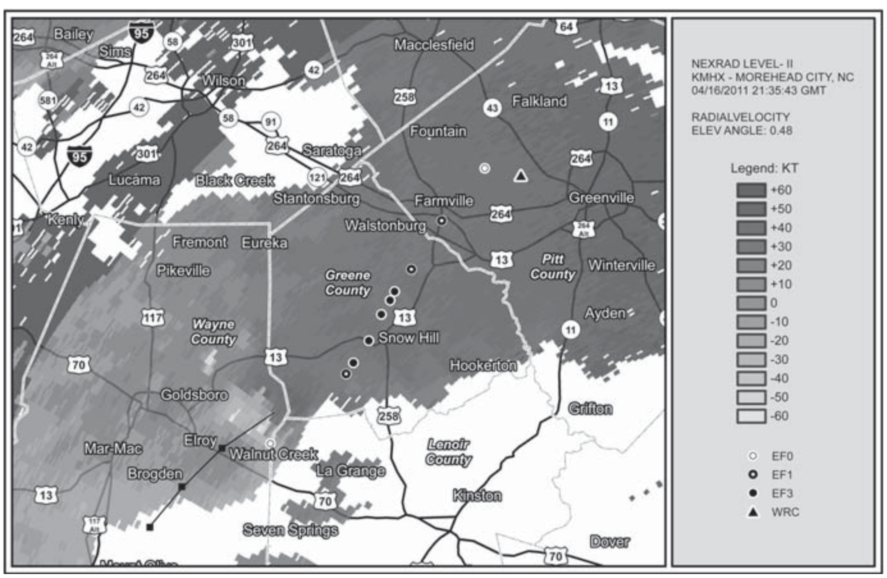

Figure 11. As in Figure 7 and Figure 9, but for 21:35 UTC.

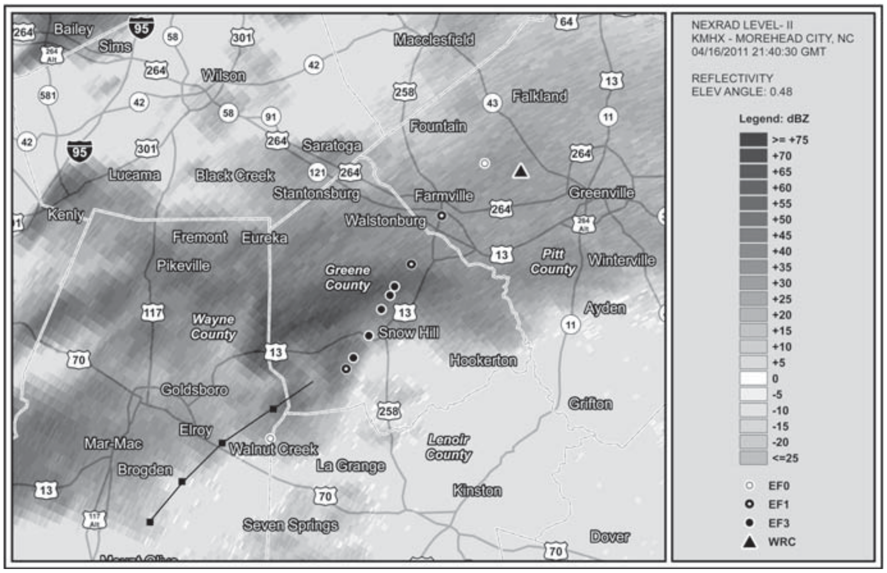

Figure 12. As in Figure 6 and Figure 8, but for 21:40 UTC.

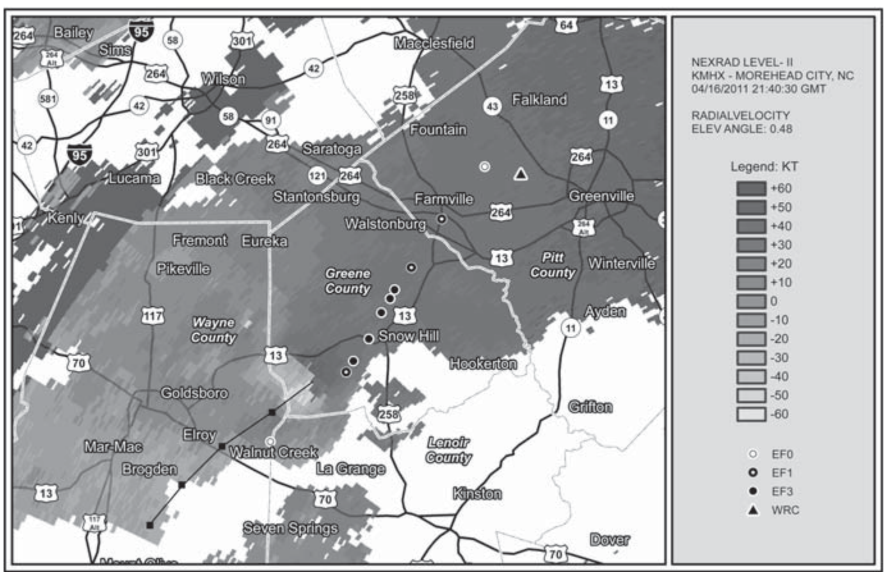

Figure 13. As in Figure 7 and Figure 9, but for 21:40 UTC.

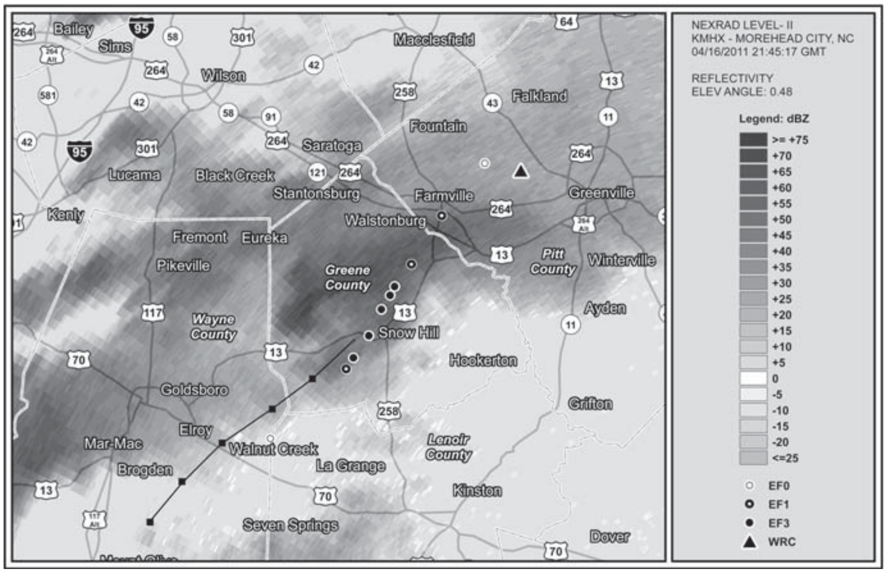

Figure 14. As in Figure 6 and Figure 8, but for 21:45 UTC.

