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SURFACE-BASED RAIN, WIND, AND PRESSURE FIELDS IN TROPICAL CYCLONES OVER NORTH CAROLINA SINCE 1989

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1. Introduction

During the recent 12-year span of hurricane seasons (1989-2000), several major hurricanes, tropical storms, and tropical depressions affected North Carolina. These tropical cyclones included: 1989, Hurricane Hugo; 1995, the remnants of Hurricane Allison and the remnants of Tropical Storm Jerry, Hurricane Opal; 1996, remnants of Tropical Storm Arthur, Hurricane Bertha, Hurricane Fran, the remnants of Tropical Storm Josephine; 1997, the remnants of Hurricane Danny; 1998, Hurricane Bonnie, the remnants of Hurricane Earl; 1999, Tropical Storm Dennis, Hurricane Floyd, Hurricane Irene; 2000, the remnants of Hurricane Gordon and the remnants of Tropical Storm Helene.

This paper will examine the observations in surface-based storm total rainfall, wind, and pressure fields taken during these 16 tropical cyclone events, which affected all areas of North Carolina. Where wind was not a factor to the people, as in remnants of tropical cyclones, only rain and pressure fields in the form of a track of the system will be discussed and used.

This study will indicate that while strong winds are a function of storm intensity, the rainfall and subsequent flooding is not. Further, the heavy rains are not limited to storms on the North Carolina coastline. Often a secondary rainfall maximum is well removed from the immediate coast. In some cases mid- to upper-level wind shear will transpose the rainfall maximum either left, right, or north of the center of circulation. Both of these findings about the position of the rainfall maximum are previously unpublished results.

The paper will demonstrate with these 16 different tropical systems dating back to1989 a great variability in track, winds, and pressure. The data will show that in all 16 systems the heavy rainfall and the resulting inland flooding have presented a threat to life in North Carolina.

2. Data Collection and Instrumentation

During each storm event, surface-based rainfall, wind, and pressure measurements were observed from all over North Carolina. The recording locations ranged from the National Weather Service (NWS), Federal Aviation Administration and military installations, North Carolina Agricultural Network, Cooperative Observer Networks in partnership with the NWS, and the North Carolina State Climate Office. Observations from local television station observer networks, buoys, ships, C-MAN stations, river observing point rain gauges, city and county government sites, marinas, water and sewer plants, fire stations, golf course rain gauges, amateur radio operators, and the general public also supplemented this weather reporting.

During Hurricane Fran, more than 245 observations in the eastern third of North Carolina alone helped to report weather conditions. With some of the remnant systems, statewide observations numbered 100-130.

NWS Doppler Radar storm total precipitation helped in either confirming or adding data with rainfall totals, and, in one instance, reconnaissance aircraft from the Hurricane Research Division provided wind and pressure observations. All these data were quality controlled by the author.

Observations considered to be erroneous based on time of occurrence, calibration, exposure of the instruments, damaged sensors, communication problems or power outages were eliminated. No attempt has been made to standardize these readings, and this includes wind reports not standardized to 10-meter height level in conformance with the recommendations of the World Meteorological Organization, because the time averaging periods for this wind data varied widely for the different types of observing equipment.

This paper relies heavily on graphical displays to make statewide assessments of observed data easier in each of the surface-based data fields. These graphical displays also show the track of the tropical cyclone centers whenever definable.

In looking at the life threatening effects of these tropical systems, this paper focuses on deaths directly related to the storm conditions. It does not consider fatalities such as electrocutions and heart attacks, which may be only indirectly related to the effects of the storm.

All mentions of hurricane wind categories refer to the Saffir-Simpson Scale (Simpson 1974). This scale is described at http://www.nhc.noaa.gov/aboutsshs.html .

Data for this study -- other than direct observations – come from *Natural Disaster Survey Reports, Service Assessments, Preliminary Reports* from the Tropical Prediction Center/National Hurricane Center (NHC), as well as *Storm Data.*

North Carolina newspaper graphics departments provided the graphics, which plot wind speeds in miles per hour, rainfall in inches, and pressure in millibars (mb). The artists relied on collected data and plots by the author, to contour the graphics, using appropriate quality control with the author present.

3. The Tropical Cyclones

A. Hurricane Hugo 1989

i. Overview

Hugo began as a Cape Verde type hurricane with a tropical wave moving off the shore of West Africa and becoming a tropical depression on 10 September 1989. The system strengthened to tropical storm force the next day and reached hurricane status on the 13 September, battering the Leeward Islands in the Caribbean with 72 ms^{-1} (160 mph) winds.

The hurricane made landfall in Charleston, South Carolina, near Sullivan's Island with winds in excess of 58 ms^{-1} (130 mph) around midnight locally on 21 September. It traveled inland, hitting North Carolina at Charlotte by 1000 UTC 22 September. The hurricane moved over Hickory, Northg Carolina at 1100 UTC, with gusts of more than 38 ms^{-1} (85 mph), and then continued across the northwest sections of the state.

Hugo caused an estimated $1 billion in damage to North Carolina. The state suffered $250 million damage to timber alone, with about 2.7 million acres of forests damaged in 26 counties.

One person died in Union County, as a direct result of Hugo's winds.

ii. Rainfall field interpretations

Hugo dropped most of its rain on the taller mountain peaks near Grandfather Mountain and Mount Mitchell as well as on the ridge of the Appalachians, due to orographic effects on the southeast facing slopes (see Figure 1). The southeast slopes were in the direct path of the storm. The area from Charlotte to Boone also received heavy rainfall when the tropical cyclone center collapsed. As the center collapsed, rain bands that would have been further removed from the center were now closer in proximity and trained over the same location. This resulted in higher rain amounts in a brief period of time.

Because it moved rapidly over the state, Hugo caused no major river flooding in North Carolina. Minor flooding did occur in the northern mountains, along with highway flooding in seven northwest counties.

iii. Wind field interpretations

Hugo's winds were still hurricane force when the storm reached the Charlotte area (see Figure 2). Before they abandoned the Charlotte FAA Control Tower, observers reported wind gusts to near 40 ms^{-1} (90 mph). Sustained winds of 29 ms^{-1} (65 mph) battered Charlotte leaving a 50-mile wide swath of downed trees and powerlines.

iv. Pressure field interpretations

Hugo made landfall with a central pressure of 934 mb at midnight locally (see Figure 3). By 1200 UTC, Hugo's center had moved inland to near Hickory, North Carolina, with a central pressure of 989.5 mb (about 7 millibars per hour filling rate). This rate was less than that of Hurricane Hazel, which traveled across North Carolina in 1954 at 11 millibars per hour, or Hurricane Camille in 1969 at 8 millibars per hour (Powell 1991), but more than the average of 2 millibars per hour (Malkin 1959).

v. Hugo's most notable characteristics

Hugo will be remembered for the high winds and long damage path well inland in North Carolina. Major damage occurred from Charlotte and Hickory to parts of northwestern North Carolina despite being several hundred miles from the landfall location of South Carolina. The relatively fast translational speed of Hugo helped to sustain strong winds well inland. Despite the fast translational speed of the system, seven inches of rain fell in the mountains of North Carolina during the short period of time that Hugo was in the state.

B. Remnants of Hurricane Allison 1995

i. Overview

Allison formed from a tropical wave over the Windward Islands on 28 May, which moved into the West Caribbean Sea on 1 June. At 0000 UTC 3 June, a tropical depression formed 425 km (230 nautical miles) east of Belize City, then became Tropical Storm Allison at 1200 UTC 3 June in the Yucatan Channel.

Allison strengthened to hurricane status with 33.5 ms^{-1} (74 mph) sustained winds 445 km (240 nautical miles) west of Key West, Florida. At 1400 UTC 5 June, with wind speeds of 28-31 ms^{-1} (63-69 mph), Allison made landfall along the coast of North Florida near Alligator Point/St. Marks. The system diminished to a tropical depression over Southern Georgia at 0000 UTC 6 June.

By 0600 UTC on 6 June, Allison had become extratropical with gale force winds as it moved along the coast of Georgia and South Carolina. The remnants of Allison passed just offshore Cape Hatteras at 0000 UTC 7 June. In a short period, the system dropped 10-15 cm (4-6 inches) of rain along and near its path from Florida through North Carolina. Much of the rainfall was in advance of the system center affecting North Carolina. This was due to the mid and upper level wind shear moving the system fast translationally and weakening the wind field greatly. The winds in the mid and upper levels were pushing the system from the south to the north and oriented the secondary rainfall maximum left of the center and well inland.

See Figure 4 for Allison's rainfall totals. An image of the best track (Figure 5) of Allison across North Carolina follows the rainfall graphic.

ii. Allison's most notable characteristics

Despite the fact that Allison was less than depression status and early in the season, over ten inches of rain fell in parts of North Carolina. The system made landfall in states well south of North Carolina and had diminished to remnants in Georgia on its path toward the state.

C. Remnants of Tropical Storm Jerry 1995

i. Overview

Jerry developed from a tropical wave that moved off the shore of west Africa on 11 August.
The system formed a tropical depression off the southeast coast of Florida on 23 August.

Jerry made landfall in Florida, where the center tracked across the peninsula of the state. It moved into the Gulf of Mexico briefly before striking the Florida panhandle and passing into Georgia over the next three days. Jerry's maximum winds measured 19 ms^{-1} (43 mph), with a minimum pressure of 1002 mb.

Although Jerry had made its second landfall on the Gulf Coast – as tropical storm, not a hurricane -- it had filled only 4 mb in the 36 hours it took to cross Georgia and arrive near Greer, South Carolina, with a central pressure of 1006 mb. The filling rate averaged 1 millibar per 9 hours. As the system moved toward the Appalachian Mountains, it produced very heavy rainfall near Greer, South Carolina (Pelissier 1996). Figure 7 from Pelissier (1996), illustrates the storm track.

The center of the remnants of Jerry passed through North Carolina from 1800 UTC on 27 August to 0600 UTC on 28 August. According to the Governor, it caused an estimated $6 million in uninsured losses in the Raleigh area alone. Jerry also resulted in three deaths in North Carolina, all of them vehicle-related freshwater drownings in Alamance County.

Figure 6, based on over a hundred observations, shows rainfall data pertinent to North Carolina. It should be noted, Jerry produced an area of 46 to 51 cm (18 - 20 inches) of rainfall in the area around Greer, South Carolina. The secondary maximum of rainfall associated with Jerry occurred in two different areas of North Carolina. The first, located in the southern foothills, was due to orographic effects. The second was located over Raleigh and the western piedmont. The second rainfall maximum was due to a weakening frontal boundary in the lower levels of the atmosphere, which focused the rainfall over this feature. Convergence of moisture along the boundary, aided the tropical air across the state producing high rainfall totals.

ii. Jerry’s most notable characteristics

The major impact of Jerry on North Carolina was the heavy rainfall. Jerry, a tropical storm at peak intensity, made landfall in Florida and dissipated prior to moving into South Carolina. The flow around the remnants of the system produced over ten inches of rain in the southern foothills and mountains.

D. Hurricane Opal 1995

i. Overview

Opal began as a tropical wave moving off the shore of west Africa on 11 September 1995. The system strengthened to become a tropical depression located 130 km (70 nautical miles) south-southeast of Cozumel, Mexico, on 27 September. Three days later, Opal became a named tropical storm near the north-central coast of the Yucatan Peninsula, then strengthened to hurricane status, and on 2 October in the Gulf of Mexico, became a category 4 hurricane (on the Saffir-Simpson scale).

Hurricane Opal made landfall at 1000 UTC 4 October near Pensacola Beach, Florida, with maximum sustained winds of 52 ms^{-1} (116 mph) and a minimum pressure of 942 mb. The tropical cyclone pressed inland and weakened to tropical storm status over southern Alabama, later becoming a tropical depression over southeast Tennessee.

In North Carolina, one person died from wind damage in the western part of the state, where rainfall proved particularly destructive. Opal caused $2.5 million in damage in Jackson County alone as it rumbled west of that county through east Tennessee.

ii. Rainfall field interpretations

As Opal headed through the Lower Mississippi Valley, satellite imagery showed that much of its associated rain fell in advance and east of the center of circulation, in the direction of North Carolina. The rainfall pattern was due in large part to mid and upper level wind shear both forcing the system rapidly north and weakening it. Because Opal moved north, the south-facing slopes of North Carolina's Appalachians received the highest amounts of rainfall due to orographic lifting (see Figure 8), with Highlands in Macon County measuring 22.73 cm (8.95 inches), and Robinson Creek in Jackson County getting 25.1 cm (9.89 inches). A frontal complex and outer spiral band maximized the secondary rainfall near the Raleigh-Durham area.

iii. Wind field interpretations

By the night of 4 October as Opal passed through eastern Tennessee, the Tropical Prediction Center (formerly National Hurricane Center) had already classified the system as extratropical, with wind speeds generally 21 ms^{-1} (46 mph) around the center. The *Service Assessment of Hurricane Opal* reported that winds averaged 18 ms^{-1} (40 mph), with gusts up to 27 ms^{-1} (60 mph) in the North Carolina mountains (see Figure 9). Grant Goodge, a local cooperative observer and climatologist with the National Climatic Data Center in Asheville, recorded a peak wind gust of 36 ms^{-1} (81 mph) at his home, an elevation of 1317 m (4320 feet).

iv. Pressure field interpretations

Opal's central pressure at landfall measured 942 mb, and the lowest pressure recorded in the North Carolina Mountains was 998.6 mb. This results in a fill rate of 4.35 millibars per hour -- more than twice the average for Atlantic-landfalling hurricanes of 2 millibars per hour (Malkin 1959).

v. Opal's most notable characteristics

Although Opal never had a center of circulation in North Carolina, it will be remembered as a heavy rain and strong wind producer. Due to Opal's fast translational speed as a depression through Tennessee, the system produced strong winds in the mountains and most notably, four to eleven inches of rain. The rain field was well removed to the north and right of the center of circulation as viewed in the satellite imagery. This separation of the rain field and center was due in large part to strong wind shear in the mid to upper levels (500 mb to 200 mb) from south southwest to northeast across the system, and supports the findings of Carr and Bosart (1978).

E. Remnants of Tropical Storm Arthur 1996

i. Overview

Arthur formed from a tropical wave that moved over Puerto Rico and the Dominican Republic on 15 June. The wave continued west-northwest to the Bahamas by 16 June. The next day, at 1800 UTC, a tropical depression formed near the east end of Grand Bahama Island; then, at 0000 UTC 19 June, Tropical Storm Arthur formed, with maximum winds of 21 ms^{-1} (46 mph).

At 0000 UTC 20 June, Arthur made landfall at Cape Lookout, North Carolina, moved over the Pamlico Sound, and continued east-northeast over Cape Hatteras (see Figure 11). The storm then proceeded into the Atlantic, where it was downgraded to a tropical depression about 185 km (100 nautical miles) northeast of Cape Hatteras. Frying Pan Shoals Light recorded 17.5 ms^{-1} (39 mph) sustained winds with gusts of 21 ms^{-1} (46 mph) at 1700 UTC 19 June at a height of 44 m (145 feet). Ocracoke Island measured sustained winds of 17 ms^{-1} (38 mph) and gusts of 20 ms^{-1} (45 mph). Rainfall totals – see Figure 10 - ranged from 5-10 cm (2-4 inches) across the coastal plains of North Carolina.

Locally heavy rains occurred in advance of the cyclone center due to strong wind shear from south to north. Many locations reported rainfall totals ranging from 5 to 10 cm (2-4 inches) across the coastal plains of North Carolina.

ii. Arthur's most notable characteristics

Despite the center of Arthur making landfall on the coast of North Carolina, much of the rain from Arthur stayed to the right (east) of the center of circulation. Strong winds aloft (500 mb – 200 mb) helped to shear the rain field away from the low level (surface to 850 mb) center of circulation. This supports the earlier findings of Carr and Bosart (1978).

F. Hurricane Bertha 1996

i. Overview

On 1 July1996, Bertha began as a tropical wave moving off the shore of Africa near the Cape Verde Islands, and on 5 July, strengthened into a tropical depression in the mid-Atlantic. By 8 July, Hurricane Bertha moved through the Leeward and Virgin Islands, and then the next day turned slowly to the northwest, attaining maximum winds of 51 ms^{-1} (115 mph) at 0600 UTC some 256 km (138 nautical miles) north of Puerto Rico. No hurricane since Alma in 1966 had attained this strength this early in the season.

At 2000 UTC 12 July, Bertha made landfall between Wrightsville and Topsail Beaches in North Carolina as a Category 2 Hurricane on the Saffir-Simpson scale, with a forward speed of 8 ms^{-1} (17 mph). Its central pressure measured 977 mb at Surf City, North Carolina.

The higher wind measurements occurred to the right side of the hurricane eye. Camp Lejune and Jacksonville measured the highest wind gusts in North Carolina at 48 ms^{-1} (108 mph), and the highest sustained wind reached an estimated 46.5 ms^{-1} (104 mph). As Bertha tracked across the coastal areas of North Carolina, its sustained winds regularly measured between 20 to 27 ms^{-1} (45 to 60 mph).

Rainfall from Bertha ranged from 5 to10 cm (2 - 4 inches) across North Carolina, with isolated amounts of 15 cm (6 inches).

Bertha caused one fatality, due to drowning in the saltwater rip current. The Insurance Institute estimated damages to North Carolina at $135 million along the coast. For the entire State, damages reached an estimated $270 million.

ii. Rainfall field interpretations

Prior to Bertha crossing the Gulf Stream, satellite water vapor imagery indicated a poorly organized system but also a strong upper-level jet along the North Carolina/Virginia border from mountains to coast. The jet, along with an embedded impulse, helped form a strong vortmax that shaped the deep layer mean flow. The flow acted to move Bertha along a north-northeast track.

As Bertha crossed the Gulf Stream, the system quickly gained organization, with an abundance of strong rain falling around the center of the circulation. The pattern of heavy rainfall from Bertha (see Figure 12) clearly followed the path of the center, while a secondary rainfall maximum extended between Goldsboro, Greenville, and New Bern, due to the collapse of the hurricane eye. This collapse allowed the two innermost spiral rain bands – which would have been on opposite sides of the eye, had it remained intact, to cross over the same area, causing increased rainfall.

iii. Wind field interpretations

Winds remained very strong to the right side of the hurricane, keeping some of the highest winds over the ocean (see Figure 13). A reconnaissance aircraft recorded flight-level winds of 57 ms^{-1} (127 mph) in the northeast quadrant of circulation several hours prior to landfall. Surface winds at landfall measured 46 ms^{-1} (104 mph).

iv. Pressure field interpretations

The NHC official advisory at 0700 UTC located Bertha’s center 45 miles west-southwest of Norfolk, Virginia, placing it almost out of North Carolina some 11 hours after making landfall in the state. The central pressure at landfall measured 974 mb (see Figure 14), and the pressure at 0700 UTC was an estimated 994 mb, indicating a nearly average filling of the cyclone at 2 millibars per hour (Malkin 1959).

v. Bertha’s most notable characteristics

Bertha will be remembered in eastern North Carolina as being one of the earliest hurricanes in a season. Although much of the higher winds remained just offshore, half a foot of rain was common as Bertha moved quickly through the State.

G. Hurricane Fran 1996

i. Overview

Hurricane Fran formed from a tropical wave that moved off the shore of the African West Coast on 22 August. By 1200 UTC 23 August, the wave strengthened into a tropical depression just southeast of the Cape Verde Islands, and then increased to tropical storm status at 1200 UTC on 27 August while some 1670 km (900 nautical miles) east of the Lesser Antilles. Hurricane Fran formed at 0000 UTC on 29 August while 740 km (400 nautical miles) east of the Leeward Islands. See Figure 18 for a visible satellite image of Hurricane Fran as it neared North Carolina.

At 0030 UTC on 6 September, Hurricane Fran made landfall in North Carolina near Bald Head Island as a Category 3 hurricane on the Saffir-Simpson Scale. Hurricane Eduoard had just moved through the Atlantic ahead of Fran, veering off Cape Hatteras by several hundred miles, while Hurricane Bertha had moved across North Carolina seven weeks earlier. Not since 1955 had two hurricanes made landfall in North Carolina in the same season.

Fran proved to be the strongest storm to hit the state since Donna in 1960. Its powerful force extended well inland over North Carolina, with winds gusting to hurricane force north of Raleigh, some 230 km (125 nautical miles) from the point of landfall.

