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AN ANALYSIS OF THE 4 SEPTEMBER 1996 HICKORY NUT GORGE FLASH FLOOD IN WESTERN NORTH CAROLINA

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1. INTRODUCTION

On the evening of 4 September 1996, a catastrophic flash flood occurred in western North Carolina approximately 40 km southeast of Asheville, along the Rocky Broad River. The heavy rainfall responsible for the flooding was localized but extreme, with an automated rain gage in eastern Henderson County measuring 31.7 cm over a 3-h period. One-hour totals exceeded 12 cm for two consecutive hours. Over $5 million dollars in damage was caused by the flooding, with numerous homes and businesses washed away. Several injuries were also reported. Thanks to a combination of timely warnings and automated rain gage information, evacuations prevented any loss of life.

The predominant mechanism responsible for the heavy rainfall was orographic ascent of moist, unstable air up the eastern escarpment of the Blue Ridge Mountains. This case is similar in many respects to "upslope" flash floods investigated by Maddox et al. (1978), and Lee and Goodge (1984), with the notable difference that it was not post-frontal. This paper will provide a brief overview of the meteorology for the time of the flooding. Doppler radar and satellite imagery documenting the event will also be discussed, along with an analysis of the rainfall totals. This work demonstrates the value of real-time rain gage data in short-term flash flood forecasting.

2. DATA AND METHODOLOGY

Five key parameters were investigated to provide a better understanding of the Hickory Nut Gorge flash flood: 1) The role of the area's unique terrain, 2) analysis of remote sensing data from satellite and the Weather Surveillance Radar - 1988 Doppler (WSR-88D), 3) upper-air and surface observations, 4) gridded numerical model analysis, and 5) rainfall measurements from all available sources. Radar data, gridded model data, and surface and upper-air observations were archived locally. Infrared and water vapor satellite imagery in 30 minute intervals was obtained from the National Climatic Data Center (NCDC). Rainfall measurements were gathered from cooperative observers, synoptic stations, weather spotters, and automated rain gages.

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3. DISCUSSION

a. Local topography

The region of interest is along the Blue Ridge Escarpment of the southern Appalachians, where terrain rises from around 300 m to 1200 m above sea level in just a few kilometers. The orientation of the Blue Ridge Mountains creates an orthogonal barrier to an east or southeast low-level flow. The Hickory Nut Gorge provides a "V"- shaped opening in this barrier. Lee and Goodge (1984) hypothesized that this unique terrain feature acted as a focusing point for low-level upslope flow into a flash flood-producing thunderstorm complex in 1978.

b. Synoptic setting

At 0000 UTC 5 September 1996, a 1018-mb surface high was centered over New England with its associated ridge extending into the Carolinas. The center of Hurricane Fran was about 1125 km southeast of the Hickory Nut Gorge. Low- and mid-level warm advection was occurring aloft around a ridge centered off the east coast. Dewpoint depressions were less than 4°C in the lowest 300 mb. The modified 0000 UTC sounding from Greensboro, North Carolina (GSO), was moist and unstable, with a lifted index of -6 and precipitable water of 4.4 cm, 151% of normal. The level of free convection was 857 mb.

The 0000 UTC 48-km eta model initial analysis showed a 10 m s^{-1} southeast 900-mb wind into western North Carolina. A theta-e ridge of 342 K air was feeding into the higher terrain from the Atlantic. Analysis of the 303 K isentropic surface showed a condensation vapor pressure of just 30 mb over the region.

A prominent circulation feature was an upper-level low over Tennessee. The gradual eastward movement of the low eventually turned the westward-moving hurricane toward the Carolina coast[1]. Also present was a 25 m s^{-1} 250-mb jet streak, a feature absent in documented upslope flash floods by Maddox et al. (1978) and Lee and Goodge (1984). The jet streak, oriented so that western North Carolina

[1]The Tropical Prediction Center's preliminary report on Hurricane Fran is available on the Internet at *http://www.nhc.noaa.gov/fran.html*.

was in the right entrance region, resulted from the height gradient between the upper low in Tennessee and the anticyclone at 250 mb associated with Hurricane Fran. An area of upper-level divergence between the two circulations extended from Georgia northward into western North Carolina.