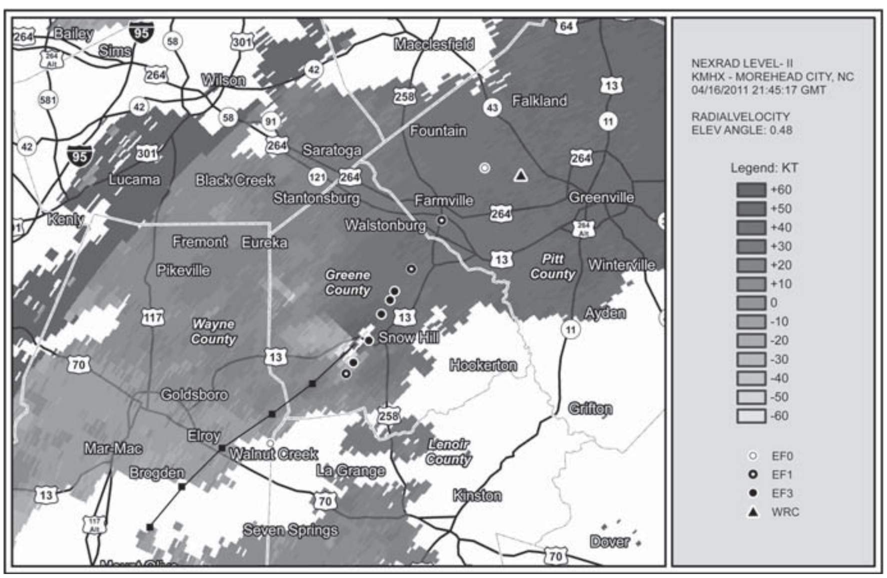

Figure 15. As in Figure 7 and Figure 9, but for 21:45 UTC.

Figure 16. Still image from video of the EF3 tornado, 1 km to the west-southwest, at the time (approximately 21:45 UTC) when the tornado severely damaged a neighborhood along Highway 13 in west Snow Hill (courtesy of Mr. Matthew Galloway, Greene County Emergency Services).

(Davies-Jones 2000). At this time the radar-observed mesocyclone was observed to contract and intensify, with several folded radial velocity range gates within 2 km of the mesocyclone center (Figure 15). The mesocyclone center passed about 1 km northwest of the first significant damage (EF3) associated with this event. A farmhouse along Warrentown Road near North Carolina Highway 903, about 3.3 km southwest of the town of Snow Hill, sustained significant roof damage, with a large metal shed wrapped in the upper branches of a tree 9 m above the ground noted by the author. A swath 100 m wide of snapped and damaged large trees was carved through the forested area around the farm, consistent with tornado damage.

The first documented tornado sighting, from video taken by a Greene County emergency medical technician, occurred 2.5 km northeast of the damaged farmhouse as the tornado approached west Snow Hill at approximately 2145–2150 UTC (1745–1750 local time). A still image from the video footage (Figure 16) shows the tornado about 1 km west-southwest of the camera, as the tornado entered a neighborhood along Highway 13 in west Snow Hill. Several houses were completely destroyed, resulting in several injuries but fortunately no deaths. The debris from one house was scattered 100 m northward across Highway 13 while another house was displaced 10 m northeastward off its foundation (aerial photo shown in Figure 17). The di-

Figure 17. Aerial photo of EF3 damage to the neighborhood along Highway 13. View is to the northeast. Highway 13 runs left to right (courtesy of the National Weather Service).

rection of downed trees and scattered building debris was consistent with EF3 damage from a strong southwesterly wind estimated at 71.5 m s^{-1} (160 mi hr^{-1}) by a National Weather Service Newport/Morehead City public information statement (NCDC Storm Event Database 2011). At this time (2145 UTC) the mesocyclone center at the lowest radar scan (1.65 km above the surface) moved closest to the location of damage, to within 0.5 km northwest of the damage swath. The intensification of the mesocyclone structure and observations of damage from a strong tornado corresponded in time to a degradation of the bounded weak echo structure, consistent with previously published case studies (Lemon and Doswell 1979). As the tornado passed 0.5 km northeast of Highway 13, video footage showed large suspended debris at least 0.25 km above the surface moving northeastward along the southeastern edge of the tornado. Based on the damage swath and on foreground trees and structures in the video, the tornado was approximately 300 m in diameter at that time. The tornado continued moving northeastward at 24 m s^{-1} (54 mi hr^{-1}) and produced EF3 damage through 2155 UTC. Specifically, the tornado inflicted roof and significant structural damage to Greene County Middle School in Snow Hill as well as extensive damage to several farmhouses and mobile homes in north-central Greene County, 3 km southwest of the town of Farmville.