The storm also caused nine deaths in North Carolina -- four fatalities from fallen trees, one from a collapsed home, two from freshwater drowning, one from hypothermia exposure (though possibly a suicide), and one (in a HUM-V driving along the coast) attributable to storm surge. Damage due to Fran reached an estimated $2.3 billion, making it the most expensive hurricane to date in North Carolina (Cline 1997).

ii. Rainfall field interpretations

According to the satellite water vapor imagery, Fran actually weakened as it passed over the Gulf Stream. As it hit North Carolina, the storm showed little moisture in the entire southern half of the system. The collapse of the hurricane eye, however, resulted in maximum secondary inland rainfall (see Figure 15) and allowed two very heavy spiral bands of rainfall to pass directly over Raleigh. In contrast, before the hurricane eye collapsed, areas on either side of the center of circulation received about half as much rain as Raleigh. This pattern of two spiral bands passing through Raleigh was observed from the National Weather Service Raleigh Doppler Radar images from that night.

iii. Wind field interpretations

With Fran, higher wind speeds occurred to the right of the center of circulation. Satellite imagery showed that the area of higher winds near Beaufort to New Bern matched the location of a strong spiral band near the center of the system. Winds on the right side of Fran deteriorated quickly as Fran moved inland (see Figure 16). Wind speeds left of the center dropped off significantly in a short distance.

At landfall, Figure Eight Island (east of Wilmington) estimated sustained winds at 52 ms^{-1} (115 mph), while Frying Pan Shoals Light measured gusts of 55 ms^{-1} (123 mph) and 56 ms^{-1} (124 mph). An unprecedented overland reconnaissance flight 76 km to the northeast of the storm center reported flight-level winds of 55 ms^{-1} (123 mph). At 231400 UTC on 5 September, 96 km east of the center, winds measured 58 ms^{-1} (130 mph) at flight level near 3,050 m (10,000 feet) (Mayfield 1996).

iv. Pressure field interpretations

The pressure rose steadily from 954 mb at the time of landfall to 976.6 mb at the Raleigh-Durham airport at approximately 070000 UTC (see Figure 17). This represented a steady rise of nearly 3.5

millibars per hour -- nearly double the average filling rate of 2 millibars per hour of 11 hurricanes described by Malkin (1959), but less than that for Hurricane Hazel (1954, 11 millibars per hour), which had passed through nearly the same area of the state.

v. Fran's most notable characteristics

Fran will be known for the widespread damage well inland in North Carolina. Despite wind speeds sustained at tropical storm strength by the time the center of the system reached south of Raleigh, tree and structural damage to the area was devastating. Although Fran was only in the state for seven hours, heavy rains of over ten inches fell several hundred miles from the landfall area (secondary maximum well inland). Inland flooding was a problem associated with Fran.

H. Remnants of Tropical Storm Josephine 1996

i. Overview

Josephine formed from an old frontal boundary over the southwestern Gulf of Mexico on 29-30 September. A low pressure area developed over the Bay of Campeche on 1-2 October, became a tropical depression at 1800 UTC 4 October, then strengthened to Tropical Storm Josephine on 1800 UTC 6 October, with a central pressure of 1001 mb.

With maximum sustained winds measuring 31 ms^{-1} (69 mph), Josephine made landfall at 0330 UTC 8 October at Apalachee Bay, Florida, in Taylor County. It became extratropical over southern Georgia at 0600 UTC 8 October as the forward speed increased to 21 ms^{-1} (46 mph). The remnants of Josephine moved over Cape Cod by 0600 UTC 9 October.

Figure 19 illustrates Josephine's rainfall. Visible satellite imagery illustrated the tropical cyclone was sheared to the north-northeast, which helped to push rainfall well in advance of the center of the system. Figure 20 shows the best track of Josephine over North Carolina.

ii. Josephine's most notable characteristics

Though just remnants of a weakened tropical storm, Josephine will be remembered in southeastern North Carolina as producing ten inches of rain. This continued the inland flooding from this area of state, begun by Bertha and Fran.

I. Remnants of Hurricane Danny 1997

i. Overview

Danny grew out of a non-tropical system. It began as an upper-tropospheric trough over the southwestern United States that helped form a small, weak area of low pressure in the north-central Gulf of Mexico near the Louisiana coast on 14 July. By 1200 UTC on 16 July, this slow moving system reached tropical depression status, and then, because of information gathered by hurricane hunter aircraft reconnaissance, was upgraded to tropical storm strength at 1500 UTC on 17 July.

The system became Hurricane Danny at 0600 UTC on 18 July, with a center near the Mississippi River Delta. The storm's maximum winds measured 36 ms^{-1} (81 mph), with a minimum central pressure of 984 mb. Danny made landfall in southwest Alabama on 19 July, then moved slowly inland.

On 22 July, the system -- no longer classified as a storm or hurricane -- passed near Greer, South Carolina, and then moved south and east of Charlotte, North Carolina, in the predawn hours of 23 July, where it again formed a center with cyclonic rotation (Riordan 1999). The system continued moving northeast, passing near Raleigh before moving offshore at Norfolk, Virginia, where it was renamed Tropical Storm Danny at 1900 UTC on the 24th.

While in North Carolina, Danny produced 20 to 30.5 cm (8 to 12 inches) of rainfall, and caused three fatalities. In Charlotte, two people in a vehicle died from freshwater drowning, while a girl also drowned in freshwater, swept into a creek by floodwaters near Charlotte.

ii. Rainfall field interpretations

As Danny moved into North Carolina, a well-defined spiral rain band formed to the east of the center of circulation due to deep layer mean winds blowing west-southwest to the east-northeast across the system. Danny's highest rainfall totals in North Carolina occurred near the Charlotte area (see Figure 21) as the system became better organized with a definitive center of circulation.

As the system moved toward Raleigh and on to Norfolk, it became clear, by applying a logarithmic spiral curve to the radar imagery from nearby NWS sites, that the storm exhibited trochoidal motion. Trochoidal oscillations are high-frequency oscillations in the location of the vortex center about a mean trajectory. Because the spiral rain bands remained on one side of the system and rotated cyclonically about the center, they helped to make the high-frequency oscillations in the motion of the system (trochoidal) by shifting the mass of the rainfield from one side to the other. As the larger mass in the rainfield moves toward the side of the system in the direction of mean motion the system increases translational speed. The opposite is true when the mass of the rainfield is on the opposite side of the mean trajectory the system slows translational speed.

And because the storm center and its rain bands passed over the same area in a short period of time, Danny's rainfall measured two to three times the totals from areas just outside its direct path.

iii. Pressure field interpretations

As Danny moved toward North Carolina, water vapor satellite imagery and upper-level analysis indicated an upper level trough of moderate amplitude approaching from the west as surface conditions began to intensify. An old decaying frontal boundary stretched from Greer, South Carolina, to Charlotte. The system followed this path, moving east of Charlotte, where a stationary front formed on the low-pressure area that was Danny.

As a poorly defined center began to take shape, the central pressure near Greer measured 1009 mb. Within 14 hours, the system's central pressure registered 1007 mb east of Charlotte (see Figure 22). The system now became better organized, moving through Raleigh with a central pressure of 1004 mb, and then on to Norfolk, Virginia, with a central pressure of 1000 mb. At the coast, it was renamed Tropical Storm Danny.

Winds within Danny increased from 14 ms^{-1} (31 mph) over Anderson, South Carolina, to 18 ms^{-1} (40 mph) near Monroe, North Carolina, just east of Charlotte. As the system continued to become better organized, it produced winds of 23 ms^{-1} (51 mph) at Raleigh-Durham International Airport, while Raleigh radar VAD winds -- located east of the city and closer to the track of the center – reported 27 ms^{-1} (60 mph). As Danny moved over Norfolk, Virginia, NWS WSR-88D Doppler Radar estimated winds of 32 ms^{-1} (72 mph).

iv. Danny's most notable characteristics

Danny was an enigma. Five days after making landfall along the Gulf Coast the system intensified over land in North Carolina. The resultant convection about the newly formed center aided in producing heavy rains of seven or more inches along the path and was responsible for inland flooding.

J. Hurricane Bonnie 1998

i. Overview

Bonnie formed from a tropical wave that moved over Dakar, Senegal, in west Africa on 14 August; this wave moved off the shore of Africa and formed a tropical depression by 1200 UTC 19 August. The system strengthened to become Tropical Storm Bonnie on 1200 UTC 20 August, and then skirted the Leeward Islands; at 0600 UTC on 22 August, it was upgraded to Hurricane Bonnie 370 km (200 nautical miles) north of Hispaniola. About 280 km (150 nautical miles) east of San Salvador in the Bahamas, Bonnie reached maximum intensity of 51 ms^{-1} (115 mph), with a minimum pressure of 954 mb.

Bonnie's eye passed just east of Cape Fear, North Carolina, at 2130 UTC 26 August; then, the following day, the system -- a strong category 2/weak category 3 hurricane -- made landfall near Wilmington, North Carolina at 0330 UTC, with a maximum wind of 49 ms^{-1} (109 mph) and minimum pressure of 964 mb. Winds measured 53.5 ms^{-1} (120 mph) at 0138 UTC at the North Carolina State Port in Wilmington, and 51 ms^{-1} (115 mph) at 1951 UTC at Wrightsville Beach. The third hurricane in three years to hit the coast of North Carolina, Bonnie slowed over eastern North Carolina, leaving 20 to 28 cm (8 to 11 inches) of rain in the coastal plain. Then it weakened to a tropical storm, before moving offshore where it regained hurricane strength.

In its wake, Bonnie left an estimated $240 million in damages in North Carolina, according to the Property Claim Services Division of American Insurance Services Group. That may be a low estimate, however, since there is a 2:1 ratio in total damage estimate to insured damages. Bonnie's true costs, therefore, may have reached $1/2 billion in total damages in the state.

The hurricane caused one fatality. A 12-year-old girl in Currituck County died when a tree crashed through her home.

ii. Rainfall field interpretations

At the time of landfall, satellite imagery indicated a very symmetrical tropical cyclone. As it approached the coast of North Carolina, Bonnie dropped higher amounts of rainfall along its direct path and to the right of the storm, especially when the system slowed and turned to the northeast. Again, the highest rainfall totals fell in the direct path of the center of circulation; thus the area of coastline north and east of Wilmington received rain nearly twice as long as most other regions (see Figure 23).

Rainfall totals then decreased along Bonnie's direct path from Swanquarter northeastward, because the system was moving much faster – due, in part, to a middle-level trough from the west.

iii. Wind field interpretations

Because of the direct path of the center of circulation, Bonnie's wind fields proved strongest in the Southport to Topsail Beach section along the North Carolina coast (see Figure 24). Winds remained strong for an extended period as the system slowly turned from a northwest motion to a northeast motion.

As the wind field graphic shows, the stronger winds widened as the system moved toward New Bern and Nags Head, due to a faster translational speed, as well as a weakening of the overall system. It is characteristic of a weakening tropical storm for the wind field to become widely spread.

iv. Pressure field interpretations

At landfall near Wilmington, central pressure measured 964 mb (see Figure 25). During the 24 hours that Bonnie remained over North Carolina before moving offshore, the pressure rose to 984 mb. The rise of nearly 1 millibar per hour was below the average of 2 millibars per hour (Malkin 1959), due, in part, to the close proximity of Bonnie's center of circulation to the coast and the nearly flat terrain over which it passed.

v. Bonnie's most notable characteristics

Bonnie will be remembered from the slow translational speed, as the long anticipated turn in track to the right occurred just inland of southern North Carolina. This resulted in winds that met hurricane force along the southern coast for an extended time period. Similarly, eight to eleven inches of rain were a result of the longer time period when Bonnie was moving over extreme southeastern sections of the state.

K. Remnants of Hurricane Earl 1998

i. Overview

Earl formed from a tropical wave moving off the shore of West Africa on 17 August, following, by only three days, the tropical wave that eventually became Hurricane Bonnie. The close proximity to Bonnie kept Earl from strengthening, and only a weak circulation formed as it passed through the

Lesser Antilles on 23 August.

Then, at 1200 UTC 31 August, the tropical wave moved into the Gulf of Mexico, forming a tropical depression between Merida and Tampico, Mexico. It became Tropical Storm Earl at 1800 UTC 31 August, 927 km (500 nautical miles) south-southwest of New Orleans. The system was upgraded to Hurricane Earl, at 1200 UTC 2 September, while located 232 km (125 nautical miles) south-southeast of New Orleans.

Earl made landfall at 0600 UTC 3 September near Panama City, Florida, as a Category 1 hurricane on the Saffir-Simpson scale. It moved northeast out of the area around Florence, South Carolina, into Sampson County, North Carolina, at 0600 UTC 4 September. The system continued to the northeast, passing through Washington, North Carolina, at 1200 UTC 4 September, and then, as an extratropical system, moved off the Mid-Atlantic Coast just east of Norfolk, Virginia, at 1800 UTC 4 September. In North Carolina, rainfall totals commonly ranged from 7 to 15 cm (3 to 6 inches).

ii. Rainfall field interpretations

Water vapor and visible satellite imagery indicated strong wind shear in Earl at the time of landfall along the Gulf Coast. This shear continued as the hurricane passed over North Carolina, helping to keep the rain field well in advance of the actual center of circulation. The center tracked through the eastern sections of the state, where rainfall was twice as heavy as in those areas outside the direct path of the hurricane (see Figure 26). As the system moved through North Carolina, rainfall diminished as the system weakened, due, in part, to the strong wind shear.

iii. Pressure field interpretations

Along its path over Florida and Georgia, Earl's pressure rose 15 mb over 39 hours (Weekly Weather and Crop Bulletin). The system made landfall with a central pressure of 988 mb, then moved on to Florence, South Carolina, with a central pressure of 996 mb. Earl’s pressure measured 999 mb through much of eastern North Carolina (see Figure 27), and 1003 mb just offshore Norfolk, Virginia. Because of the system’s poor organization and the strong wind shear as it passed over the southeastern United States, the filling rate of 0.4 millibars per hour was well below the average of 2 millibars per hour (Malkin 1959).

iv. Earl’s most notable characteristics

Despite being in North Carolina for a short period of time, Earl was able to produce rains of one to almost five inches. The track of Earl took it close to areas earlier impacted by Bonnie.

L. Tropical Storm Dennis 1999

i. Overview

Dennis developed from a tropical wave that moved off the shore of West Africa on 17 August. The circulation created a tropical depression at 0000 UTC 24 August, 350 km (190 nautical miles) east of Turks Island. At 2100 UTC 24 August, Tropical Storm Dennis formed while in the southeastern Bahamas; then, two days later, while still in the Bahamas, it reached hurricane strength.

Dennis, with no visible eye, passed 111 km (60 nautical miles) south of North Carolina on 28th and 29th of August, and then moved to 204 km (110 nautical miles) east of Cape Hatteras on 31 August. The system slowed greatly and weakened to a tropical storm on 1 September, decreasing to 23 ms^{-1} (52 mph), when a ridge to the north turned Dennis back toward North Carolina. Just below hurricane strength, Dennis made landfall near Cape Lookout at 2100 UTC on 4 September.

On 30 August, during Dennis's first pass by North Carolina, Oregon Inlet measured maximum sustained winds at 27 ms^{-1} (61 mph) and gusts up to 40 ms^{-1} (89 mph) at 2030 UTC. Wrightsville Beach measured a gust of 49 ms^{-1} (110 mph), while Hatteras Village reported 44 ms^{-1} (98 mph). Frying Pan Shoals Light, an offshore station with wind equipment 44 m (145 feet) above the surface, measured winds of 42 ms^{-1} (93 mph) and a gust of 50 ms^{-1} (112 mph), with a minimum pressure of 977.2 mb. During Dennis's second pass on 4 September, Cherry Point Marina measured winds at 21 ms^{-1} (47 mph), with gusts up to 27 ms^{-1} (61 mph) at 2005 UTC.

Ocracoke Island reported total rainfall from Dennis at 48.6 cm (19.13 inches), and throughout the eastern half of the state, storm total amounts ranged from 15 to 25 cm (6 to 10 inches).

ii. Rainfall field interpretations

Dennis's rainfall pattern in North Carolina over an eleven-day period reflected the erratic path of the system as it first passed the state and then turned slowly to come back toward shore (see Figure 28).

During its first pass on 30 August, higher amounts of rain fell on the southern coast. Then, as Dennis tracked inland in the early morning hours of 5 September, higher amounts fell on areas around Raleigh, Durham, Rocky Mount, Greenville, and Kinston, while the outer banks and central coast of North Carolina experienced higher rainfall totals over a period of several days.

The table below shows the eleven-day rainfall totals in North Carolina, ending at 1200 UTC 8 September 1999, that are greater than or equal to 15 cm (6 inches). Data courtesy of the National Climatic Data Center.

Station	Rainfall (cm)	(in)	Station	Rainfall (cm)	(in)
Aurora	27.13	10.68	Greenville	19.46	7.66
Jacksonville	26.77	10.54	Edenton	18.62	7.33
Cherry Point	25.86	10.18	Wilsonville	18.06	7.11
Hatteras	23.62	9.30	Enfield	17.81	7.01
Apex	22.53	8.87	Kinston	17.27	6.80
Raleigh/Durham	21.49	8.46	Rougemount	16.99	6.69
Elizabeth City	20.75	8.17	Rocky Mount	16.59	6.53
Goldsboro (GSB)	20.42	8.04	Butner	16.51	6.50
Goldsboro	19.71	7.76	Arcola	16.10	6.34
Neuse	19.61	7.72	New Bern	15.47	6.09
Wilson	19.53	7.69	Oxford	15.42	6.07

iii. Wind field interpretations

The highest wind measurements appeared as Dennis, a hurricane at that point, passed offshore near Wilmington. These higher amounts continued through the extreme eastern sections of the central coast. By the time Dennis tracked back toward North Carolina on 4-5 September, the system had weakened to a tropical storm, with its wind fields diminishing as it moved inland. Figure 29 has the highest sustained winds for the eleven-day period contoured with peak gusts during the same period plotted for specific locations.

iv. Pressure field interpretations

As a hurricane, Dennis underwent many changes in both track (see Figure 30) and intensity as it lay to the northeast of Cape Hatteras, North Carolina, for several days. By the time Tropical Storm Dennis made landfall near Cape Lookout the pressure measured 984 mb, while the storm system filled to 996 mb as it moved out of the state into Virginia. This constitutes a filling rate of 12 mb over 18 hr or 0.67 millibars per hour.

v. Dennis's most notable characteristics

Dennis will long be remembered as the storm that lasted eleven days for North Carolina. It should be noted that prior to Dennis affecting North Carolina the state was in both a heat wave and drought. The rainfall from Dennis helped to fill inland reservoirs, and estuaries. Rainfall totals of six to eleven inches were common during the eleven-day passage of Dennis. The effect from Dennis's winds as it lay offshore North Carolina for several days was to fill the sounds and rivers that empty into those sounds with water pushed inland.

M. Hurricane Floyd 1999

i. Overview

Floyd formed from a tropical wave that moved off the shore of West Africa on 2 September. As the system became better organized, it was upgraded to a tropical depression at 1800 UTC 7 September about 1850 km (1000 nautical miles) east of the Lesser Antilles. Tropical Storm Floyd formed at 0600 UTC 8 September while located 1390 km (750 nautical miles) east of the Lesser Antilles, and was further upgraded to hurricane status at 1200 UTC 10 September while located 370 km (200 nautical miles) east-northeast of the northern Leeward Islands.

Hurricane Floyd became a category 5 hurricane between 0600 and 1800 UTC 12 September, while just southeast of the Bahamas and north of Puerto Rico. Aircraft reconnaissance reported winds at flight level to be 77 ms^{-1} (171 mph) at 0930 UTC and 70 ms^{-1} (155 mph) at 1120 UTC. The minimum pressure was estimated to be 921 mb. See Figure 34 for a visible satellite image of Floyd near the Bahamas.