Along-stream variation of the 250-mb wind speed had increased during the day. The developing jet took on a classic straight-line character, promoting dominance of the inertial-advective component of the ageostrophic wind. Uccellini and Johnson (1979) demonstrated that along-stream variation of the wind in entrance and exit regions of jet streaks was the most important factor in the magnitude of the ageostrophic wind and resultant vertical motion.

c. Radar presentation

The WSR-88D at Greer, approximately 65 km to the south of the affected area, offered an ideal perspective for investigating this flash flood event. Convection developed and increased in coverage across the area of interest between 2300 and 0000 UTC. The Velocity Azimuth Display (VAD) Wind Profile (VWP) at 0011 UTC (Fig. 1) shows an increasing southeasterly flow in the lowest levels, very weak southerly flow between 3000 m and 5500 m, and 20 m s^{-1} southwesterly flow at 8500 m. The pronounced veering signature is indicative of warm advection. From the VWP alone, one can identify the low-level southeasterly upslope flow, the weak steering winds in the middle levels of the atmosphere, and the presence of seasonally significant jet stream winds in the upper levels.

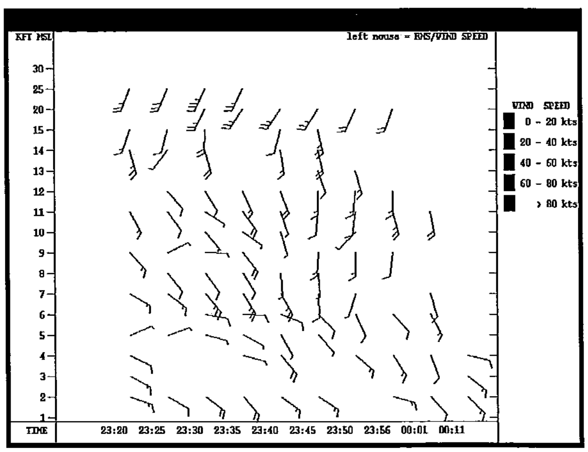

Figure. 1. Greer, South Carolina, WSR-88D VAD Wind Profile product for 2320 UTC 4 September 1996 through 0011 UTC 5 September 1996. The vertical axis is altitude in thousand foot increments. Wind barbs follow standard meteorological convention.

The most intense convection occurred between 0000 and 0230 UTC, with a loop of reflectivity values greater than 50 dBZ across the Rocky Broad Basin for most of this period. Cells redeveloped to the east of the Hickory Nut Gorge, then merged into the convective cluster anchored by the higher terrain to the west. Around 0230 UTC, the convective cluster began to collapse, accompanied by the appearance of a well-defined outflow boundary to the southeast. This collapse was associated with a backing of low-level flow to a northeasterly direction on the VWP. By 0430 UTC 5 September, rainfall had ended. Fig. 2 shows a filtered Storm Total Precipitation (STP) product for the event, with a maximum estimation of 16 cm (6.3 inches) near the headwaters of the Rocky Broad River in southeast Buncombe County.

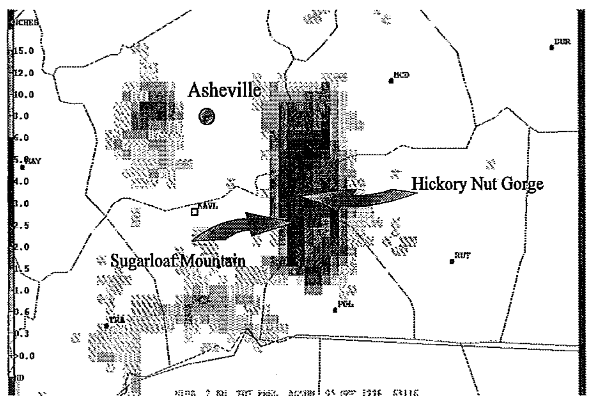

Figure. 2. Greer, South Carolina, WSR-88D storm total precipitation product for the period 1755 UTC 4 September through 0558 UTC 5 September 1996. Range of coverage is 124 n mi (230 km) and resolution is 1.1 n mi x 1.1 n mi (2 km x 2 km). The gray scale on the left depicts the intervals of estimated accumulated precipitation in inches. The maximum accumulation is 6.3 inches

d. Satellite presentation

Water vapor imagery from 0015 UTC 5 September revealed a broad ring of dry mid-level air in an arc from south Florida into the central Carolinas. The drying was associated with Hurricane Fran's subsidence region (Pelissier 1997, personal communication). This subsidence helped limit convective coverage across the central and eastern Carolinas, allowing the Atlantic airmass to reach the mountains virtually unmodified. The mid-level circulation across eastern Tennessee was also evident.