The radar imagery from 2150–2155 UTC (Figures 18–21) suggest that the mesocyclone center continued to fill in with precipitation, degrading the hook echo structure, as the system approached Farmville. The mesocyclone center be-

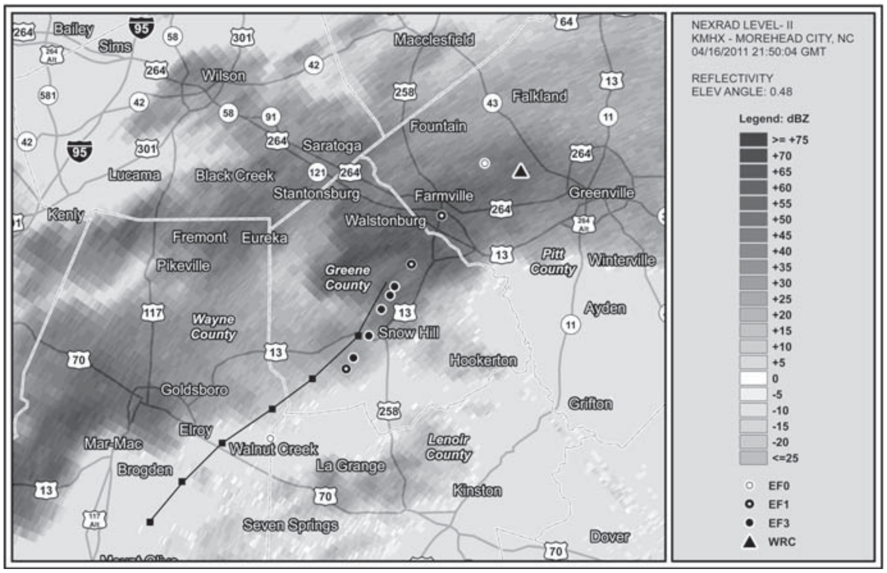

Figure 18. As in Figure 6 and Figure 8, but for 21:50 UTC.

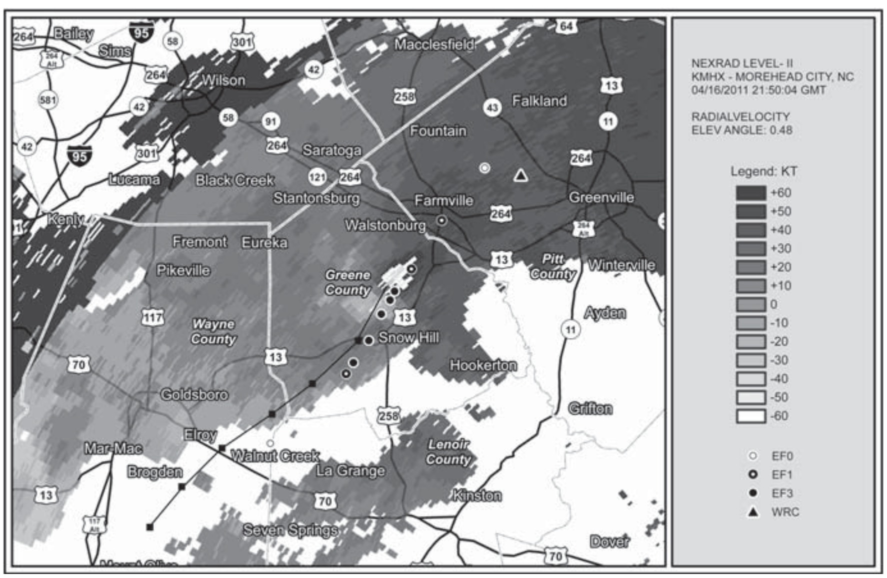

Figure 19. As in Figure 7 and Figure 9, but for 21:50 UTC.

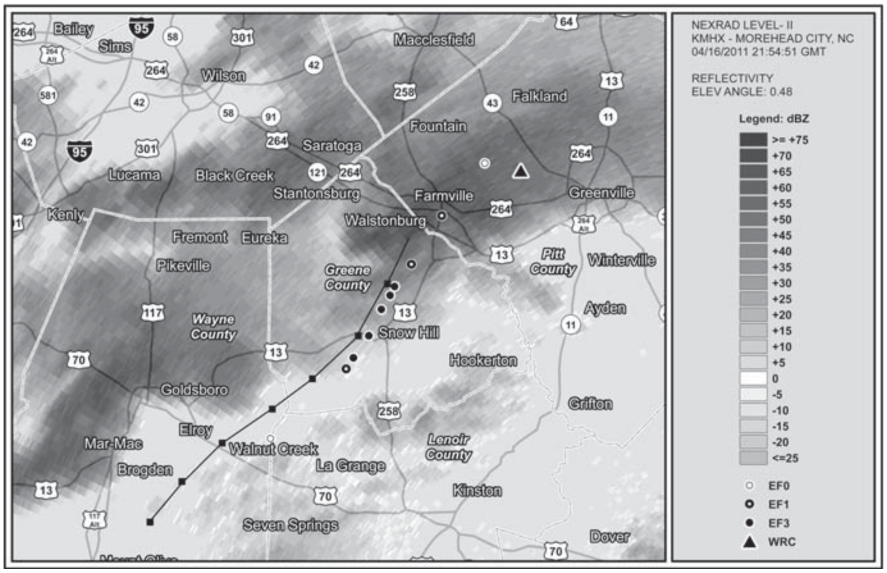

Figure 20. As in Figure 6 and Figure 8, but for 21:55 UTC.

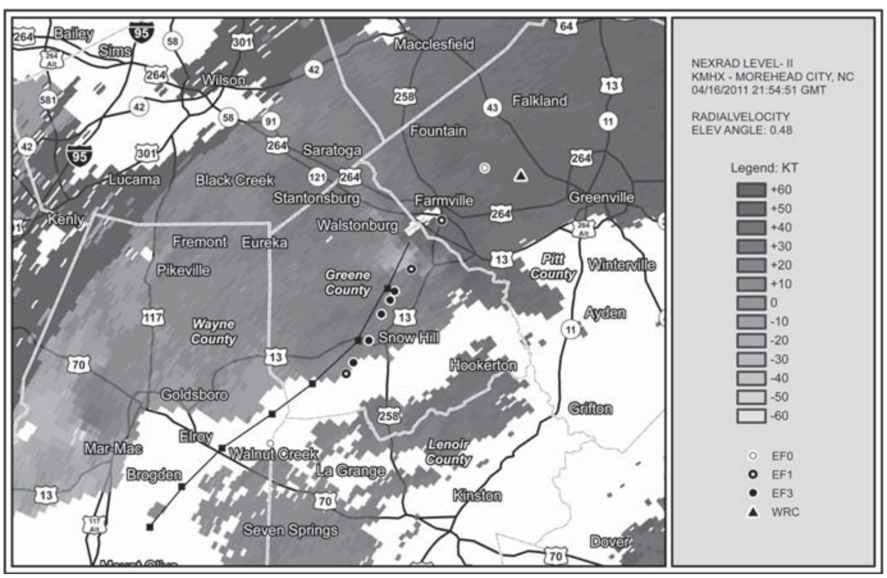

Figure 21. As in Figure 7 and Figure 9, but for 21:55 UTC.

came displaced from 0.5 km to about 2 km northwest of the damage swath during this period, while the circulation inferred from the radial velocity pattern appeared to weaken and expand in diameter (further discussion later in the paper). The damage (EF1) 3 km south of Farmville was limited to scattered snapped pine trees and minor roof damage to farm structures (NCDC Storm Event Database 2011), with no apparent damage between that point and Farmville. This observation led the National Weather Service to conclude the tornado lifted from the surface in that region. EF1 damage resumed on the south end of downtown Farmville, with snapped and uprooted trees and minor roof damage to an apartment complex.