At 0630 UTC 16 September, Floyd made landfall in North Carolina at Cape Fear as a category 2 hurricane on the Saffir-Simpson scale. Maximum winds were 46 ms^{-1} (104 mph) while moving forward at 8 ms^{-1} (17 mph). During the day on 16 September, Floyd moved through eastern

North Carolina and then headed back to Norfolk, Virginia.

ii. Rainfall field interpretations

As Floyd moved through eastern North Carolina, the highest rainfall followed the center of circulation and just to the left of the center of circulation, due in part to: mid and upper level wind shear blowing from the southeast to northwest over Floyd, an old frontal boundary over eastern North Carolina, and in part to its trochoidal motion. This motion allowed the largest amounts of the rain field to rotate cyclonically about the center, shifting the mass of the rain field slightly. This, in turn, slowed the system down when the larger spiral bands wound up on the opposite side of its forward motion. As the center slowed, more of the mass of the rain field passed across the same surface area, thus adding significantly to rainfall totals. The frontal boundary was just to the left of the actual best track of Floyd. Secondary rainfall maxima were all located to the left of the track (see Figures 31 and 33).

iii. Wind field interpretations

Floyd's winds were strongest in the direct path of the center and quickly diminished over inland areas. Corridors of higher winds existed as the system made landfall and moved in a straight line through eastern North Carolina during a ten-hour period.

Figure 32 illustrates the highest wind gusts and contours the sustained wind field.

iv. Pressure field interpretations

At landfall, Floyd's central pressure measured 956 mb near Cape Fear. As the system passed, Norfolk recorded 977 mb, with an estimated central pressure of 974 mb, indicating a filling rate averaging 1.8 millibars per hour.

v. Floyd's most notable characteristics

Floyd will be remembered best for its 500-year major flood event over inland North Carolina. The large death toll from Floyd (appendix A) was mainly attributed to people driving their vehicles into flooded roadways. This death toll makes Floyd the most devastating tropical system to impact the region in 45 years (Hurricane Hazel, 1954).

Floyd delivered more than 46 cm (18 inches) of rain to several locations in eastern North Carolina, and the cumulative effect of these rains along with those from Hurricane Dennis ten days earlier caused widespread flooding that lasted for two months across the eastern third of the state. Because of Dennis, inland reservoirs and estuaries had filled, and ground water tables had risen to near the surface in inland regions. And, as Dennis lay offshore for several days, it had sent water backing up into the coastal rivers and sounds. The water was slow to recede because there are only three inlets through which the water could return to the Atlantic Ocean.

Much of the rain in Floyd was directed in areas to the left (west) of the track of the center in contrast to the findings of Carr and Bosart (1978). This was due in most part to wind shear in the middle to upper levels across Floyd displacing the rain field slightly left from the center of circulation, and in part due to an old frontal boundary across eastern North Carolina.

Dennis and Floyd thus combined to cause inland flooding lasting months and covering 500-year flood plains. The flooding, in turn, resulted in 35 deaths and final estimated damages between $5 and $6 billion in North Carolina.

N. Hurricane Irene 1999

i. Overview

Irene formed from a broad area of low pressure remaining over the southwestern Caribbean between 8 and 10 October. On 11 October, a tropical wave interacted with this area of low pressure. A tropical depression officially formed in the northwestern Caribbean at 0600 UTC 13 October. At 1200 UTC, Tropical Storm Irene developed and moved across the Isle of Youth, Cuba.

Irene strengthened to hurricane status over the Florida Straits near Key West at 1300 UTC 15 October, but was downgraded to tropical storm status near Cape Sable, Florida. As Irene re-intensified to hurricane status at 0000 UTC 16 October, it moved offshore at Palm Beach County near Jupiter, Florida, and then ran parallel to the Florida east coast to North Carolina.

Near 0000 UTC 18 October, Hurricane Irene passed offshore Cape Fear, North Carolina, by 28 km (15 nautical miles), then moved parallel to the North Carolina coast to Cape Lookout before heading northeast into the Atlantic.

At 0600 UTC 18 October, Irene's winds measured 49 ms^{-1} (109 mph) sustained, with a minimum pressure of 964 mb. Coming just 32 days after the devastating rainfall of Floyd, this system's rains averaged between 7.25 and 17 cm (2.86 - 6.69 inches) across the eastern third of North Carolina, and helped the flooding from Floyd to continue well into November.

ii. Rainfall field interpretations

Irene delivered rains of 15 to 23 cm (6-9 inches) across some the hardest hit regions of flooded eastern North Carolina. The system's spiral rain bands caused these rainfall totals, in part, along with shearing in the middle and upper levels of the atmosphere that helped to move heavier rains inland over eastern North Carolina in front of the center of circulation (see Figure 35). This shearing resulted from an upper-level trough that forced Irene on a fast track to the northeast.

iii. Wind field interpretations

Because Irene tracked just offshore southeastern North Carolina, both its highest sustained winds and wind gusts remained restricted to the coastal areas (see Figure 36). The offshore buoys and automated station at Cape Lookout -- closest to Irene's center of circulation -- recorded the highest wind gusts.

iv. Pressure field interpretations

Figure 37 shows the best track of Hurricane Irene. Because its center of circulation never made landfall or passed over North Carolina, the system's rate of filling is not given.

v. Irene's most notable characteristics

Despite the fact that Irene never made landfall in North Carolina, heavy rains atop the already saturated land of eastern North Carolina from Dennis and Floyd prolonged the 500-year flood. The rain field in Irene was separated from the low-level center of circulation resulting in heavy rains over eastern North Carolina. The rain field was separated from the center of circulation due to strong wind shear over the middle to upper levels of Irene. This resulted in the heavier rains being displaced to the left (west) of the center of circulation These findings are in contrast to Carr and Bosart (1978).

O. Remnants of Hurricane Gordon 2000

i. Overview

Gordon formed from a tropical depression that was located just south of Cozumel, Mexico, at 1200 UTC 14 September. The depression moved across the Yucatan Peninsula and into the Gulf of Mexico. By 1200 UTC 15 September, it increased to tropical storm strength offshore the northwest tip of Cuba.

As the system moved northeast, it became Hurricane Gordon west of Ft. Myers, Florida, then made landfall as a tropical storm north of St. Petersburg near Cedar Key at 0300 UTC 17 September. Gordon moved inland to just north of Jacksonville, Florida, and west of Savannah, Georgia, before being downgraded to a tropical depression at 1500 UTC 18 September. The remnants of Gordon passed through North Carolina between 1800 UTC 18 September and 1800 UTC 19 September. Rainfall data are given in Figure 38.

ii. Gordon's most notable characteristics

Despite making landfall in Florida and being less than tropical storm strength by the time Gordon arrived in North Carolina, rainfall totaled 5 to more than 10 cm (2 to 4+ inches) in the state.

P. Remnants of Tropical Storm Helene 2000

i. Overview

Helene formed from a tropical wave that became a tropical depression several hundred km east of the Leeward Islands at 2000 UTC 15 September. The depression moved through these islands and into the Caribbean, finally crossing the western tip of Cuba on 1500 UTC 20 September. At 1500 UTC the next day, Tropical Storm Helene formed in the northeast Gulf of Mexico, and made landfall on the western end of the Florida Panhandle near Destin at 1500 UTC 22 September. Helene moved inland, weakening to tropical depression status over southwestern Georgia by 2100 UTC 22 September. Rainfall data appears in Figure 39.

ii. Helene's most notable characteristics

Heavy rains from Helene came to North Carolina despite its landfall on the Florida panhandle. The remnants of Helene moved through North Carolina from 0000 UTC 23 September until 2100 UTC 23 September, bringing 5 to 10 cm (2 to 4 inches) of rain to the state.

4. Conclusions

With these 16 different tropical systems dating back to 1989 a great variability in track, winds, and pressure is seen. The one common thread in all 16 systems remains the heavy rainfall and the resulting inland flooding have presented a threat to life in North Carolina.

The review of surface-based rainfall fields resulted in important findings. Rainfall sufficient to cause flooding does not necessarily require a tropical system to make landfall. Tropical remnants are as big a threat to life in some cases as hurricanes due to the rainfall and subsequent inland flooding. And often – as in the case of Hurricane Fran and others-- a secondary rainfall maximum can occur inland as the center of the system collapses, allowing for two rain bands to pass over the same area in a short period of time making the threat of flooding imminent. Thus, rainfall and subsequent flooding is not a function of storm intensity at all.

Wind shear can shift the rain field either well to the east, west or north of the approaching center and is a factor in determining where the rain fields will be most heavy. Hurricane Irene, for example, just missed North Carolina, while the center of Hurricane Opal moved through eastern Tennessee. Yet heavy rains from these systems did pass through North Carolina. Hurricane Floyd had all of the heavier rainfall to the left of the track as well. Thus, the track of the center is not necessarily a function of the track of the heavy rain field. Carr and Bosart (1978) found heavy rain may fall to the right of the track. However, observations of rainfall patterns and tropical cyclone tracks indicate, for North Carolina, the heavy rain can be sheared to the left of the track as well.

Rainfall patterns that manifest a secondary maximum well inland can also be attributed to several other factors including; slow translational speed (as when a system is turning, i.e., Bonnie), low level boundaries focusing the wind and moisture fields to produce heavy rains well removed from the center of circulation, orographic lifting, and the motion of the eye (trochoidal).

Since all systems affecting North Carolina were recurving, often due to the mid- and upper-level wind shear, a rapid drying occurred on the south side of the center of circulation.

A review of surface-based wind fields resulted in important findings too. Wind damage can be extensive in coastal areas for well-defined tropical systems making landfall in North Carolina. Wind damage can also come as a result of strong hurricanes making landfall from east of the Mississippi River to North Carolina. In all cases of extensive wind damage, either at the coast or inland, it was due to a well-defined hurricane. Therefore, wind field patterns and the resultant damage is unlike rainfall fields in that wind is a function of storm intensity.

Surface pressure fields are directly related to the path of the center of the tropical system with the lowest pressure being the path.

Media attention is directed toward geographical areas where the initial landfall is anticipated. This attention heightens the public awareness and thus the threat to life. Often media attention is in North Carolina is directed to systems making landfall in the state. Therefore, the affects of tropical systems on North Carolina are not necessarily a function of whether the system makes landfall in the state. Media attention needs to be widened to cover areas where landfall occurs in other states and will move to affect North Carolina within days or less.

Future work will build on the data in this paper to look at tracks of even earlier tropical systems with life-threatening rainfalls that moved through North Carolina. A paper is forthcoming that analyzes the reasons for fatalities in North Carolina due to tropical systems in order to focus attention on the rainfall in inland areas and the associated flooding from tropical weather.

Finally, work is being done using surface pressure changes, with and without diurnal variations removed, to better forecast a tropical system’s inland track in North Carolina 12 hours prior to landfall. The track could be forecast for 12 hours inland as well.

Better short-term forecast of inland tracks through North Carolina using the surface pressure will lead to better rainfall and surface wind forecasts, and this, in turn, may lead to a better definition of rainfall totals for specific areas of North Carolina. These forecasts could then be applied when designing evacuation routes from coastal areas in order to avoid inland flooding.

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Figures

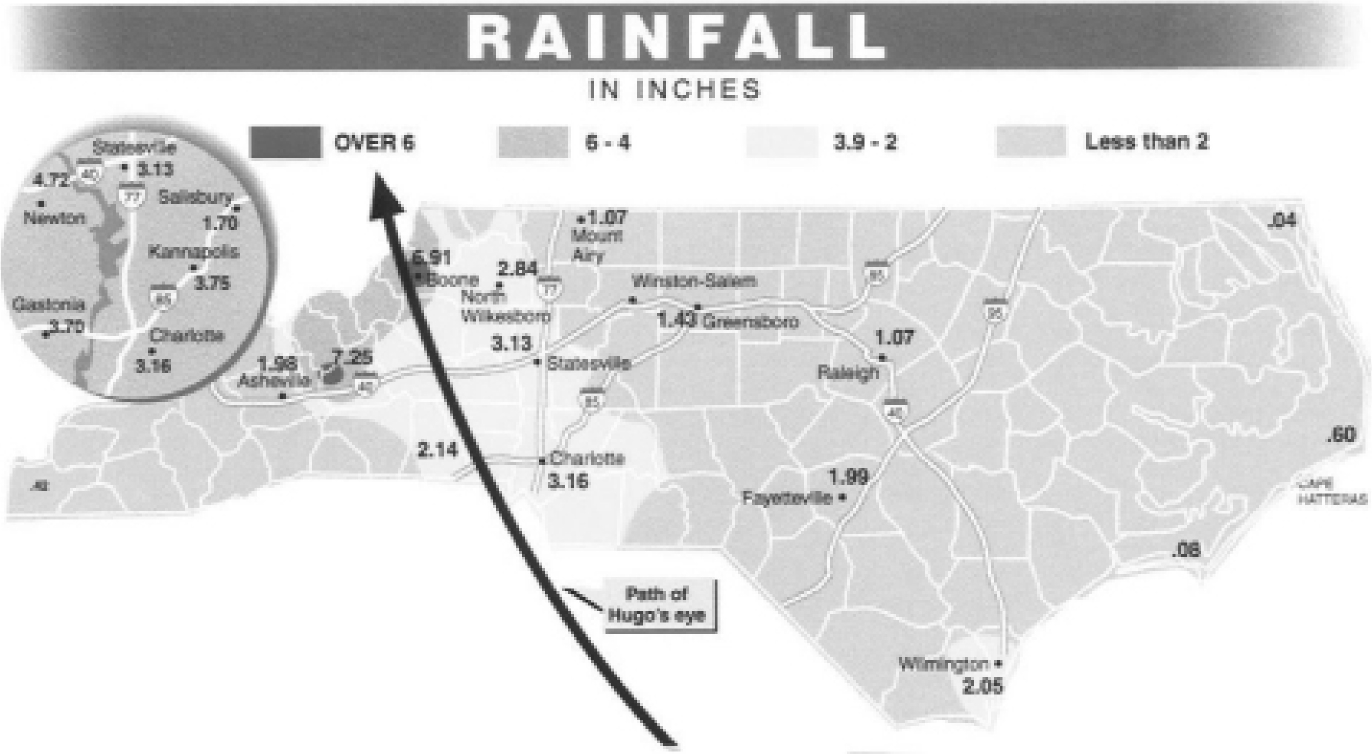


Figure 1. Storm total rainfall (in.) and track of Hugo through North Carolina.

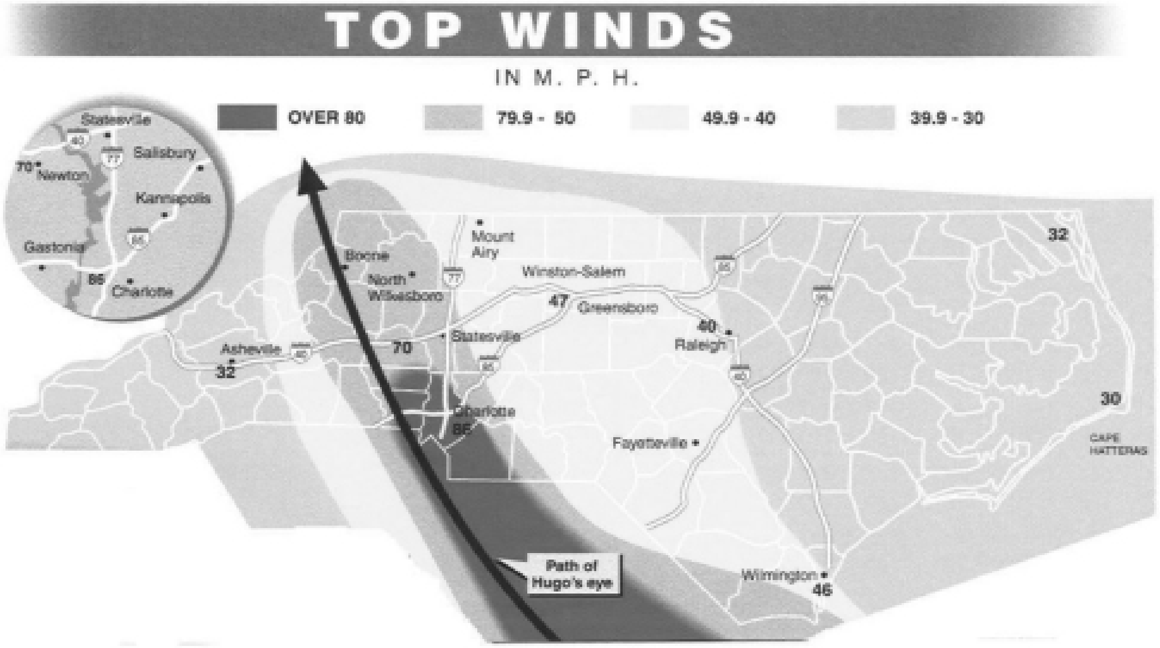


Figure 2. Contoured maximum sustained winds (MPH) with peak gusts at specific locations and track of Hugo (September 1989).

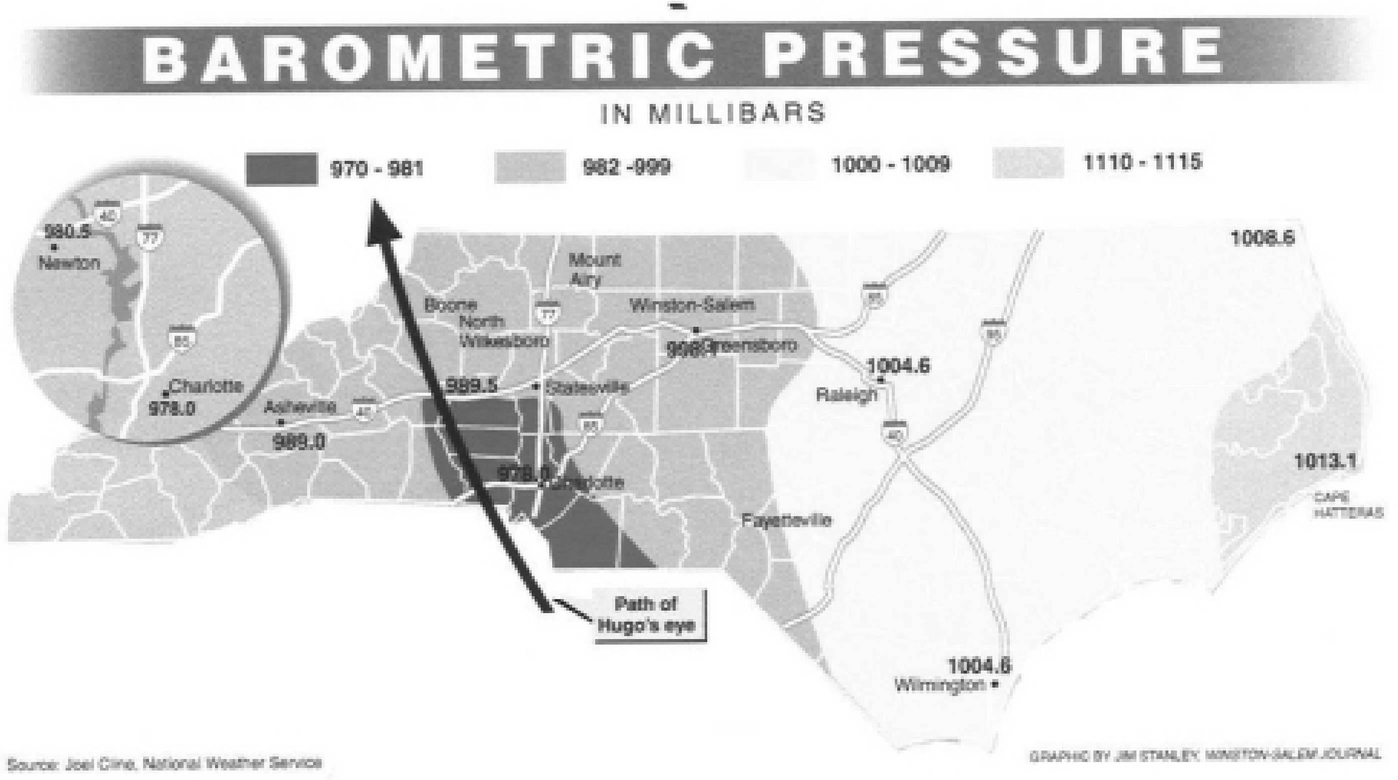


Figure 3. Contoured minimum sea-level pressure (hPa) and track of Hugo (September 1989) through North Carolina.

