15.2 TORNADO DISTRIBUTION ASSOCIATED WITH HURRICANE FLOYD 1999

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1. INTRODUCTION

On the evening of 15 September 1999, Hurricane Floyd made landfall at Bald Head Island, NC; 0630 UTC (hereafter all times UTC) 16 September. Floyd was a large and intense Cape Verde hurricane that affected the central and northern Bahamas before making landfall on the North Carolina coast. At its peak intensity, Floyd reached the top end of category four (with winds >69 m s^{-1}) on the Saffir/Simpson (Simpson 1974) hurricane scale, and arrived onshore as a category two hurricane. Prior to and during the time of landfall the hurricane interacted with a coastal front (Bosart et al. 1972; Bosart 1975; Keeter et al. 1995; Garner 1999) and remained coupled with the front as the hurricane weakened rapidly, and accelerated northward along the East Coast into New England (Bosart and Atallah 2000; Kong 2000).

Eighteen tornadoes associated with Floyd were reported in the U.S. and all occurred in North Carolina on the day of landfall (*Storm Data* 1999). The two strongest tornadoes produced F2 damage. Smith (1965) and McCaul (1991) identified the right-forward quadrant of a hurricane as the most favored area for tornado development; maximum shear and helicity values occur within the quadrant. Tornadic events associated with Hurricane Floyd supported this assessment. What is interesting about the landfall event was that 88.9% (16 of 18) of the tornadoes developed either immediately along the coastal front or within the warm sector east of the front (Fig. 1).

2. METHODOLOGY

Surface data were obtained and analyzed for the period of 0900 15 September through 1200 16 September, inclusive. The observations from Automated Surface Observing System (ASOS), Automated Weather Observing System (AWOS), Coastal-Marine Automated Network (C-MAN), buoy, and ship data were analyzed subjectively for temperature, dewpoint, sea level pressure, and wind fields. In situ mobile mesonet data (Straka et al. 1996) were similarly included to improve data density over land, aiding in frontal boundary placement.

National Weather Service rawinsonde data, and NOAA/AOML Hurricane Research Division (HRD) GPS dropsonde data, were used to create constant pressure and cross-sectional plots. These plots were then subjectively analyzed for synoptic and mesoscale features. Soundings from Morehead City, NC (MHX), Greensboro, NC (GSO), and Roanoke, VA (RNK), launched at 0000 and 0600 on 16 September, were selected for frontal analysis. These sites were downstream of the hurricane and closest spatially and temporally to landfall location.

Weather Surveillance Radar-1988 Doppler (WSR-88D) (Crum and Alberty 1993) level II data (Crum et al. 1993) from MHX, Wilmington, NC (LTX), and Charleston, SC (CLX) were utilized to aid in boundary placement. LTX was selected for analysis, as the radar was located closest to the area of landfall and level II data were available for the majority of the event, 1329 15 September to 1039 16 September, inclusive. Unfortunately, level II data from CLX and MHX were either not available or sporadic. Based on the work of Rasmussen et al. (2000), evidence was presented that *Storm Data* reports must be verified for accuracy. An effort was made to verify each report for location and time accuracy utilizing WSR-88D level II data. Unfortunately, the lack of archived WSR-88D data at MHX prevented a thorough investigation. Consequently, none of the 18 tornado reports recorded by *Storm Data* could be refuted, and all were assumed to be valid.

3. DATA AND RESULTS

A coastal front developed downstream of the hurricane, during the mid-morning hours of 15 September, along the coastal plain of the Carolinas and Virginia, 12 hours prior to the landfall (Pietrycha 2001).

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As Hurricane Floyd approached shore, the pressure gradient over the coastal plain intensified, accelerating the surface flow over the eastern Carolinas. The baroclinic zone associated with the temperature gradient strengthened, owing to increased horizontal deformation (Bluestein 1993), but remained nearly stationary throughout the day. Frontogenesis would continue further north, immediately inland from the shoreline and downstream of the advancing hurricane. By 0000 16 September, a coastal front oriented north-south was well established, spanning the area east of Charleston, SC, to east of Virginia Beach, VA.