The northernmost extent of damage from this tornado event occurred 5 km northeast of Farmville, along the southern edge of Highway 121. Though no structures were present, the author noted that at this location three large pine trees were snapped 5 m above the base toward the north while a wooden fence remained intact, consistent with EF0 damage. The mesocyclone center passed to within 1 km southeast of the EF0 damage location northeast of Farmville by 2205 UTC (Figures 22–25), while a small but well-defined weak echo region reformed in the supercell reflectivity field near the mesocyclone core. At this time the mesocyclone passed directly over the automated weather station at East Carolina University's West Research Campus. Over the next ten minutes (2209–2214 UTC, Figures 26–29), the weak echo region filled in once again and the mesocyclone appeared to weaken and lose definition as it passed 2 km southeast of the town of Falkland, west of Greenville. No damage was observed or reported in that vicinity. About 45 minutes later at 2255 UTC (beyond the time frame of the present analysis) this same supercell produced an EF3 tornado near the town of Askewville in Bertie County (75 km northeast of Farmville), resulting in 12 deaths (NWS Tornado Damage Survey 2011).

EVOLUTION OF MESOCYCLONE STRUCTURE

Between 2116 UTC and 2214 UTC the maximum radial velocity in the mesocyclone at the lowest elevation angle was identified from analysis of each data point spaced every 0.25 km along the radar beam, in the vicinity of the mesocyclone core. The intensity of the mesocyclone circulation was characterized by the difference between maximum storm-relative, dealiased radial velocity values on both sides of the circulation center. The mesocyclone diameter was defined as the distance between the two maximum radial velocity values. The highest radar reflectivity value of the associated supercell core was also found from perusal of each range gate. These parameters were identified and determined for each five-minute radar scan between 2116 UTC and 2214 UTC.

The resulting time series of the radar-observed difference in storm-relative radial velocity maxima across the mesocyclone, diameter of the mesocyclone, and maximum supercell core reflectivity (Figure 30) suggest a connection in this case between the evolving mesocyclone structure and the occurrence of a damaging tornado, in a manner described by Burgess et al. (1993). The time series suggests two periods of supercell intensification within

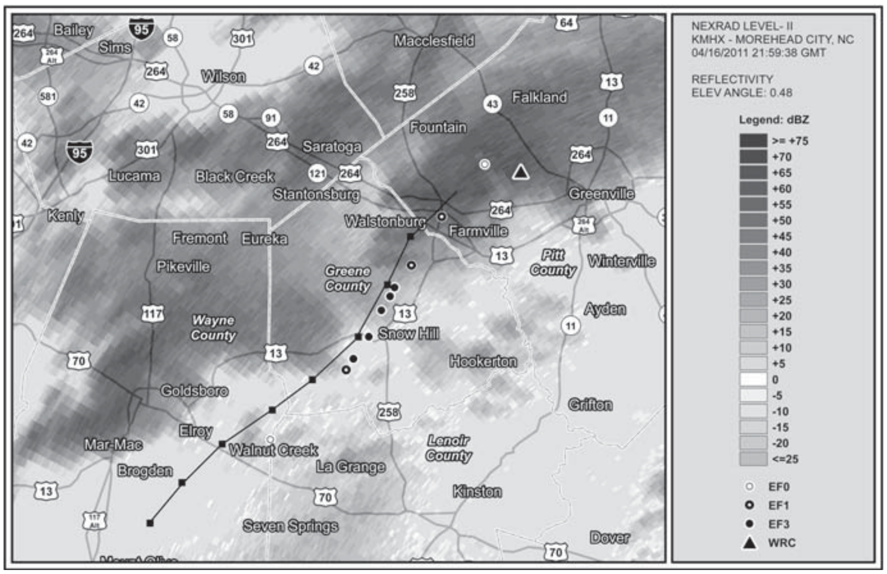

Figure 22. As in Figure 6 and Figure 8, but for 22:00 UTC.

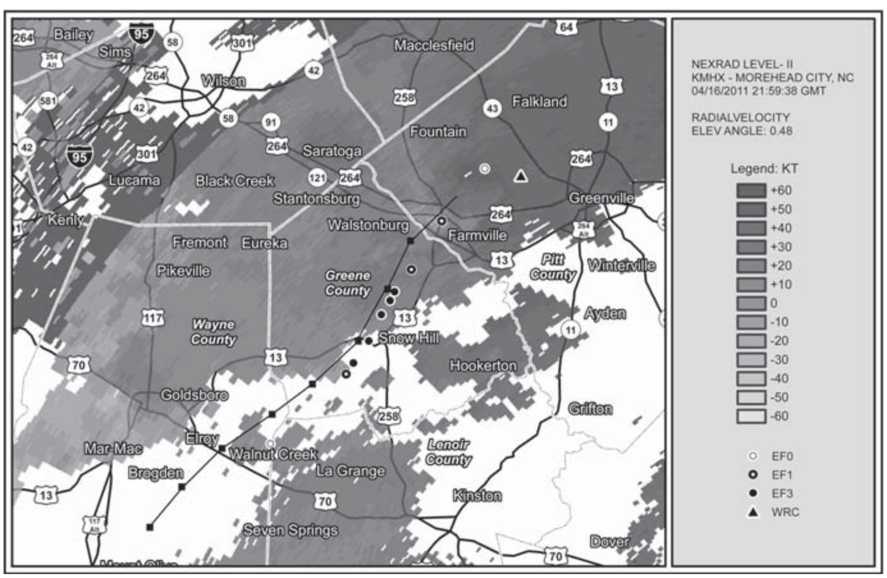

Figure 23. As in Figure 7 and Figure 9, but for 22:00 UTC.