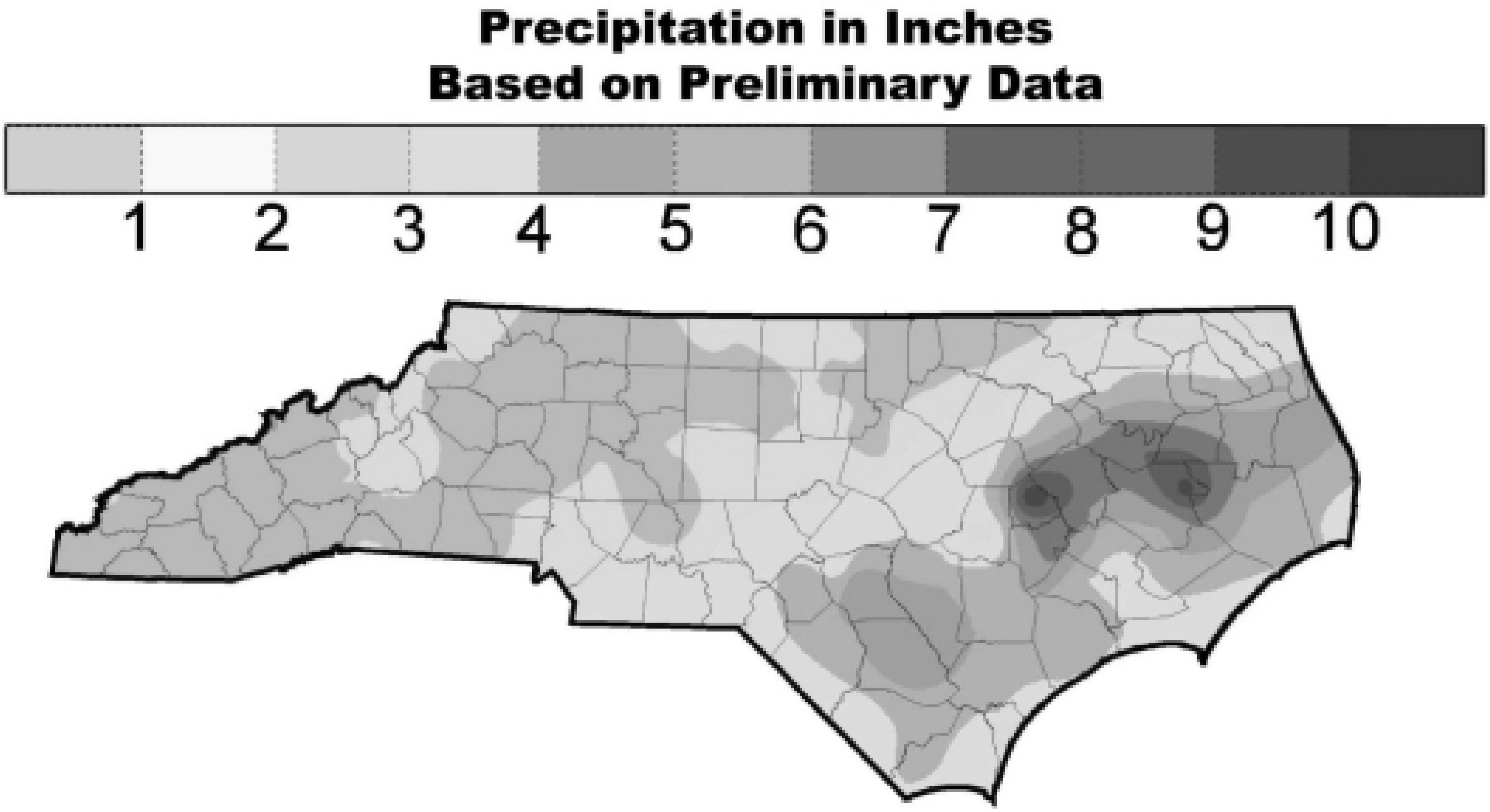


Figure 4. Storm total rainfall (in.) from Allison (June 1995).

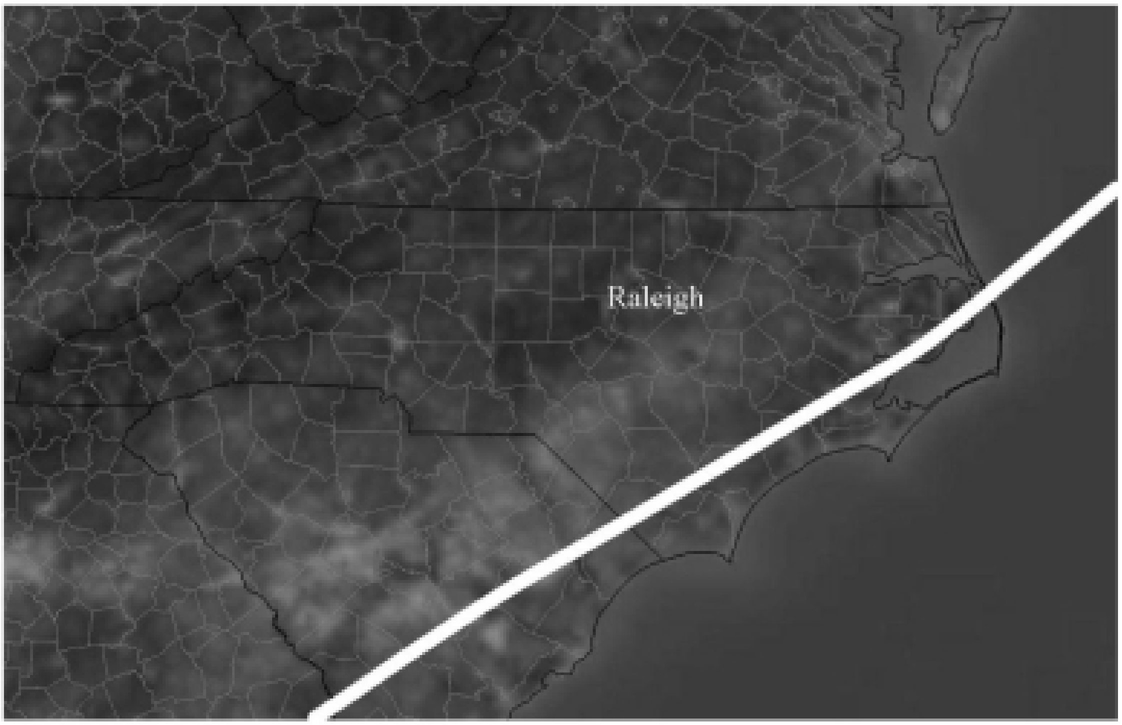


Figure 5. Track of Allison (June 1995) through North Carolina.

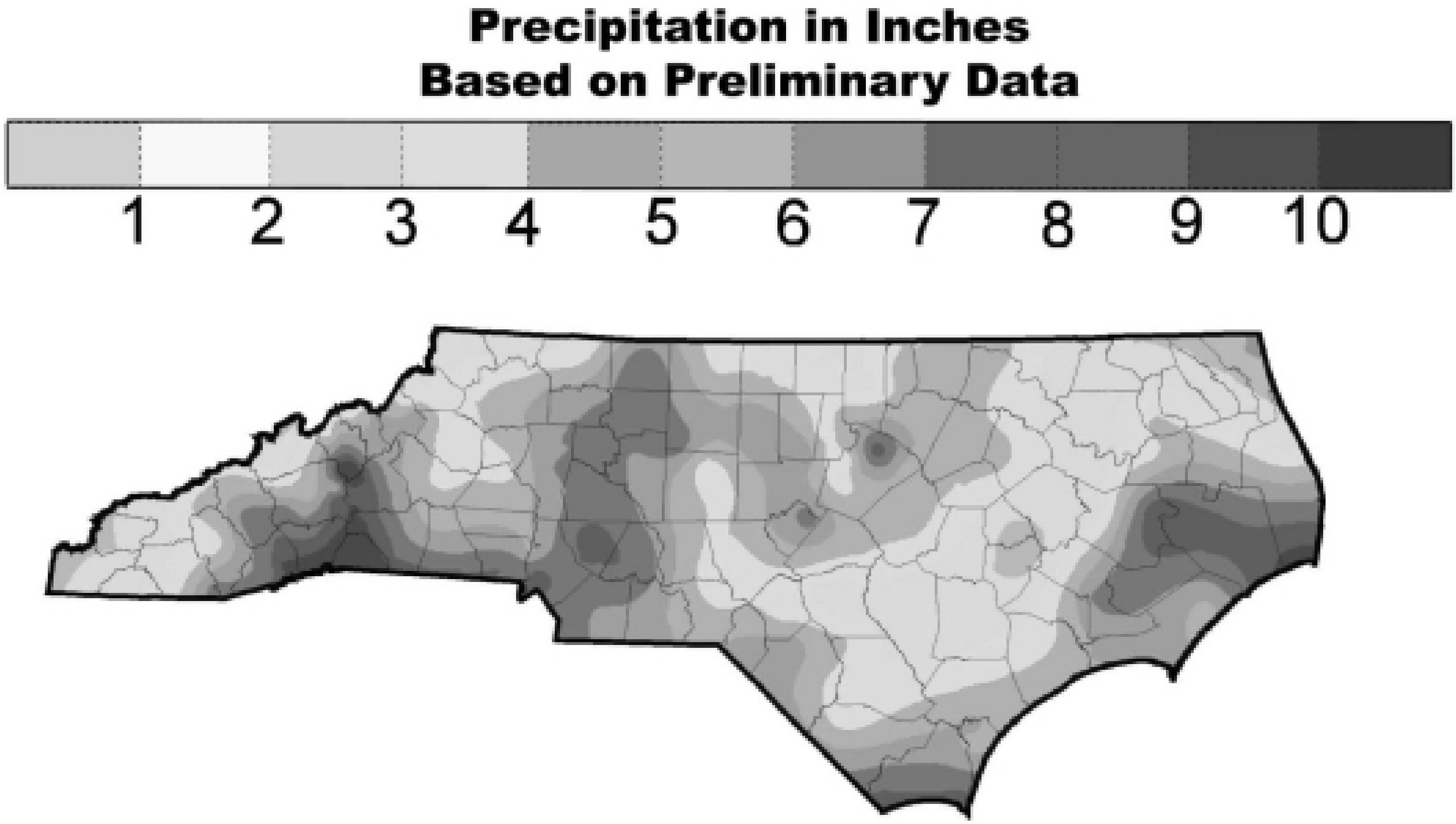
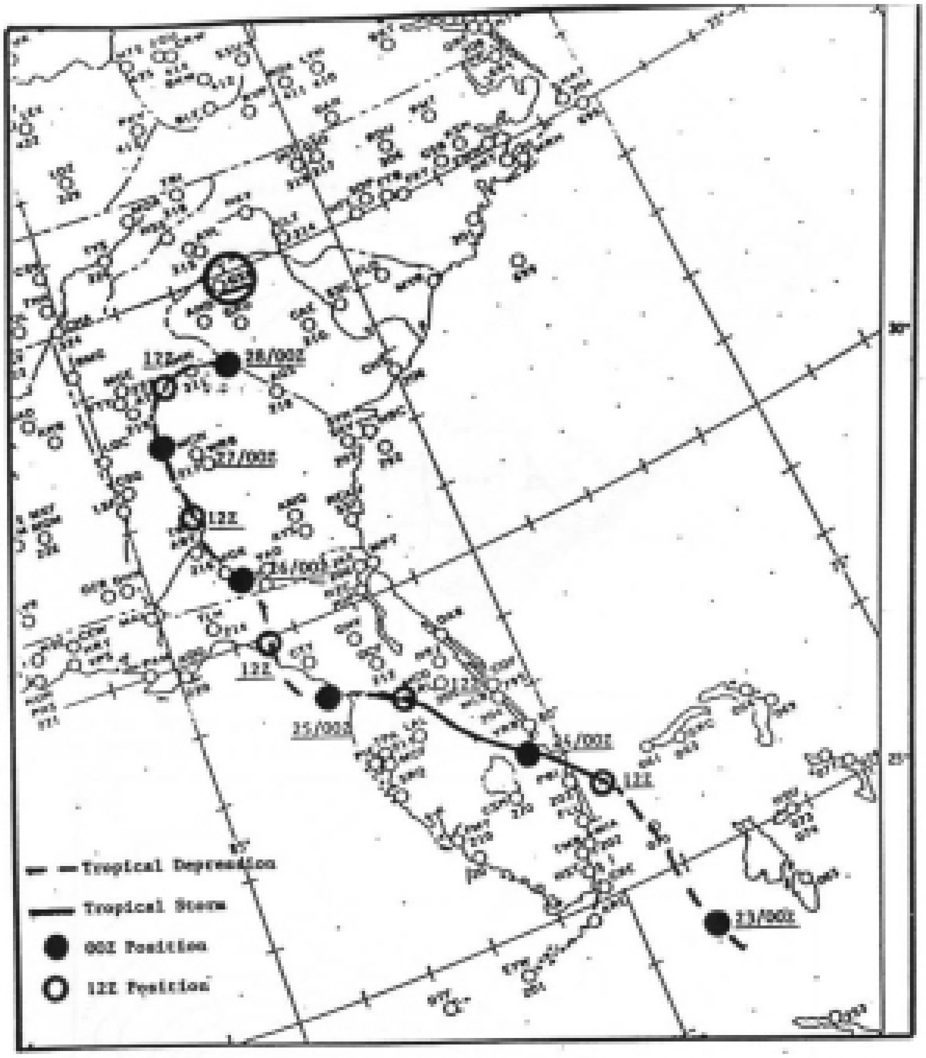


Figure 6. As in Fig. 4, except for Jerry (August 1995).



Track of Tropical Storm Jerry, August, 1995. Large circle shows the location of Greenville-Spartanburg Airport; the site of the maximum total rainfall.

Figure 7. Track of Tropical Storm Jerry (August 1995), courtesy Dr. Joe Pelissier.

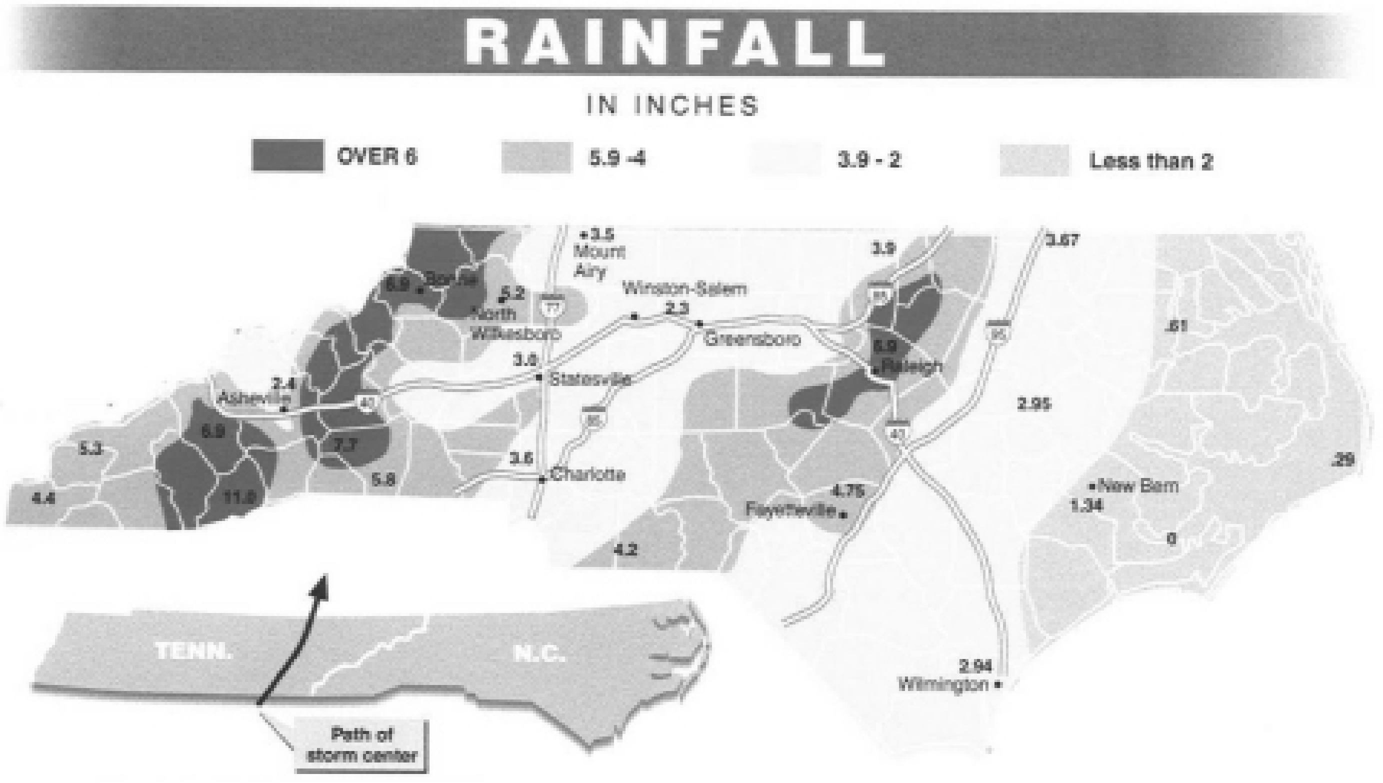


Figure 8. As in Fig. 1, except for Opal (October 1995).

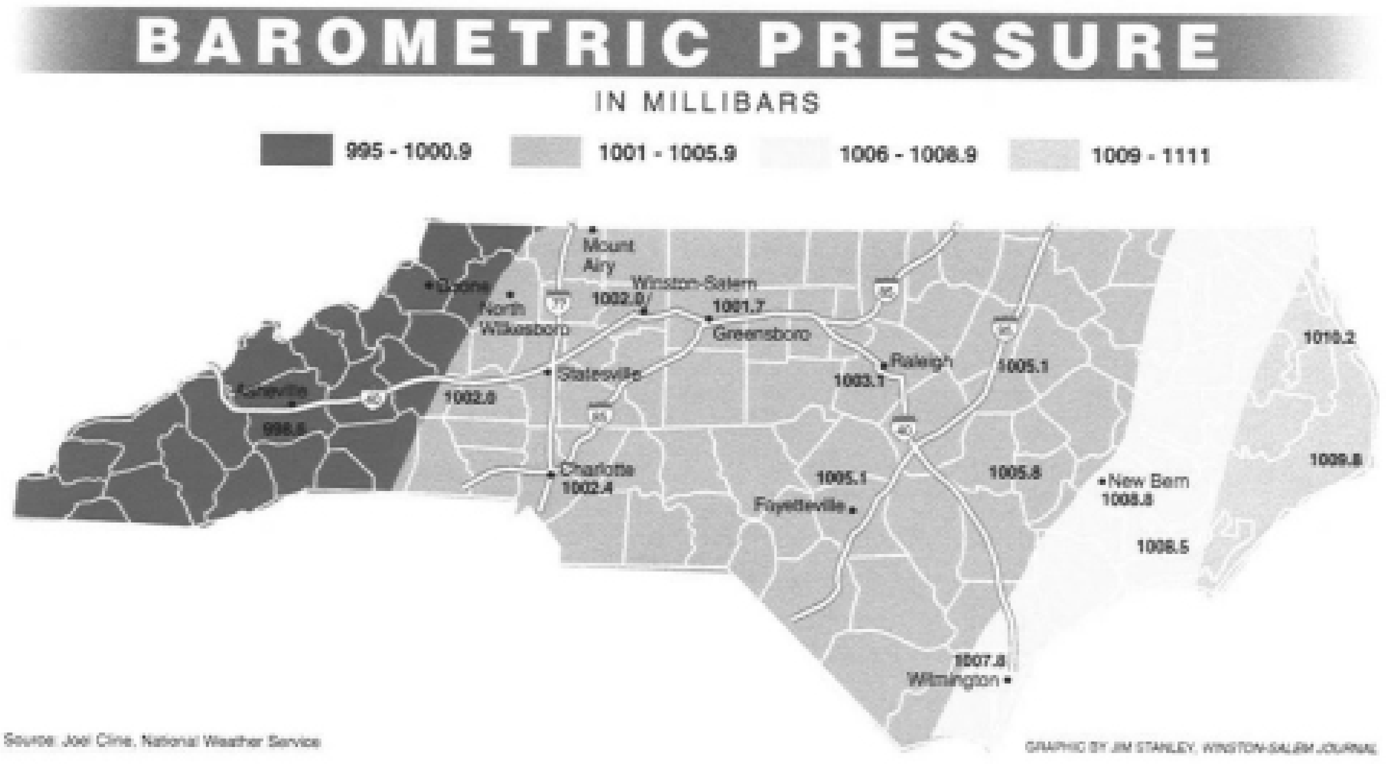


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Figure 9. As in Fig. 3, except for Opal (October 1995).