Cross-sectional analysis of potential temperature utilizing 0600 UTC rawinsonde data from RNK, GSO, and MHX, and surface observations revealed a 1 km deep surface layer of cold air existed westward from the coastal front to the mountains of North Carolina and Virginia (Fig. 2). Warm air advection and strong isentropic lift developed during the afternoon of 15 September over North Carolina, downstream of the hurricane, in the deep layer flow normal to the boundary and persisted as the storm moved onshore.

Concurrent with coastal front formation, WSR-88D reflectivity imagery over eastern North Carolina displayed the development of a persistent precipitation band in association with the front (Fig. 3). Numerous rain bands were evident in the data, rotating westward off the ocean and over North Carolina. The spiral precipitation bands associated with Floyd maintained their spatial continuity east of the front. As the spiral bands rotated westward toward the coastal front, their discrete horizontal reflectivity structure became absorbed by the more uniform frontal precipitation band. Stronger convective cells (50-55 dBZ) embedded within the spiral bands were observed to decrease in intensity and lose their reflectivity structure as the spiral bands crossed the boundary over the cooler air.

3.1. Tornado Analysis

Eighteen tornadoes occurred in North Carolina on 15 September 1999 within the northeast quadrant of the hurricane. All the parent supercells were associated with outer rain bands. No tornadoes were reported in South Carolina or Virginia during the same time frame. Of note is the fact that 88% (16 of 18) of tornadoes developed either immediately on the coastal front or within the warm sector of the boundary. The strongest two tornadoes resulted in F2 damage. One tornado occurred 3 hours prior to the development of the front, within a quasi-homogeneous airmass that existed downstream of the approaching hurricane, and another, 10 km on the cool side of the boundary. Both tornadoes produced F0 damage.

The lack of tornadoes west of the boundary is attributed to the inhibiting influence of the strong cold pool west of the coastal front. In this case, the possibility for tornado genesis appears to have been greatly diminished, given the elevated nature of the storms along and over the 1 km deep cold pool. The same effects may explain, in part, the absence of reported tornadoes in Virginia. With the exception of extreme southeast Virginia, the state was blanketed by cold air prior to and during hurricane landfall. McCaul (1991) has shown that the left forward quadrant is least favorable for hurricane spawned tornadoes; left front quadrant contains the least shear and helicity of the four quadrants. Therefore, we can not refute the apparent lack of tornadoes west of the boundary as a result of increasing spatial distance into the left front quadrant of the hurricane.

As documented by Pietrycha et al. (in review) the hurricane became secluded shortly after landfall; cold air advected completely around the eye of the hurricane. The existence of the cold airmass wrapped around the system may further explain the absence of reported tornadoes within the left or right rear quadrants, as the hurricane departed north of the region.

4. CONCLUSIONS

Eighteen tornadoes occurred over the state of North Carolina prior to the landfall of Hurricane Floyd on 15 September 1999. During the day of landfall a coastal front developed downstream of the hurricane. 88.9% of the reported tornadoes developed immediately along and/or within the warm side of the boundary. The lack of tornadoes west of the boundary was attributed to the inhibiting influence of the strong cold pool west of the coastal front. In this case, the possibility for tornado genesis appears to have been greatly diminished, given the elevated nature of the storms along and over the cold pool (Fig. 2).

Forecasters are encouraged to be cognizant of regions of deep cold air and/or hurricane/frontal boundary interactions that might demise the threat of tornadoes and thus better improve watch box coordinates and such.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Available upon request.

Fig. 1. Triangles denote the locations of the 15 September 1999 tornadoes. Solid line denotes mean location of the coastal front during the day/evening of 15 September 1999. Dashed line denotes the track of Hurricane Floyd.