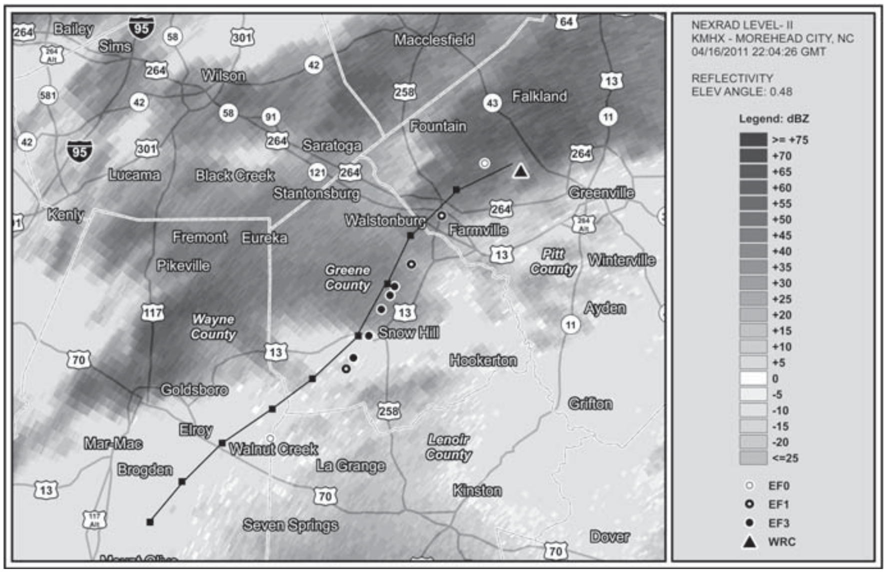

Figure 24. As in Figure 6 and Figure 8, but for 22:05 UTC.

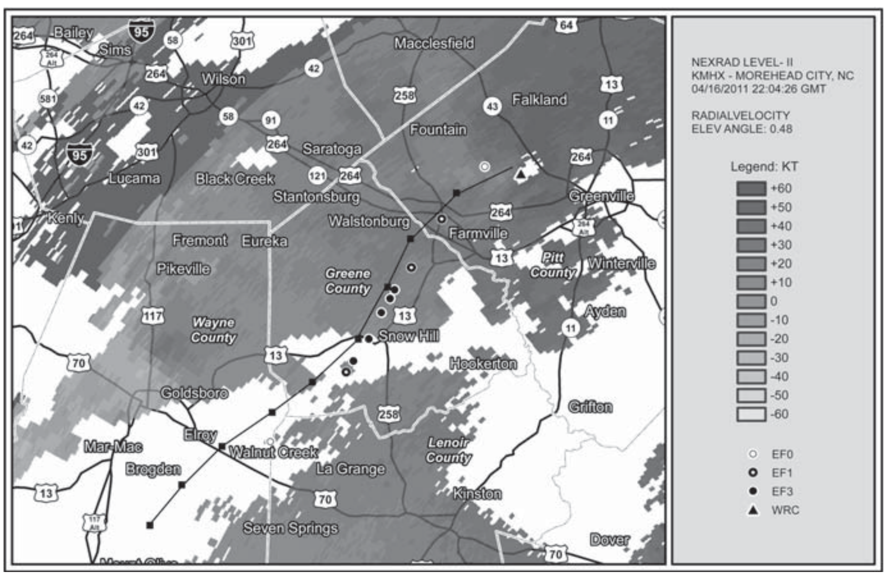

Figure 25. As in Figure 7 and Figure 9, but for 22:05 UTC.

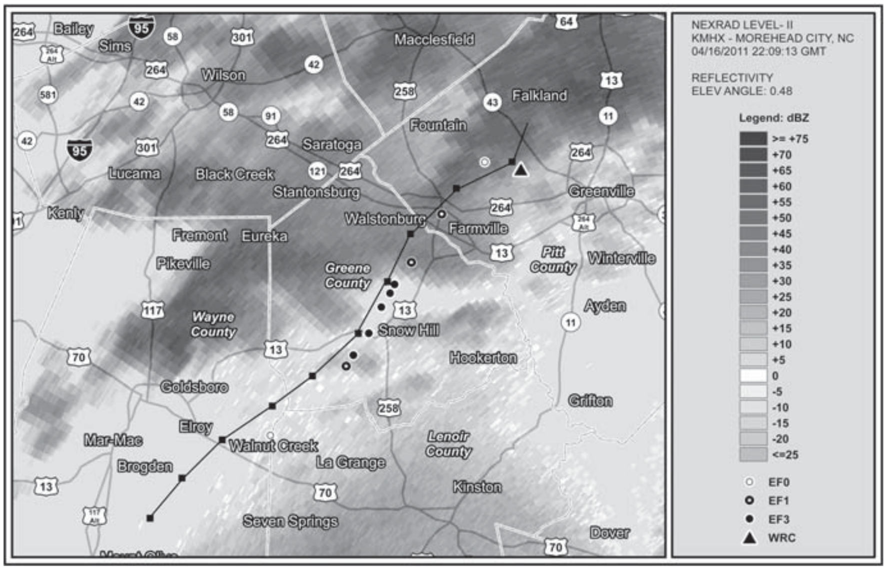

Figure 26. As in Figure 6 and Figure 8, but for 22:09 UTC.

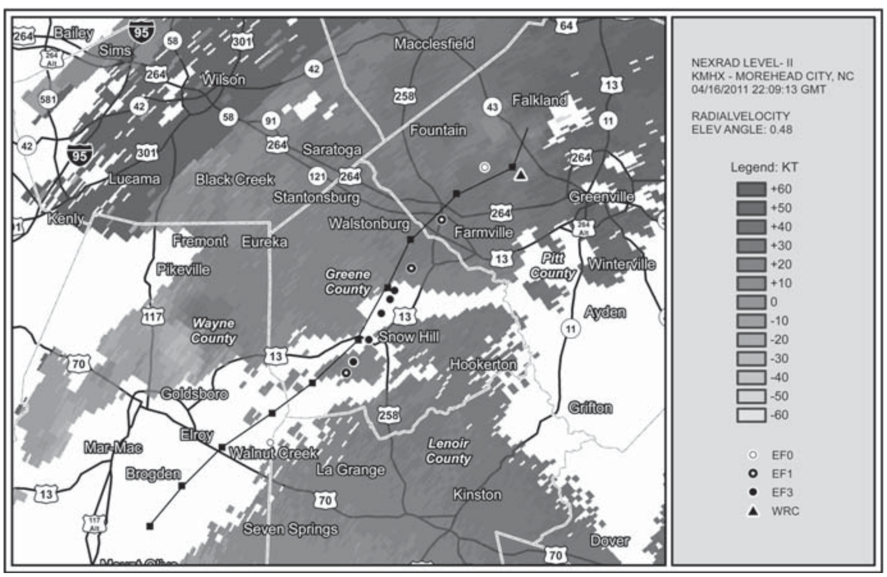

Figure 27. As in Figure 7 and Figure 9, but for 22:09 UTC.