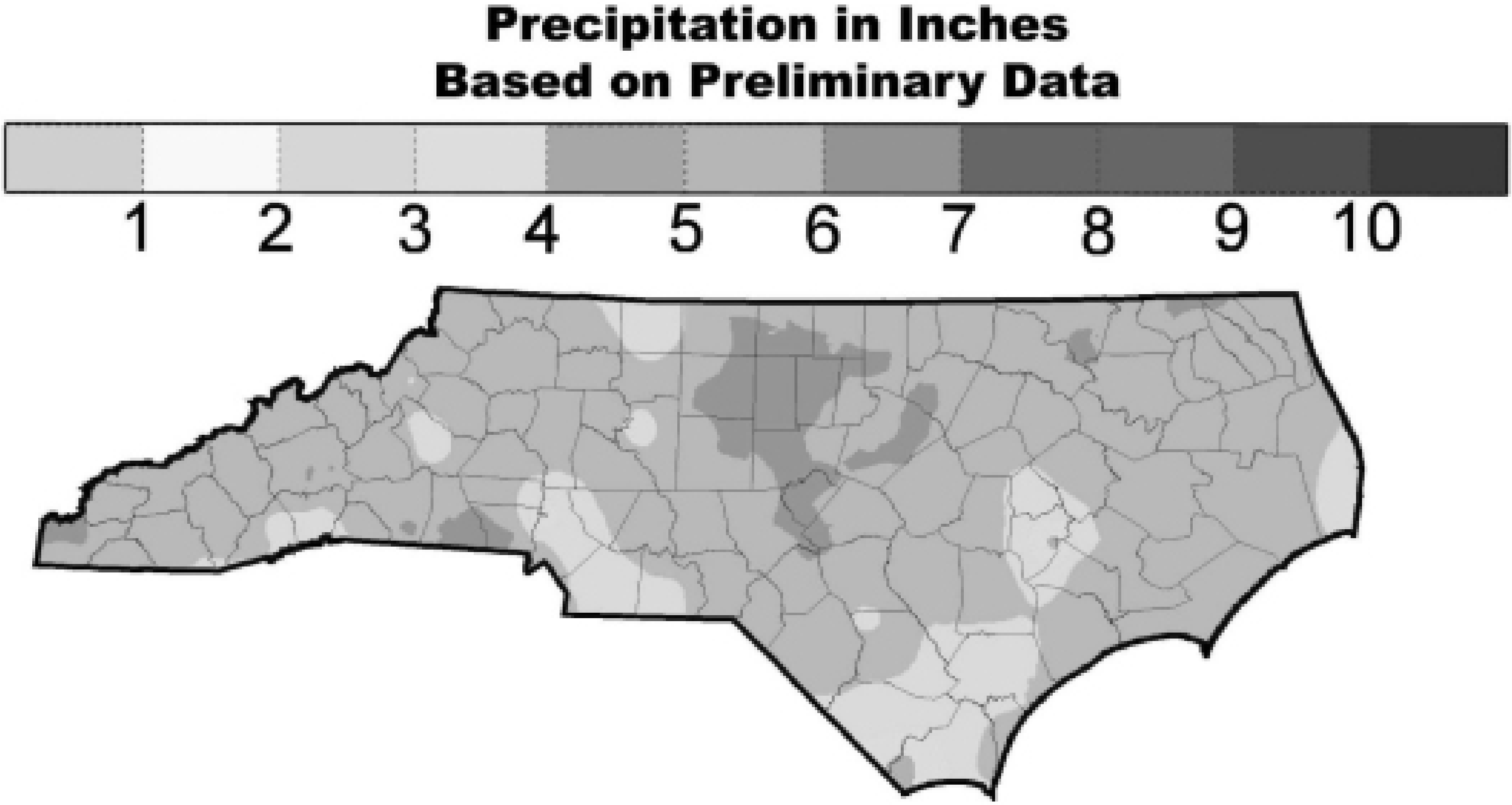

Figure 10. As in Fig. 4, except for Arthur (June 1996).

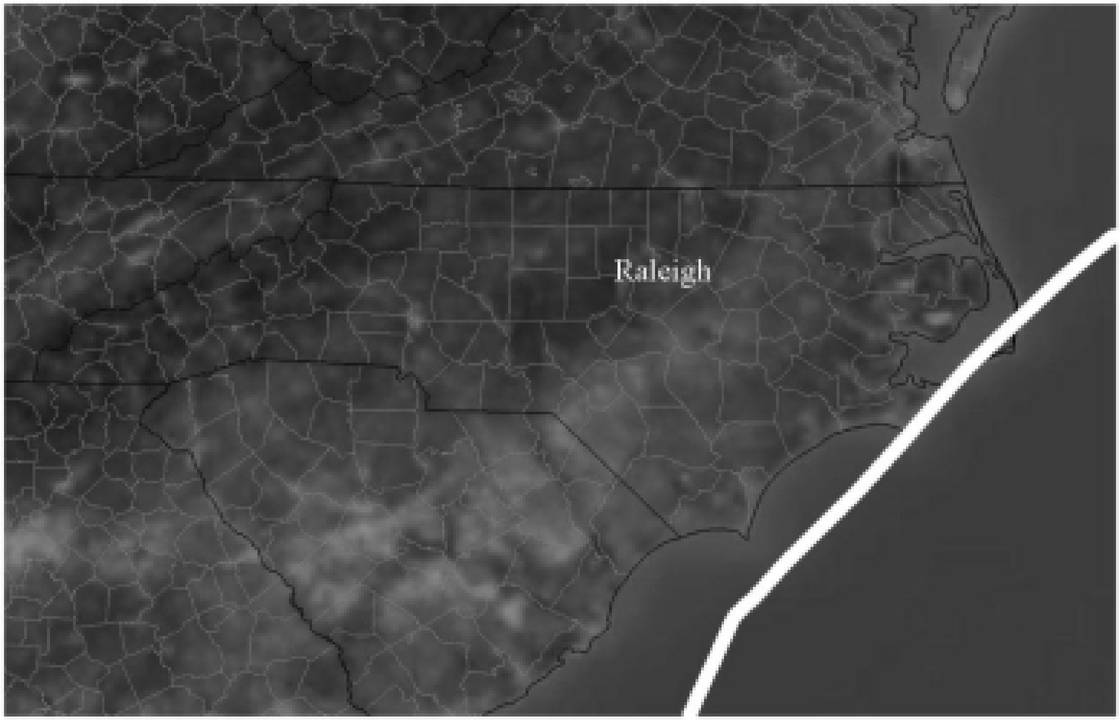

Figure 11. As in Fig. 5, except for Arthur (June 1996).

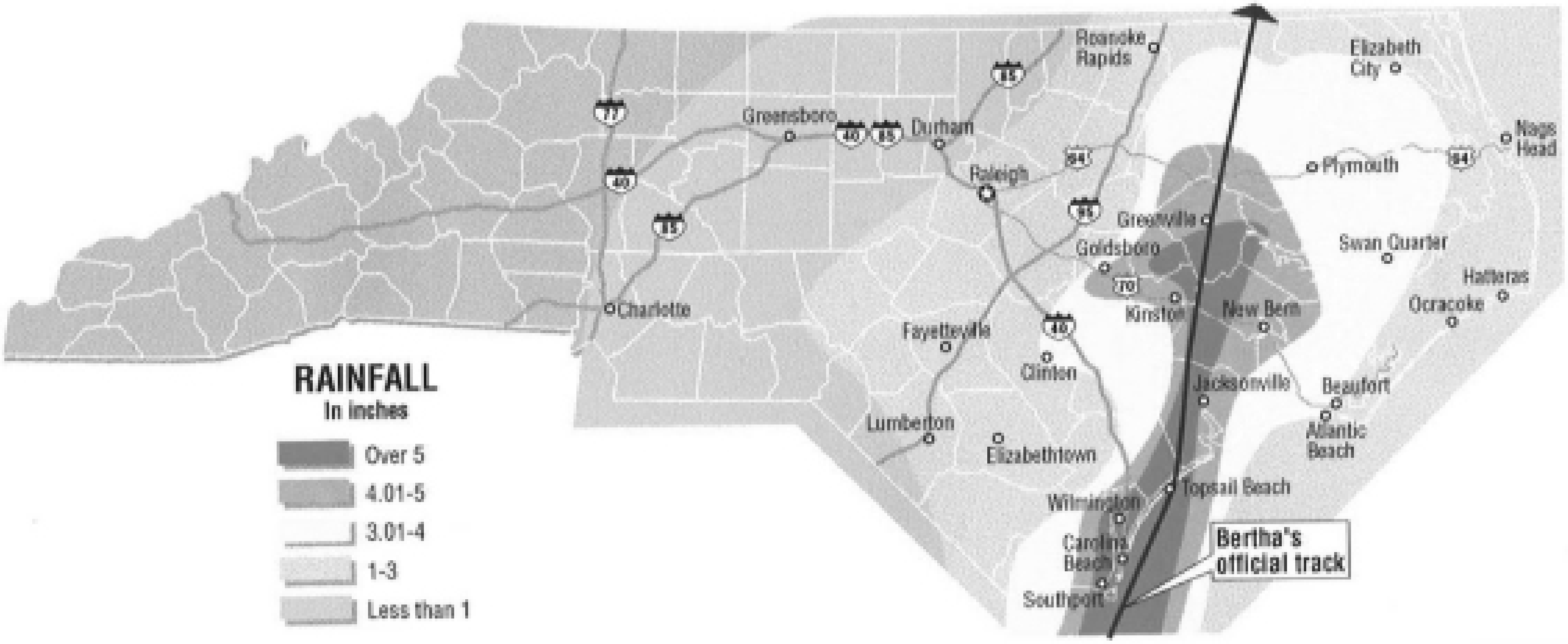

Figure 12. As in Fig. 1, except for Berth (July 1996).

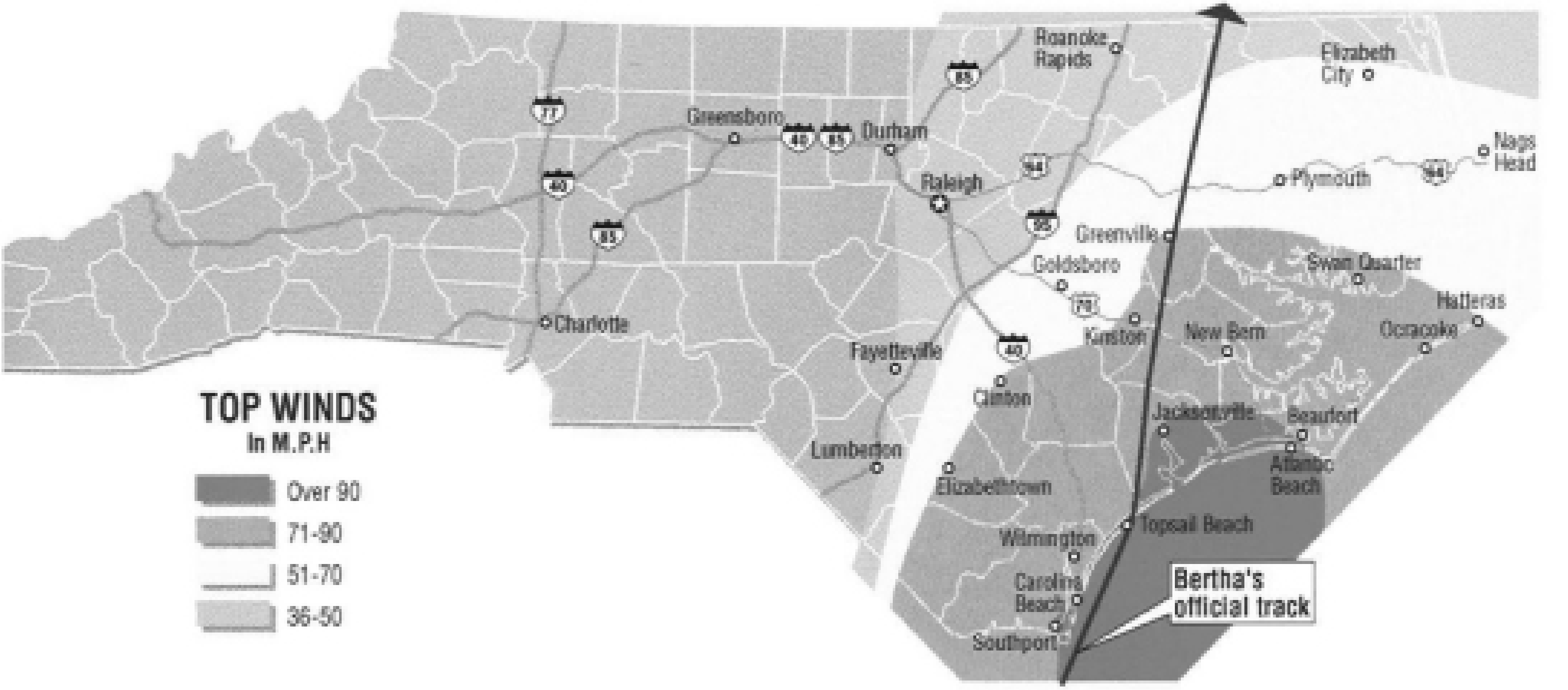

Figure 13. As in Fig. 2, except for Bertha (July 1996).

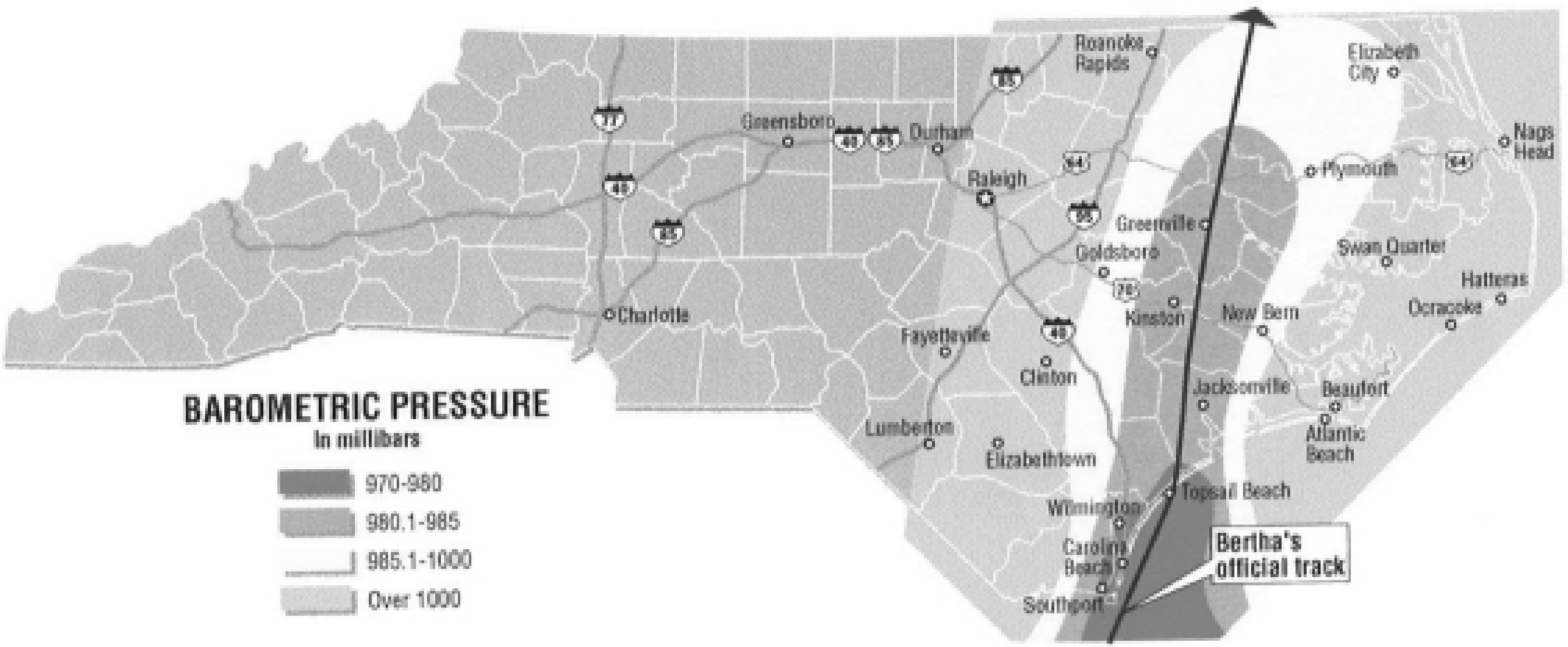

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Figure 14. As in Fig. 3, except for Bertha (July 1996).

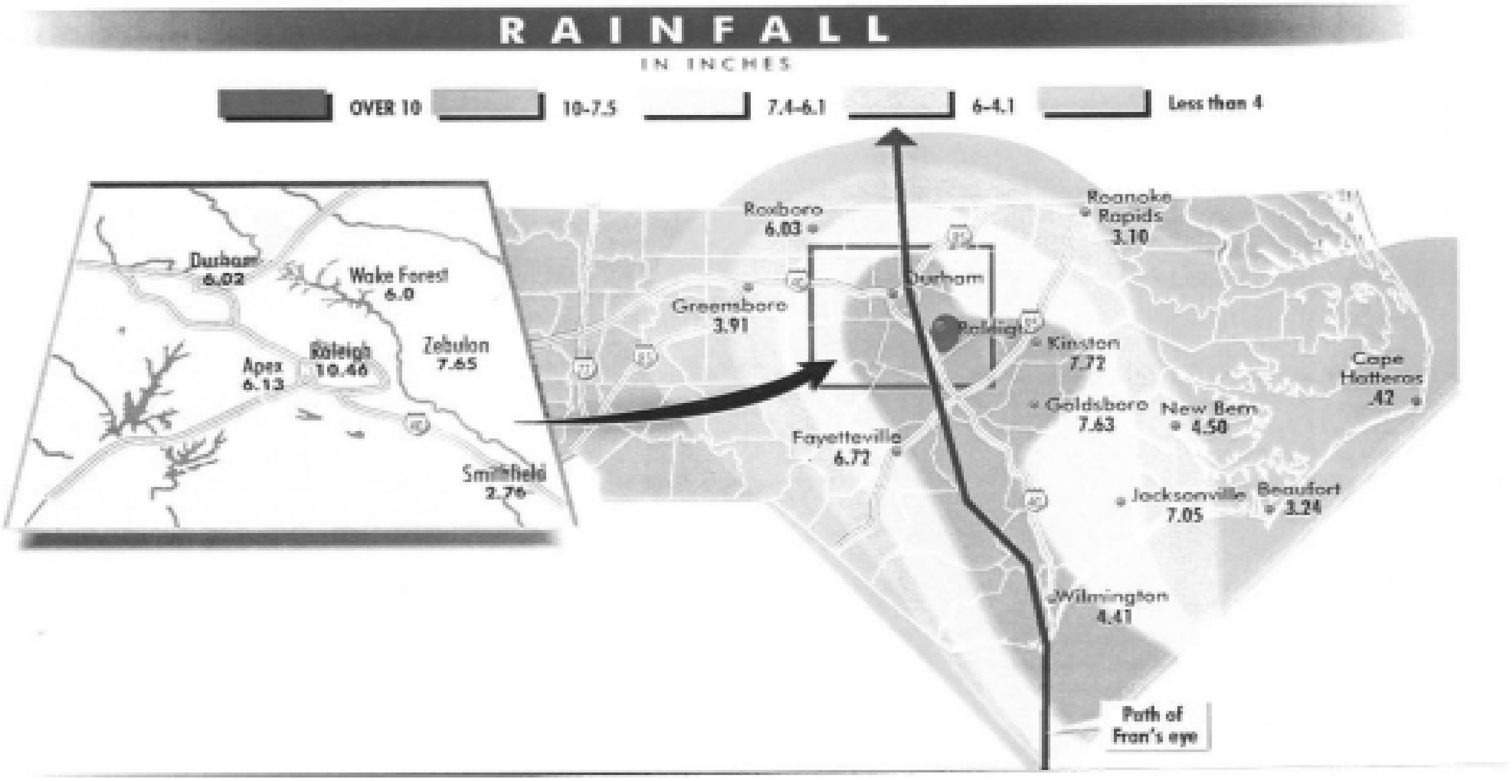


Figure 15. As in Fig. 1, except for Fran (September 1996).