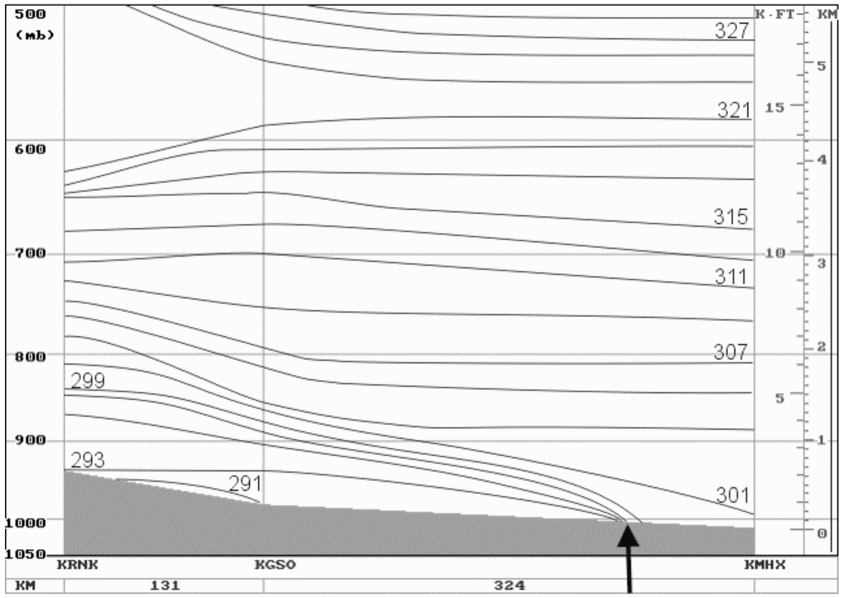

Fig. 2. An east-west subjectively analyzed cross section of potential temperature (solid, 2K internals) between Morehead City, NC, Greensboro, NC, and Roanoke, VA, on 0600 UTC 16 September 1999. Black arrow denotes 0600 UTC frontal boundary position. The kilometer scale along the bottom of the figure is distance separation between the soundings.

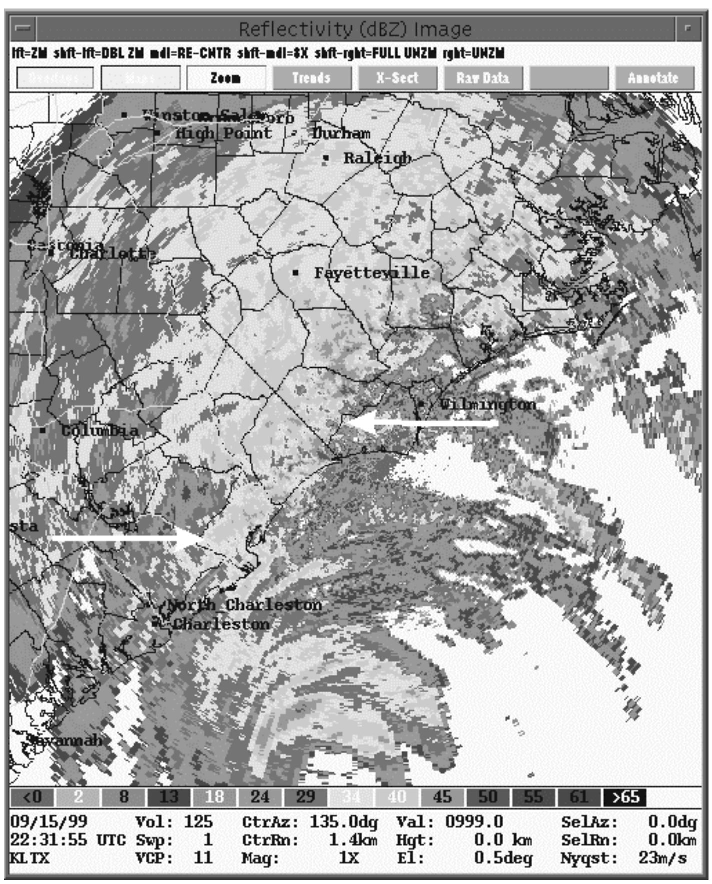

Fig. 3. Base reflectivity from KLTX at 2231 UTC 15 September 1999. White arrows denote frontal precipitation band.