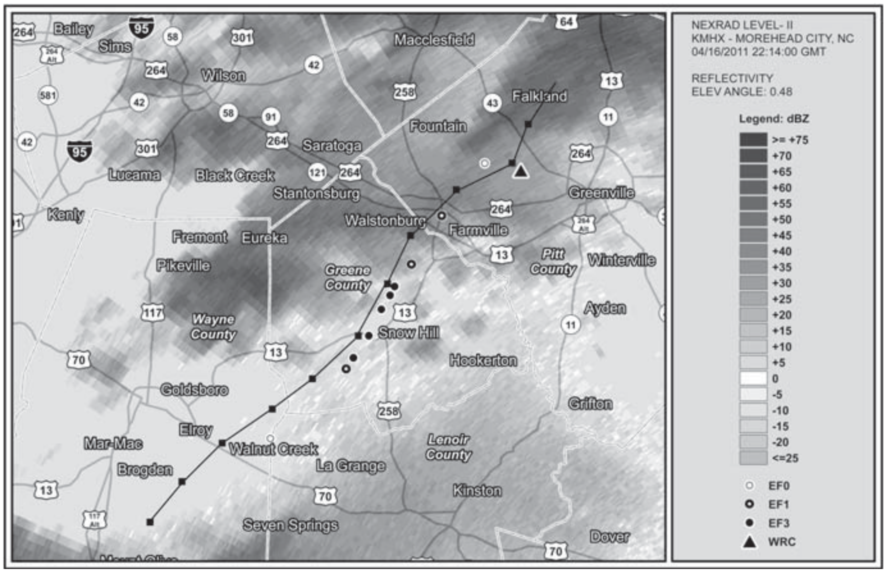

Figure 28. As in Figure 6 and Figure 8, but for 22:14 UTC.

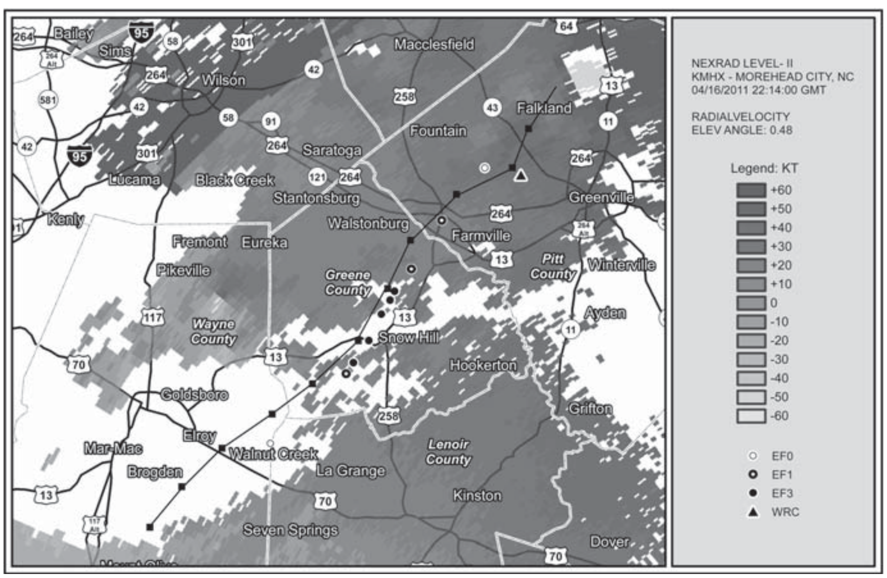

Figure 29. As in Figure 7 and Figure 9, but for 22:14 UTC.

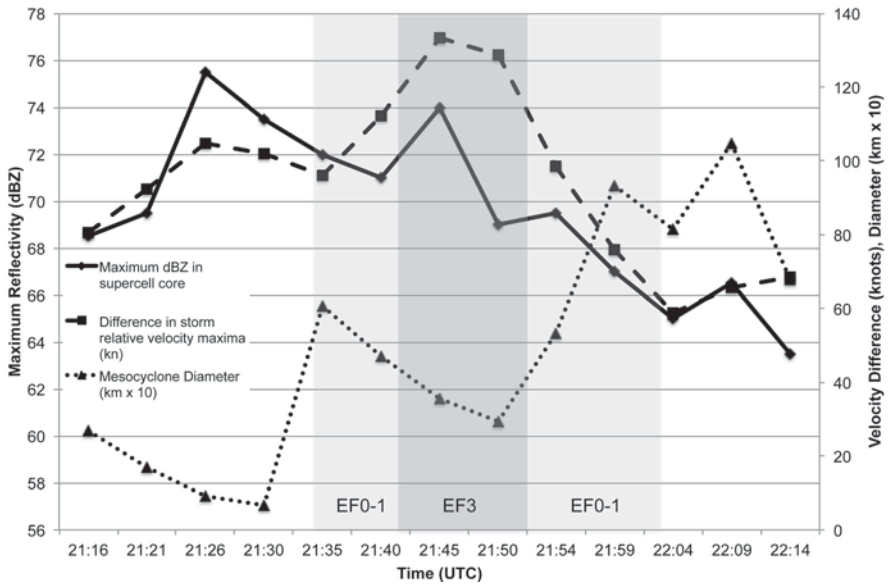

Figure 30. Time series from KMHX NEXRAD data of the maximum radar reflectivity value (dBZ) in the supercell core (solid line), difference in storm-relative radial velocity maxima (knots) across the mesocyclone center (dashed line), and mesocyclone diameter (km x 10; dotted line). Shading indicates the periods of tornado damage.