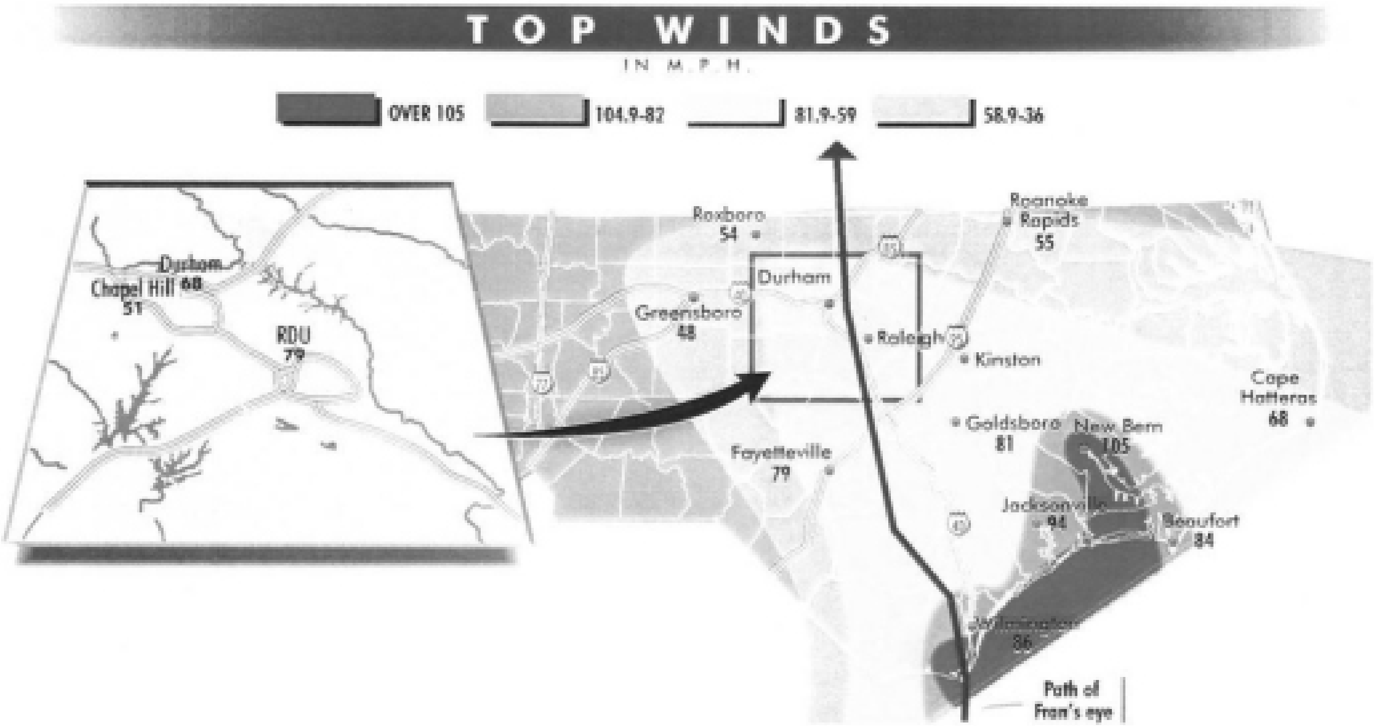
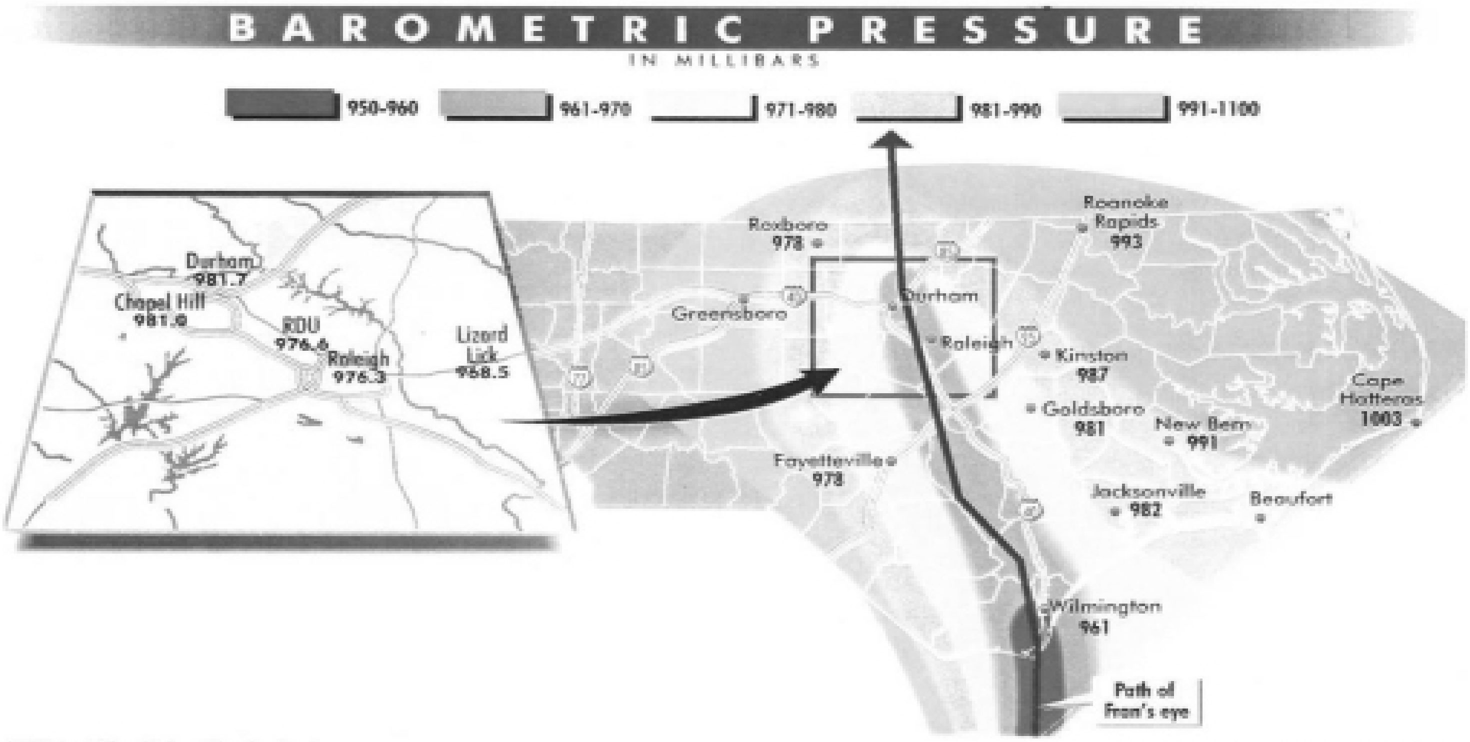


Figure 16. As in Fig. 2, except for Fran (September 1996).



URCE: Joel Cline, National Weather Service

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Figure 17. As in Fig. 3, except for Fran (September 1996).

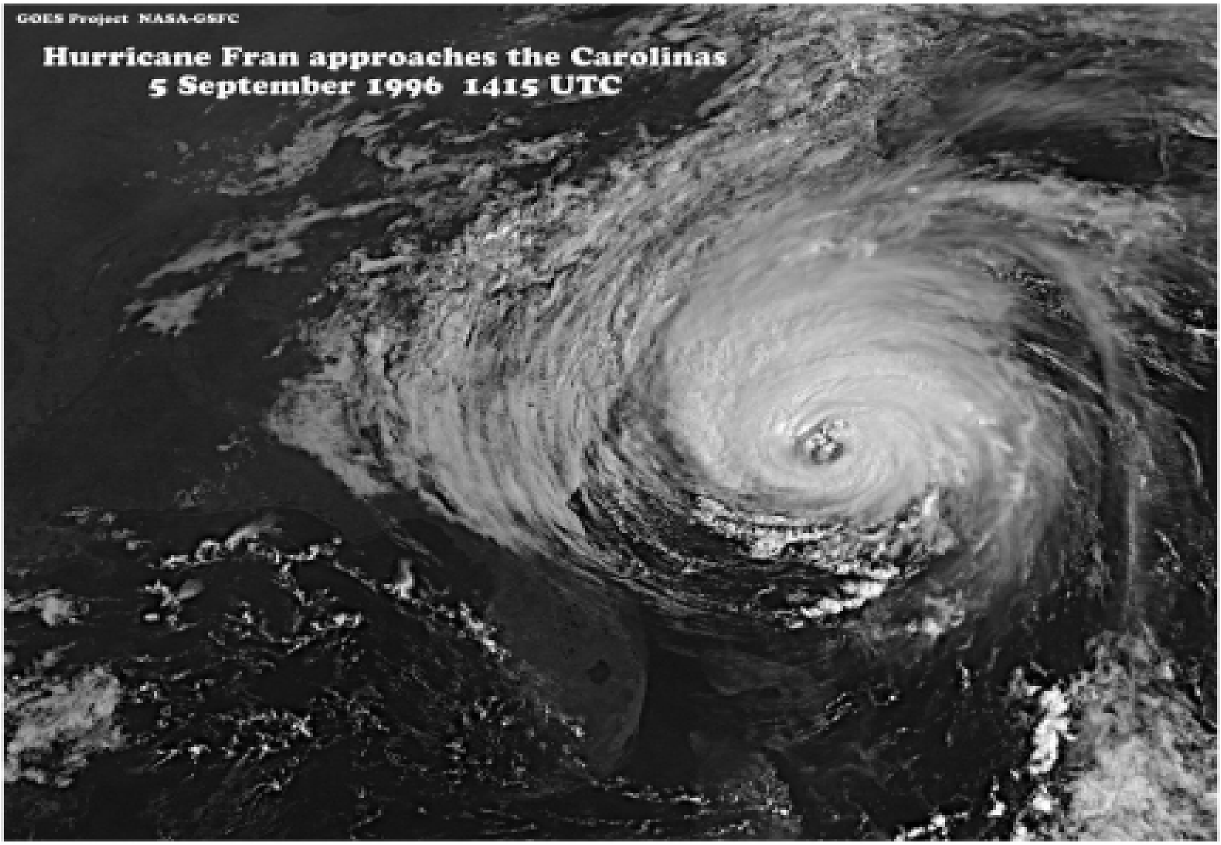

Figure 18. Visible satellite imagery of Fran at 1415 UTC 5 September 1996.

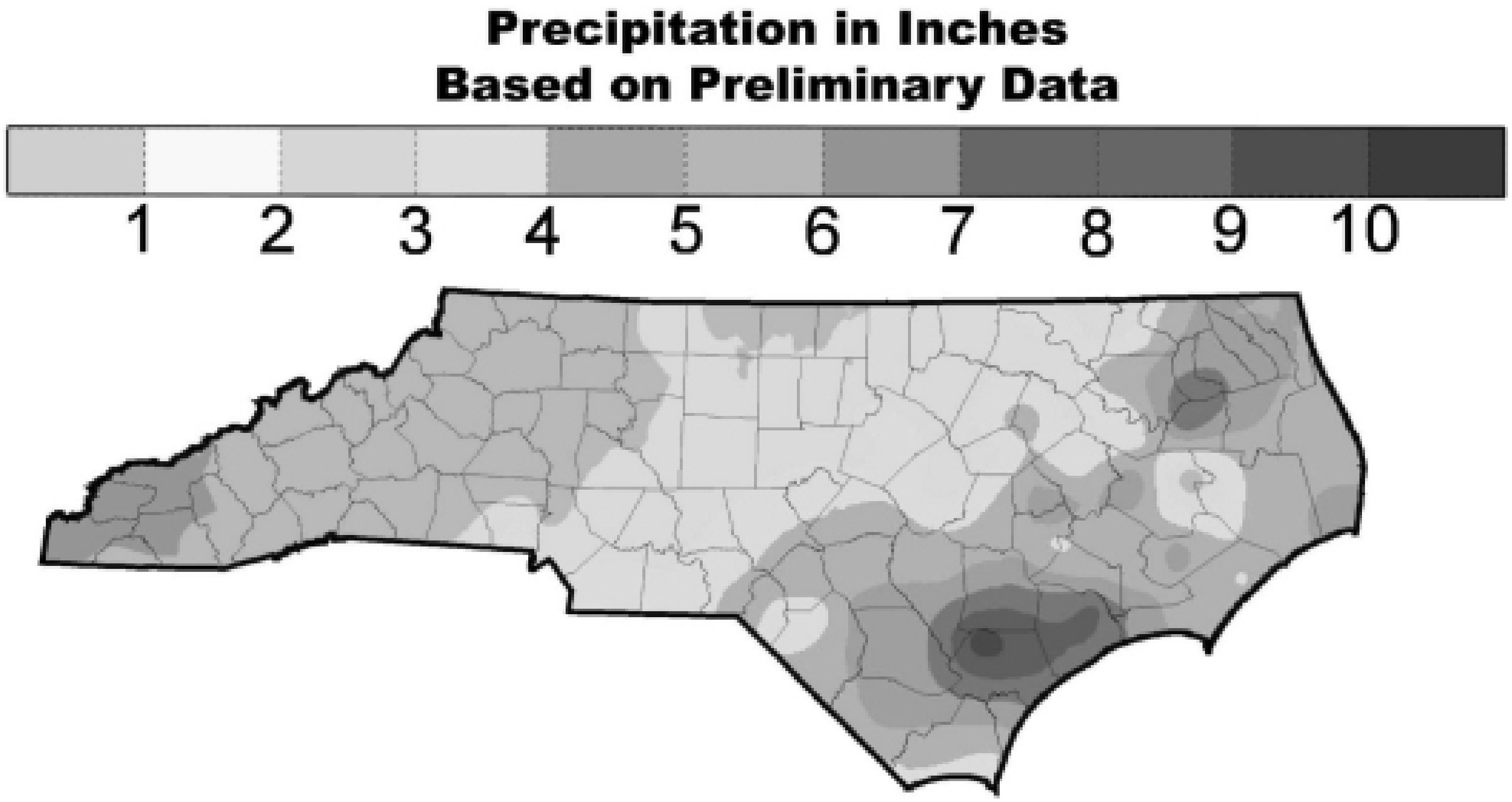

Figure 19. As in Fig. 4, except for Josephine (October 1996).

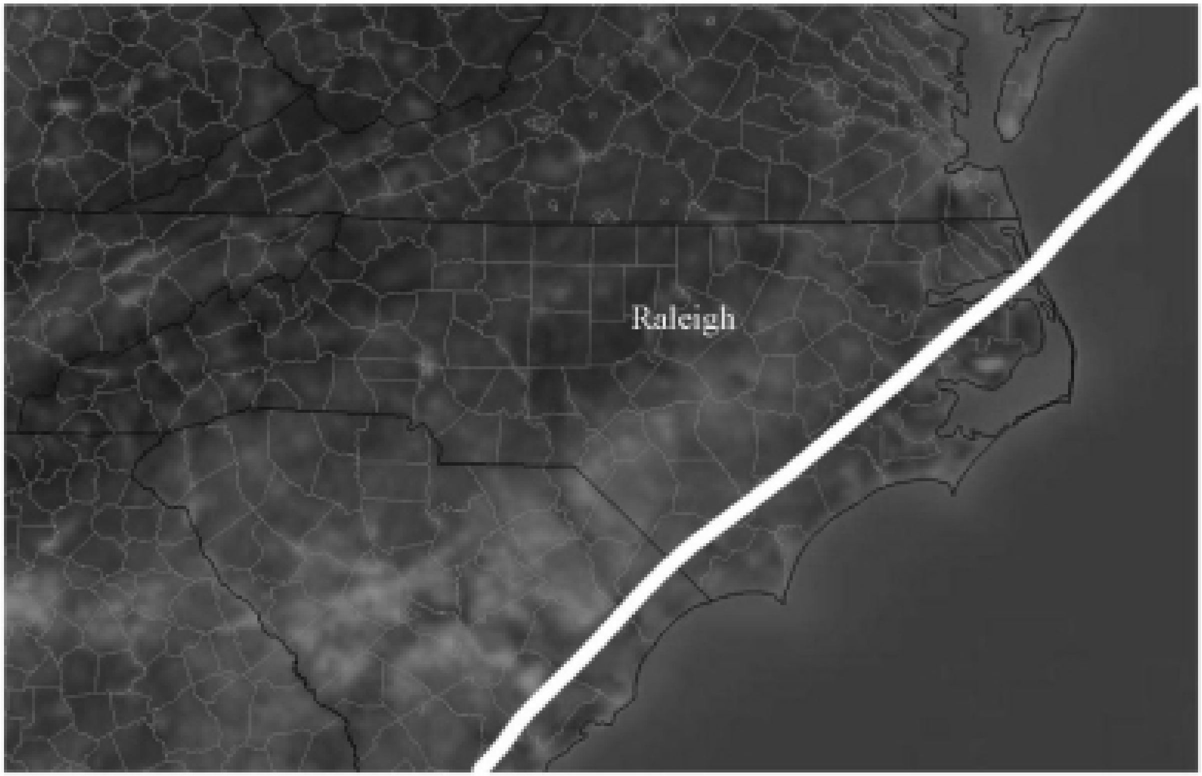

Figure 20. As in Fig. 5, except for Josephine (October 1996).

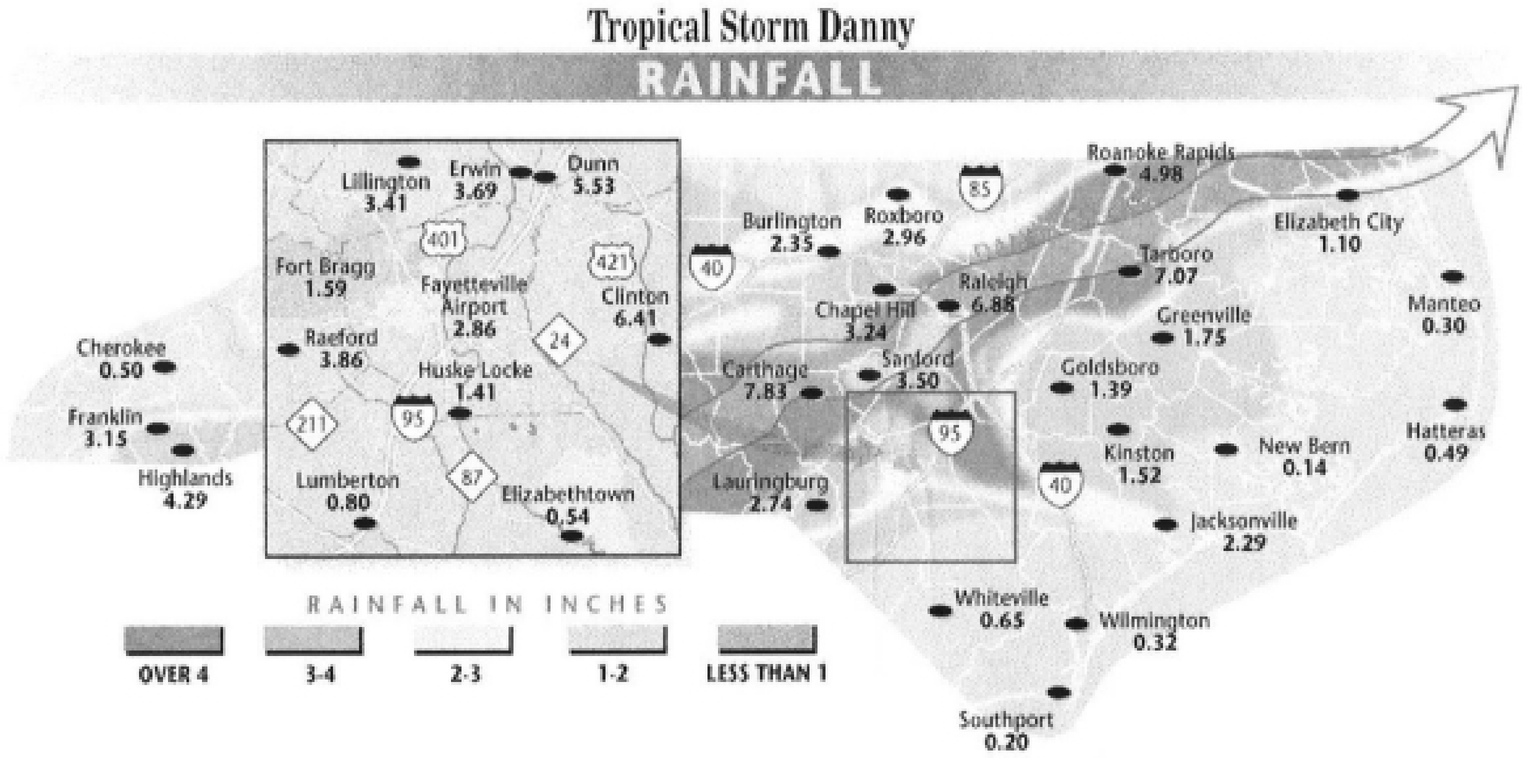

Figure 21. As in Fig. 1, except for Danny (July 1997).