The classical cloud top temperature threshold for flash flood-producing convective systems is around -62°C (Maddox 1980; Clark et al. 1980). Convection associated with cloud tops warmer than -62°C has been termed warm-top. Flash flooding accompanied by warm-topped convection is frequently associated with "Subtle Heavy Rainfall Signatures" or SHARS (Spayd et al. 1982). In SHARS events, the convective anvil forms at the equilibrium level (EL), where temperatures often are warmer than -62°C, instead of the tropopause. In this SHARS case, the coldest cloud top temperatures were generally in the -41°C to -52°C range, with a minimum at 0102 UTC between -52°C and -58°C. The 0000 UTC 5 September 1996 GSO sounding indicated an EL temperature of -50°C, and a tropopause temperature of -62°C.

Spayd categorized SHARS systems into 5 categories: 1)Synoptic Scale Cyclonic Circulations, 2) Single clustered, 3) Multi-Clustered, 4)Large-scale overrunning, and 5)Regenerative. Multi-clustered systems involve numerous cluster mergers, and have a maximum of occurrence in the early evening and nighttime hours. The Hickory Nut Gorge convection most closely resembled the Multi-clustered system. The presence of the cold core mid-level circulation just to the west of the flash flood, however, suggests elements of the Synoptic Scale Cyclonic Circulations category were also present.

e. Observed rainfall totals

Rainfall totals from cooperative observers, weather spotters, and Integrated Flood Observation and Warning System (IFLOWS) gages around western North Carolina were analyzed after the event. Chimney Rock is located midway down the Hickory Nut Gorge, approximately 40 km southeast of Asheville. The Chimney Rock Fire Department indicated that two separate rain gages measured over 30 cm of rain in 3 h during the event. The Rocky Broad River flows east out of the Hickory Nut Gorge into Lake Lure, where the cooperative observer measured an event total of 17.1 cm.

A critical data source was an IFLOWS gage at Sugarloaf Mountain. Located at 1208 m above sea level, the gage is 5 km south of Chimney Rock, 8 km west of Lake Lure, and was ideally situated to capture the maximum intensity rainfall. Between 0000 and 0200 UTC, rain was measured in excess of 12 cm h^{-1}, with a 3-h total through 0300 UTC of 31.7 cm. The 6-h total ending at 0500 UTC was an incredible 35.6 cm. This data was available in real-time to both the National Weather Service and county officials, and proved crucial in providing timely warnings and evacuations in the affected areas. Several homes, businesses and campgrounds were washed away, but there was no loss of life.

4. SUMMARY

A catastrophic flash flood occurred along the Rocky Broad River in the Bat Cave and Chimney Rock communities of western North Carolina during the late evening of 4 September 1996. Rainfall in excess of 30 cm in a 3-h period was responsible for the flooding. The heavy rainfall was the product of a continuous flow of moist Atlantic air up the eastern escarpment of the Blue Ridge Mountains, with convection anchored by the unique terrain features around the Hickory Nut Gorge.

Analysis of upper-air data and gridded model fields from the 0000 UTC 5 September eta model provided evidence of an indirect dynamical relationship between the flooding and Hurricane Fran. This was due to interactions between the flow around an upper-level low across eastern Tennessee, and the anticyclonic outflow from the approaching hurricane. A 250-mb wind speed maximum was evident between the two systems, focusing an area of upper-level divergence across the western Carolinas.

Analysis of satellite imagery during the flood reveals that this was a SHARS event, with warm-topped convection capped by the equilibrium level rather than the tropopause. Six-hour WSR-88D precipitation estimates across the affected area were generally in the 10- to 15-cm range, with a maximum of 16 cm. Actual maximum 6-h rainfall amounts were in the 30- to 35-cm range. This case highlighted the importance of real-time rain gage data for the short-term forecasting of flash flood events.

5. ACKNOWLEDGMENTS

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