the hour of analysis. In the first period, as the supercell passed the vicinity of Goldsboro (2116–2126 UTC), the mesocyclone diameter decreased from 3 km to 1 km while the maximum radial velocity difference increased from 80 to 105 kt (Figure 30). The maximum core reflectivity increased from 68.5 to 75.5 dBZ very likely associated with hail, a conclusion supported by a spotter observation of 2.2 cm hail at 2112 UTC in the town of Shine near the core location (NCDC Storm Event Database 2011). During this same period, the bounded weak echo region was particularly well-defined (Figure 6). These observations suggest a contraction and spin-up of the mesocyclone circulation in step with an increase in the amount or size (or both) of hail in the supercell core, located on the northern periphery of the circulation. Wakimoto et al. (1998) emphasized vortex stretching as the primary mechanism for mesocyclone intensification, a process that is consistent with the observed mesocyclone contraction and spin-up in this case. However, this first period of mesocyclone intensification did not coincide with a tornado on the ground, as suggested by the lack of any damage between the towns of Elroy and LaGrange in eastern Wayne County (Figure 6).

Figure 30 illustrated that from 2130 UTC to 2135 UTC the mesocyclone circulation weakened only slightly (to 96 kt storm relative velocity difference) while the diameter broadened from 1 km to 6 km, suggesting an increase in the overall angular momentum of the circulation. The location of the mesocyclone center at this time (2135 UTC) passed 1 km northwest of the first observed tornado damage (EF0) from this event (Figures 10 and 11), with several snapped trees and minor roof damage to a house near the intersection of Greene, Lenoir and Wayne Counties. This apparent touchdown of the EF0 tornado at 2135 UTC coincided with the start of a second period of mesocyclone intensification between 2135 UTC and 2150 UTC with a very similar pattern to the first (Figure 30). The mesocyclone diameter contracted from 6 km to 3 km while the storm relative velocity difference increased from 96 to 133 knots. A second increase of core radar reflectivity (to 74 dBZ) occurred within this period, at 2145 UTC, corresponding to the time and location of 4.5 cm hail observed two miles west of Snow Hill (NCDC Storm Event Database 2011). It was during this period that the tornado damage increased from EF1 to EF3 as the tornado approached Snow Hill. These observations are consistent with the study of Funk et al. (1999) who noted for their case a decrease in mesocyclone diameter as the associated weak tornado intensified. At 2145 UTC, near the time and location of the most severe damage in the neighborhood along US Highway 13 (Figures 14 and 15), the mesocyclone center passed within less than 0.5 km of the damage swath.

The supercell core and mesocyclone entered a weakening phase from 2150–2204 UTC as the tornado continued toward Farmville. The tornado damage decreased to EF1 intensity about 5 kilometers southwest of downtown Farmville. By the time of the EF1 damage in Farmville (snapped trees and roof damage to an apartment complex), the mesocyclone diameter had increased from 3 km to 9 km, with the storm relative velocity difference dropping to 59 knots, suggesting a significant spindown of the circulation (again consistent with Funk et al. 1999). The mesocyclone center passed by 2204 UTC to within 1 km of the northward limit of damage (EF0, three snapped pine trees) from the tornado. By then the maximum core reflectivity value had decreased to 65 dBZ. The time series of Figure 30 suggested further weakening to 2214 UTC, at which time the analysis period ended.

SURFACE DATA NEAR THE WEAKENING MESOCYCLONE

The Geography Department at East Carolina University maintains an automated weather station at ECU's West Research Campus (WRC), about 10 km west of downtown Greenville (Figure 6). Fortuitously, the WRC site was located in the path of the center of the weakening mesocyclone about 2 km east of the northernmost extent of EF0 damage from the tornado near 22:05 UTC (Figures 24 and 25). Shown in Figure 31 are time series of 5-minute averaged wind speed, pressure, and wind direction taken from the WRC site over a twelve-hour period centered on the time of mesocyclone passage. Over the six hours prior to passage (1600–2200 UTC), southeasterly winds gradually shifted to south-southeasterly at about 15 m s^{-1} as pressure dropped from 1009 mb to 999 mb, consistent with the approach of a strong surface cold front. At 2200 UTC pressure began to fall rapidly from 998.69 mb to a local minimum of 997.04 mb at 2205 UTC, a 1.65 mb drop in five minutes (returning to 999.1 mb by 2220 UTC), at the low end of typical surface pressure minima observed with meso-