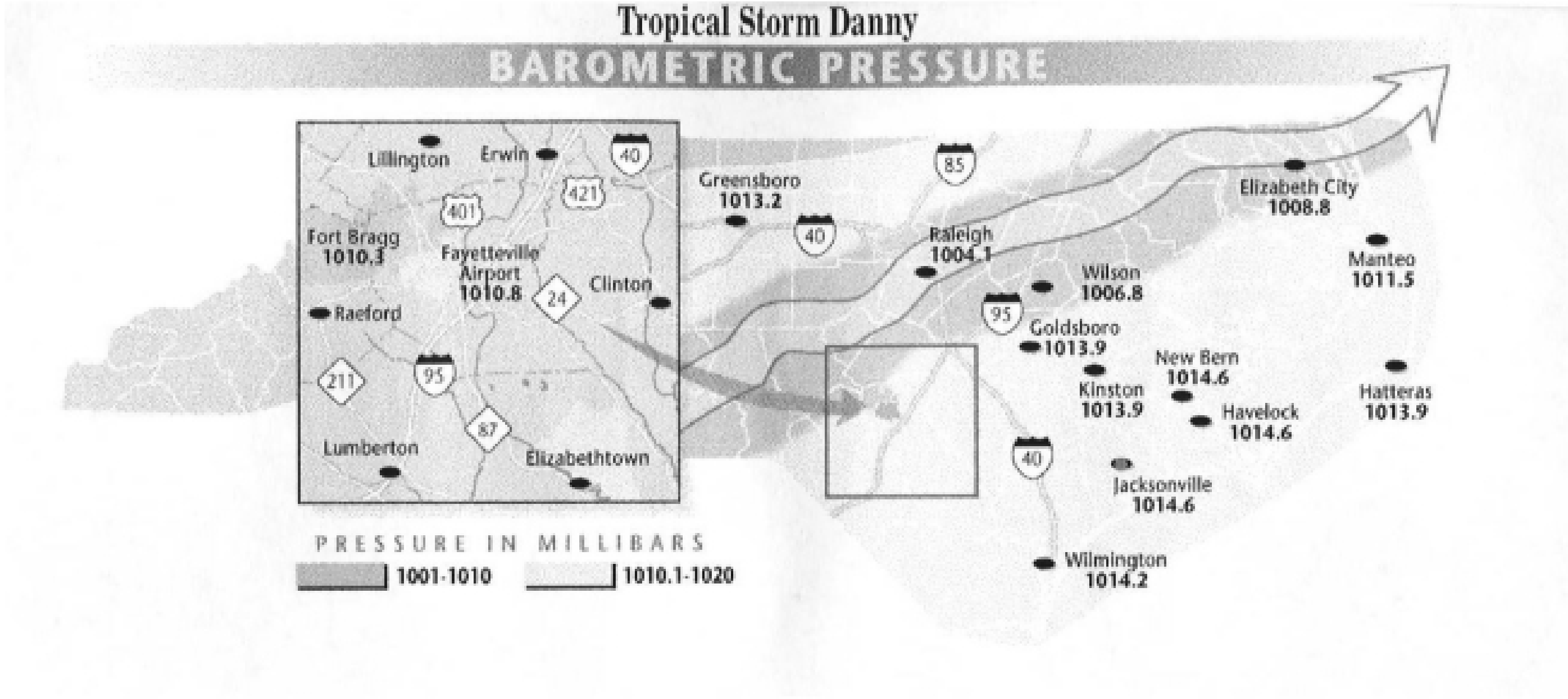

Figure 22. As in Fig. 3, except for Danny (July 1997).

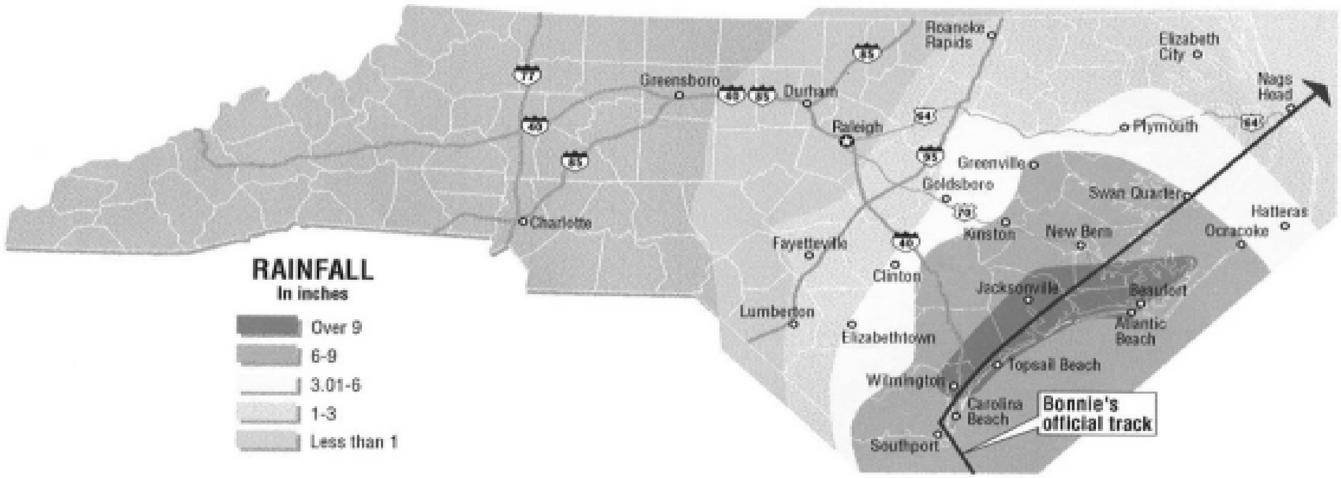

Figure 23. As in Fig. 1, except for Bonnie (August 1998).

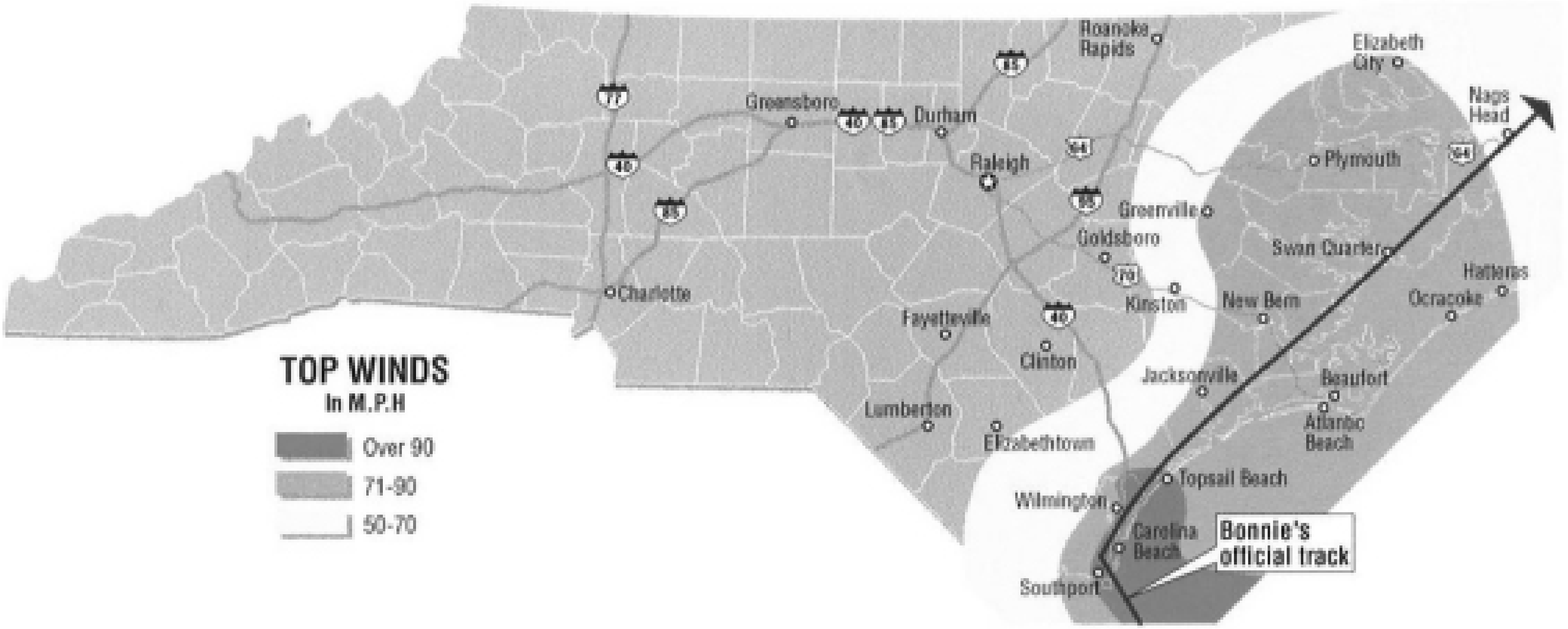

Figure 24. As in Fig. 2, except for Bonnie (August 1998).

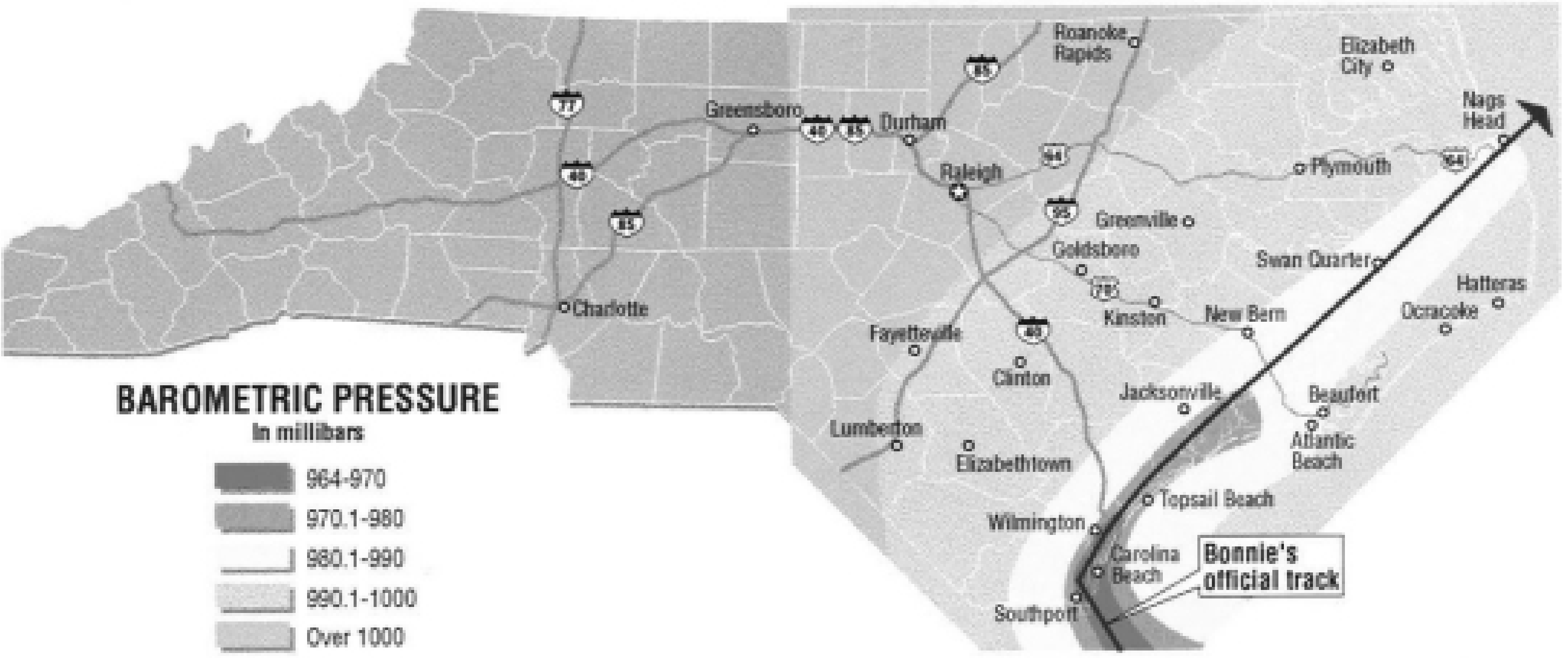

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Figure 25. As in Fig. 3, except for Bonnie (August 1998).

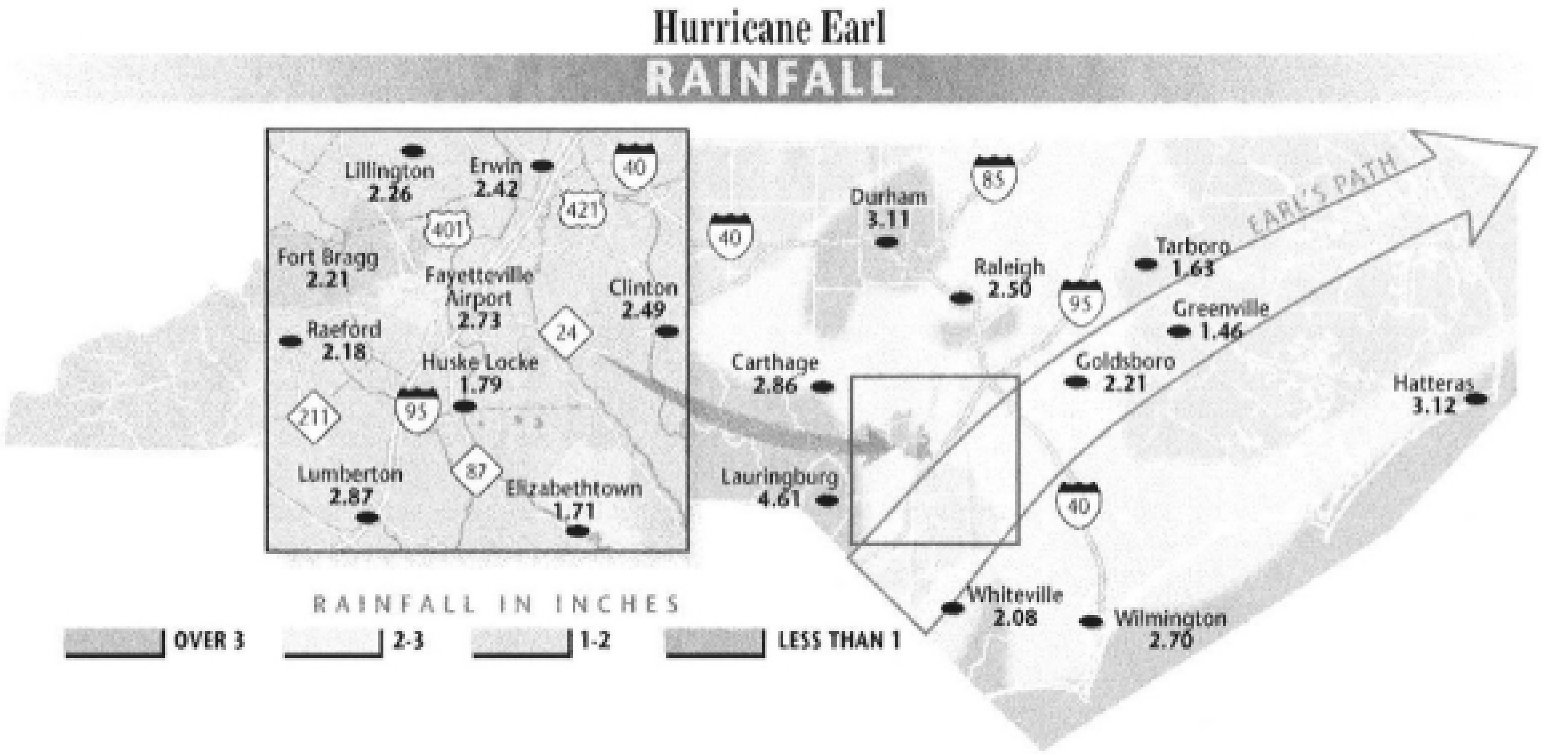

Figure 26. As in Fig. 1, except for Earl (September 1998).

Hurricane Earl

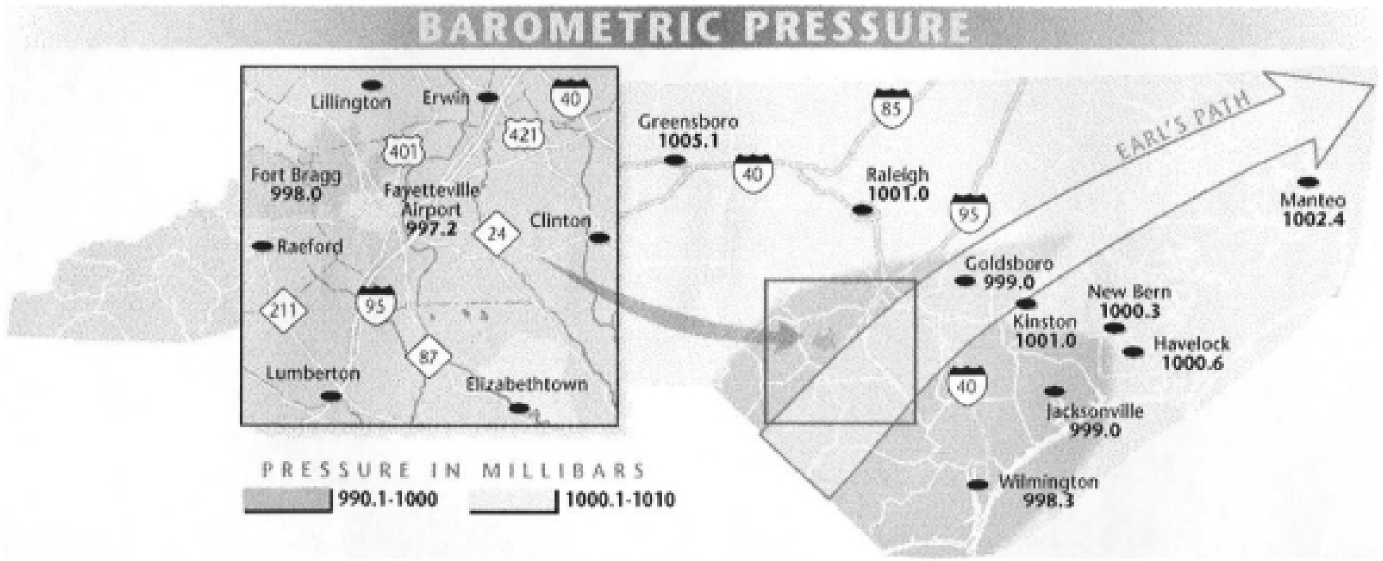

Figure 27. As in Fig. 3, except for Earl (September 1998).