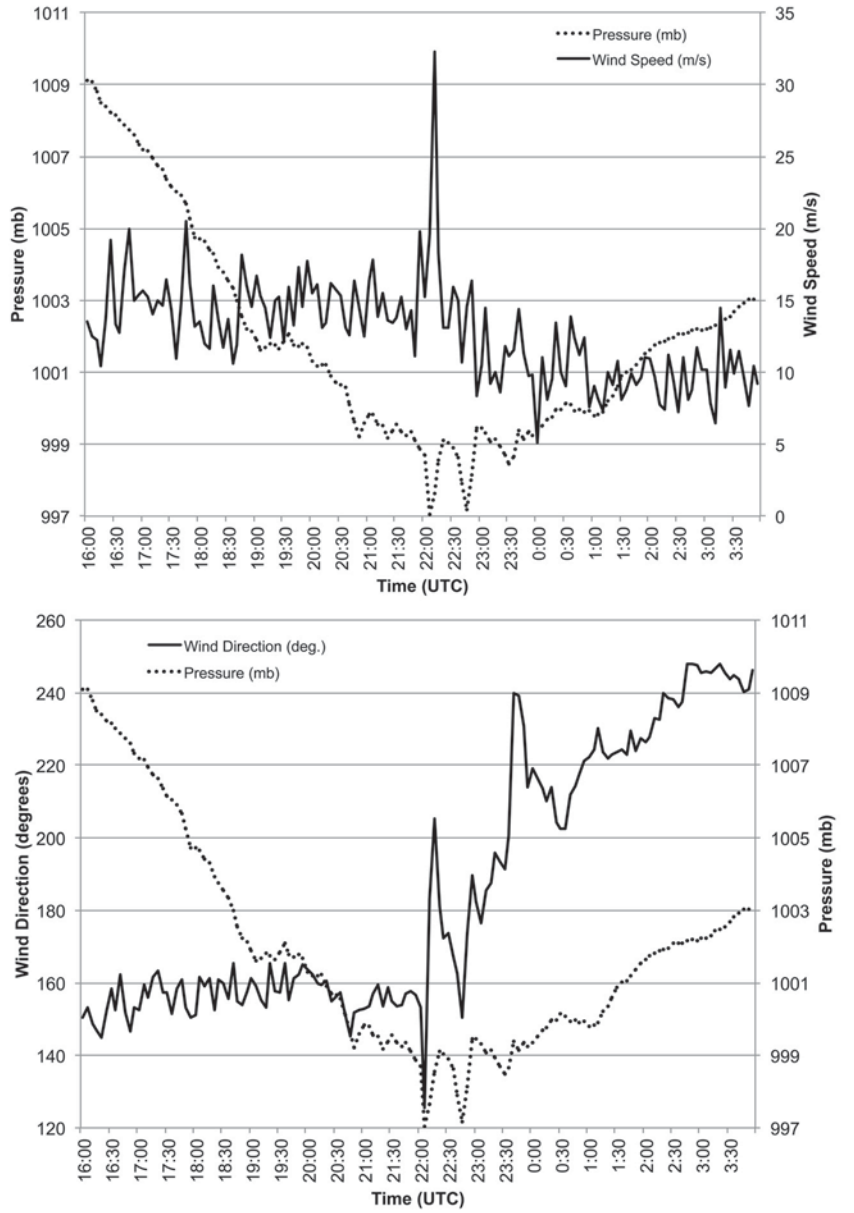

Figure 31. Time series of surface meteorological variables from the ECU West Research Campus weather station, on 16 April 2011. Upper panel shows pressure (mb, dotted line) and wind speed (m s-1, solid line), lower panel shows pressure (mb, dotted line) and wind direction (degrees, solid line).

cyclones (Bluestein 1983). Five minutes later, the surface wind speed spiked to a local maximum of 32.3 m s^{-1} (72 mi hr^{-1}, EF0 intensity) at 2210 UTC above the background wind speed of 18–19 m s^{-1}. This wind speed maximum coincided precisely with a rapid shift in wind direction from 120° to 205° from 2210–2215 UTC. The sense and timing of the wind shift, and the wind speed maximum following the pressure minimum, is very consistent with the radar-observed passage of a strong cyclonic circulation within 0.25 km northeast of the WRC site between 2205 UTC and 2215 UTC. The WRC data provided direct evidence that a surface circulation associated with the mesocyclone reached EF0 potential, though no tree or structural damage was observed at the site. Taken together, these observations suggest that the remnant surface circulation from a dissipating mesocyclone passed over the WRC site at approximately 2210 UTC corresponding to the northernmost extent of damaging surface winds associated with this event. Though it is possible that a dissipating EF0 tornado occurred at this time near the WRC site, there were no observations or direct evidence to confirm that hypothesis.

Interestingly, a similar pressure minimum and wind direction shift occurred at the WRC site about 35 minutes later, at 2245 UTC. This event was not accompanied by a wind maximum at WRC. Perusal of the radar data at that time revealed that another mesocyclone (from the supercell located 5 km north of Goldsboro at 2205 UTC seen in Figure 24) passed approximately 7 km to the northwest of the WRC site by 2245 UTC. Though located much farther from the WRC site than the event under study, the similar pressure drop suggests a stronger mesocyclone, as suggested by the radial velocity couplet (not shown). However, no damage beyond a single snapped tree was found in that area (along Route 222 at Falkland), suggesting that likely only strong surface wind gusts accompanied that mesocyclone. After 2300 UTC to 0400 UTC (17 April) surface winds shifted to west-southwesterly and weakened to below 10 m s^{-1}, while pressure climbed to 1003 mb, all consistent with the passage of the surface cold front through Pitt County at that time (not shown).

CONCLUSIONS

This paper presented an overview of a significant tornado event on 16 April 2011 between 2100–2200 UTC, which affected Wayne, Greene, and Pitt counties in eastern North Carolina. This event was one of a record number of tornadoes in the United States for a single month (April 2011). The tornado occurred as part of a line of supercell thunderstorms ahead of an approaching cold front associated with a strong middle-latitude cyclone. The study presented analysis of the evolving mesocyclone structure within a supercell thunderstorm observed by NEXRAD radar, in the context of the location of verified tornado sightings and property damage as indicated by damage reports and surface meteorological observations. The focus of the case study was to examine the relationship between the mesocyclone evolution and the location and intensity of surface damage associated with this EF3 tornado, which occurred in a region where such events are much less common than in the well-studied Great Plains region of the U.S.

During the one-hour analysis period, radar observations suggested two periods of mesocyclone intensification as the supercell moved northeastward through Wayne and Greene counties. Damage consistent with an EF0 tornado commenced as the mesocyclone began its second, more intense period of spin-up and contraction, culminating in EF3 damage from a confirmed 300 m wide tornado on the ground near the town of Snow Hill. The initial contraction and spin up of the mesocyclone circulation preceded EF3 damage by about 20 minutes. At the time of mesocyclone intensification, the damage swath and visual observation of the tornado were situated much closer to the mesocyclone center—within 1 km to the southeast—as the weak echo region began to collapse.

The mesocyclone subsequently widened and weakened as surface damage from the tornado decreased to EF0 intensity. The weakened mesocyclone passed directly over a meteorological station at ECU's West Research Campus, providing a rare opportunity for surface measurements associated with a weakening tornadic mesocyclone. Near the northern extent of EF0 damage, surface observations at the ECU WRC in the vicinity of the mesocyclone center suggested that the remnant circulation of the dissipating mesocyclone passed directly over the WRC station.

Future work may include assessment of tornado preparedness and warning response in the rural communities of Greene County in response to this event.

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THOMAS RICKENBACH is an Assistant Professor of atmospheric science in the Department of Geography at East Carolina University in Greenville, North Carolina, 27858. Email: rickenbacht@ecu.edu. His research interests include radar and satellite meteorology, the formation and evolution of precipitation systems, and how precipitation systems influence and are influenced by regional climate. His work has included studies of seasonal and interannual changes in rain systems across the global Tropics, from Australia to South America to West Africa.