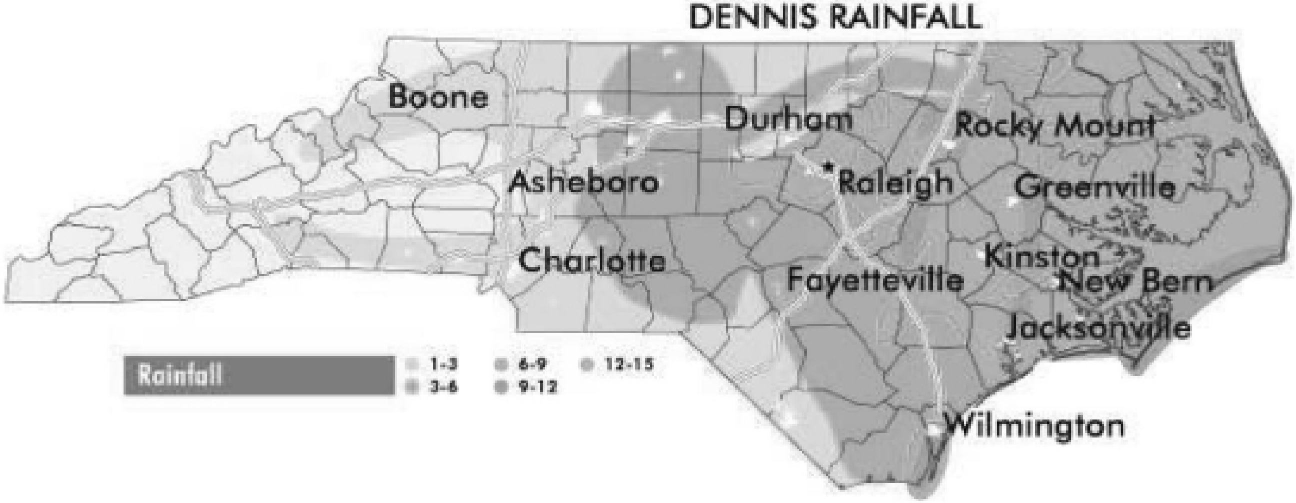

Figure 28. Storm total rainfall (in.) in North Carolina from Dennis (August-September 1999).

Figure 29. Contoured maximum sustained winds (MPH) with peak gusts at specific locations from Dennis (August-September 1999).

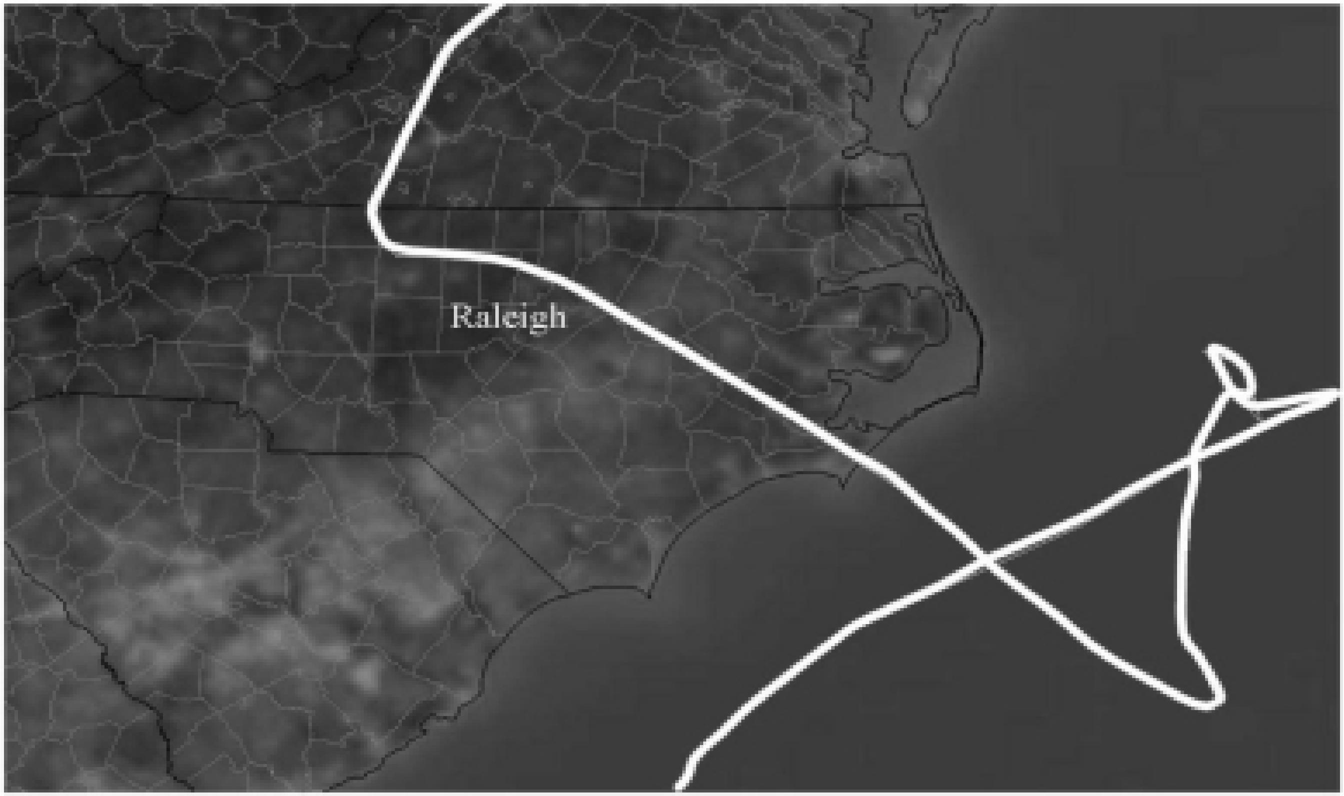

Figure 30. As in Fig. 5, except for Dennis (August-September 1999).

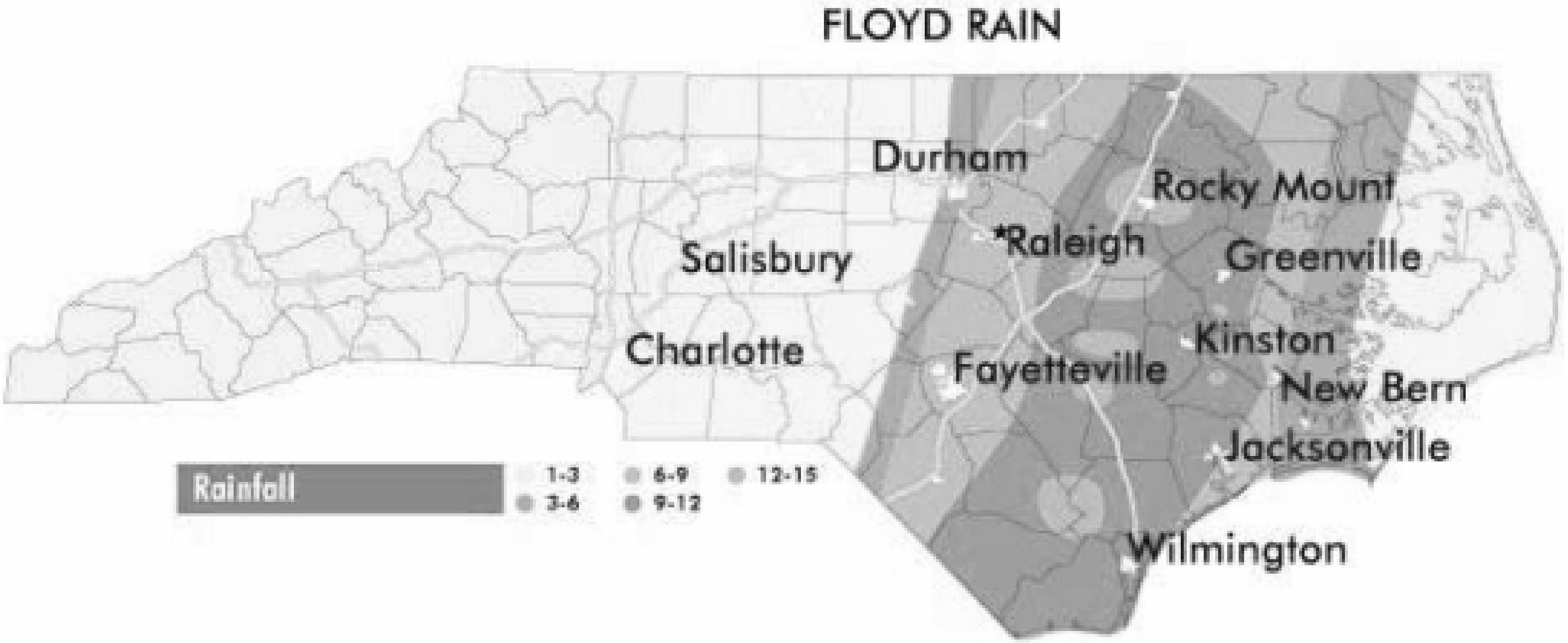

Figure 31. As in Fig. 28, except for Floyd (September 1999).

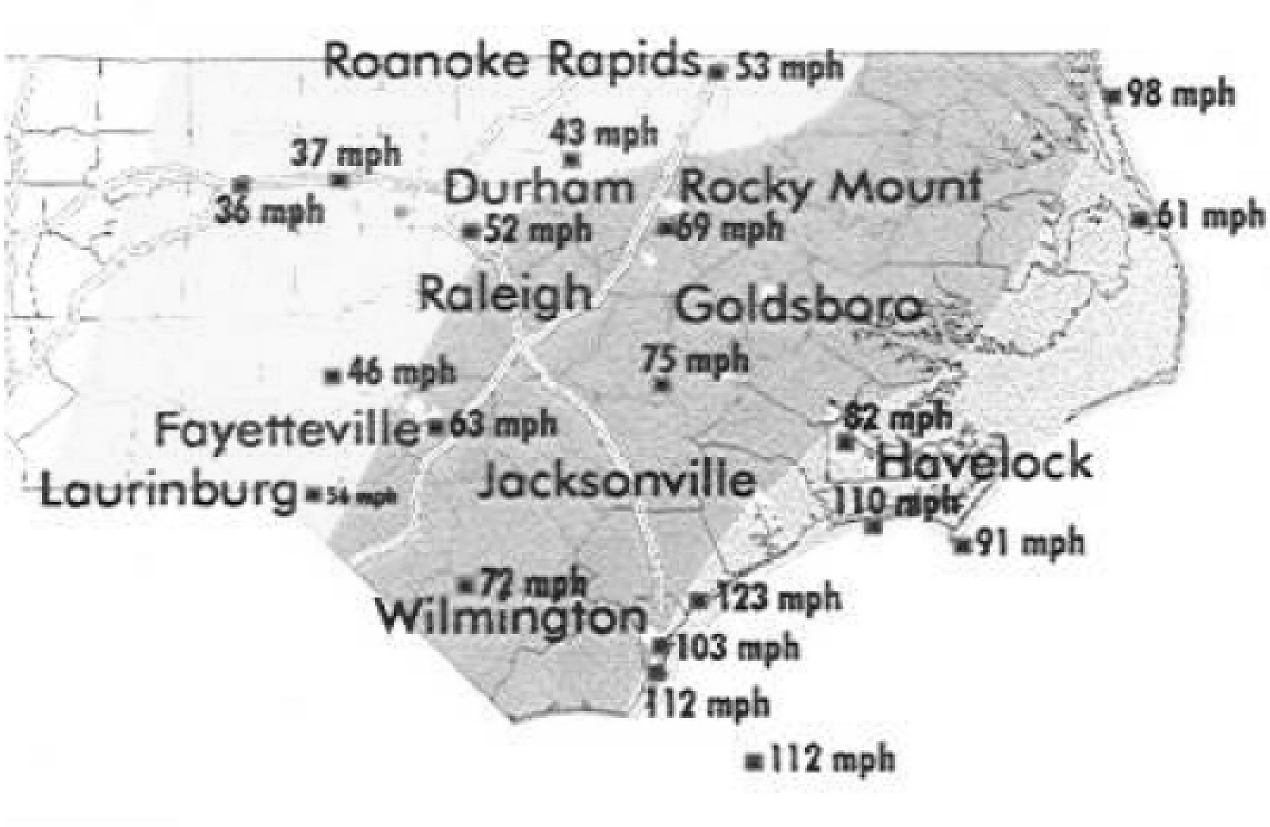

Figure 32. As in Fig. 29, except for Floyd (September 1999).

Figure 33. As in Fig. 5, except for Floyd (September 1999).

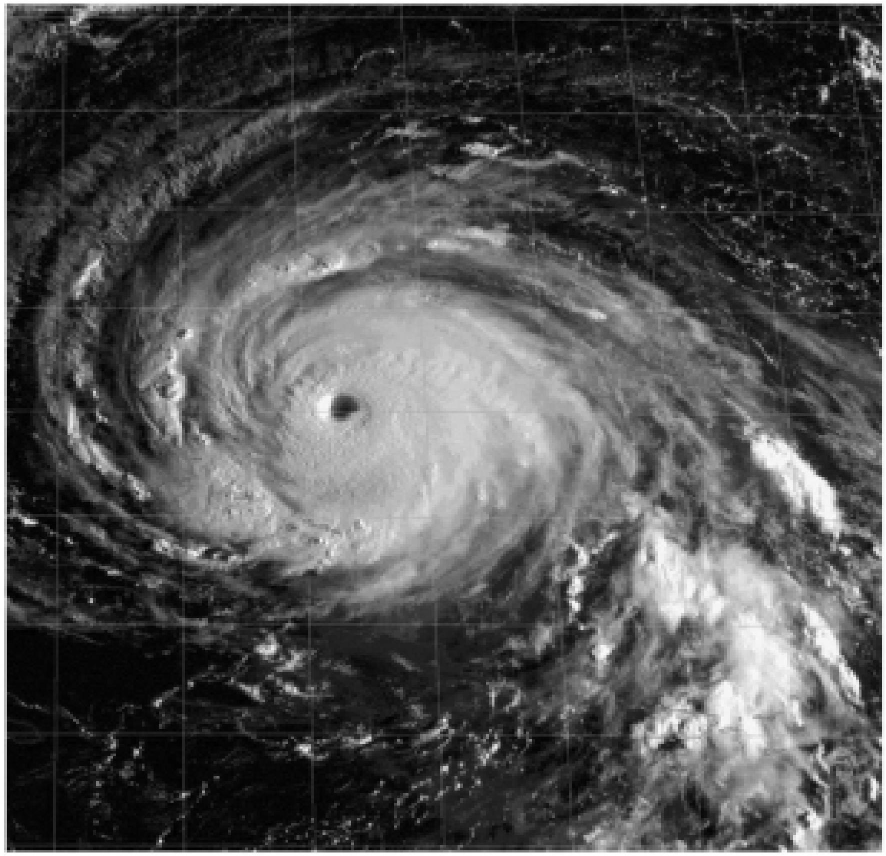

Figure 34. Visible satellite image of Hurricane Floyd (September 1999) over the Bahamas.

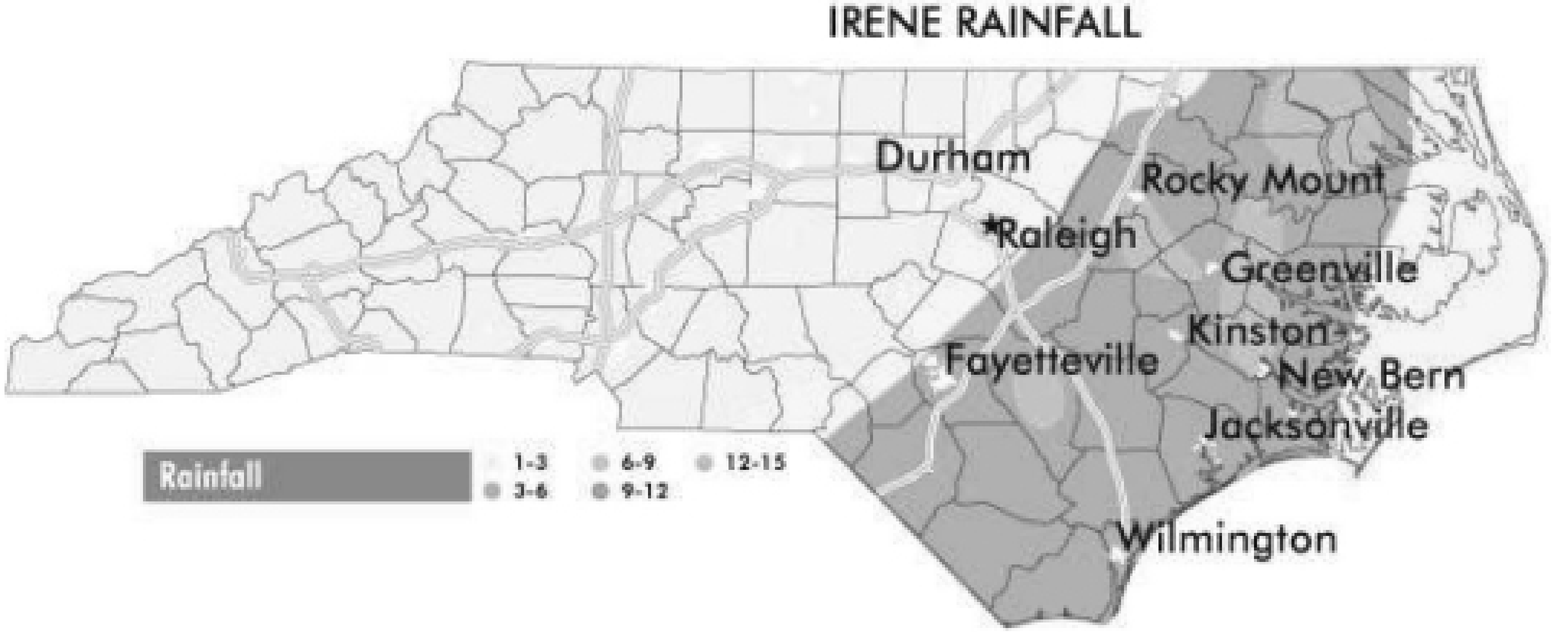

Figure 35. As in Fig. 28, except for Irene (October 1999).

Figure 36. As in Fig. 29, except for Irene (October 1999).

Figure 37. Track of Irene (October 1999) near North Carolina.

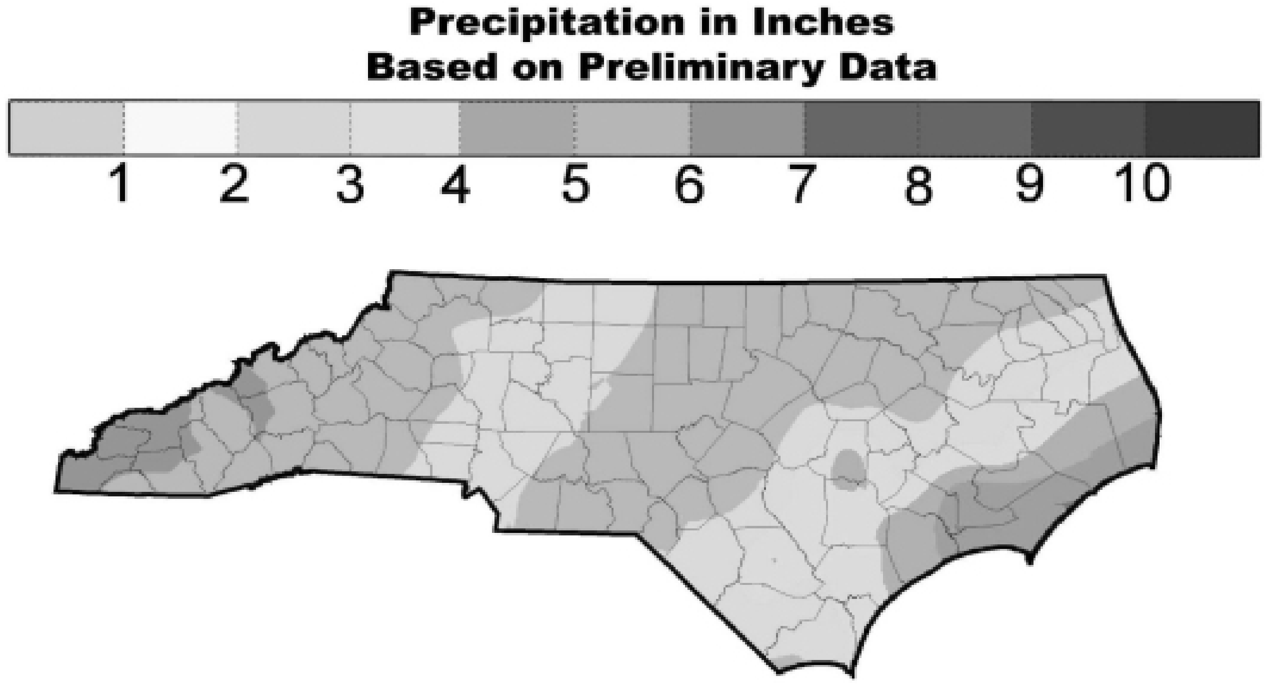

Figure 38. As in Fig. 4, except for Gordon (September 2000).

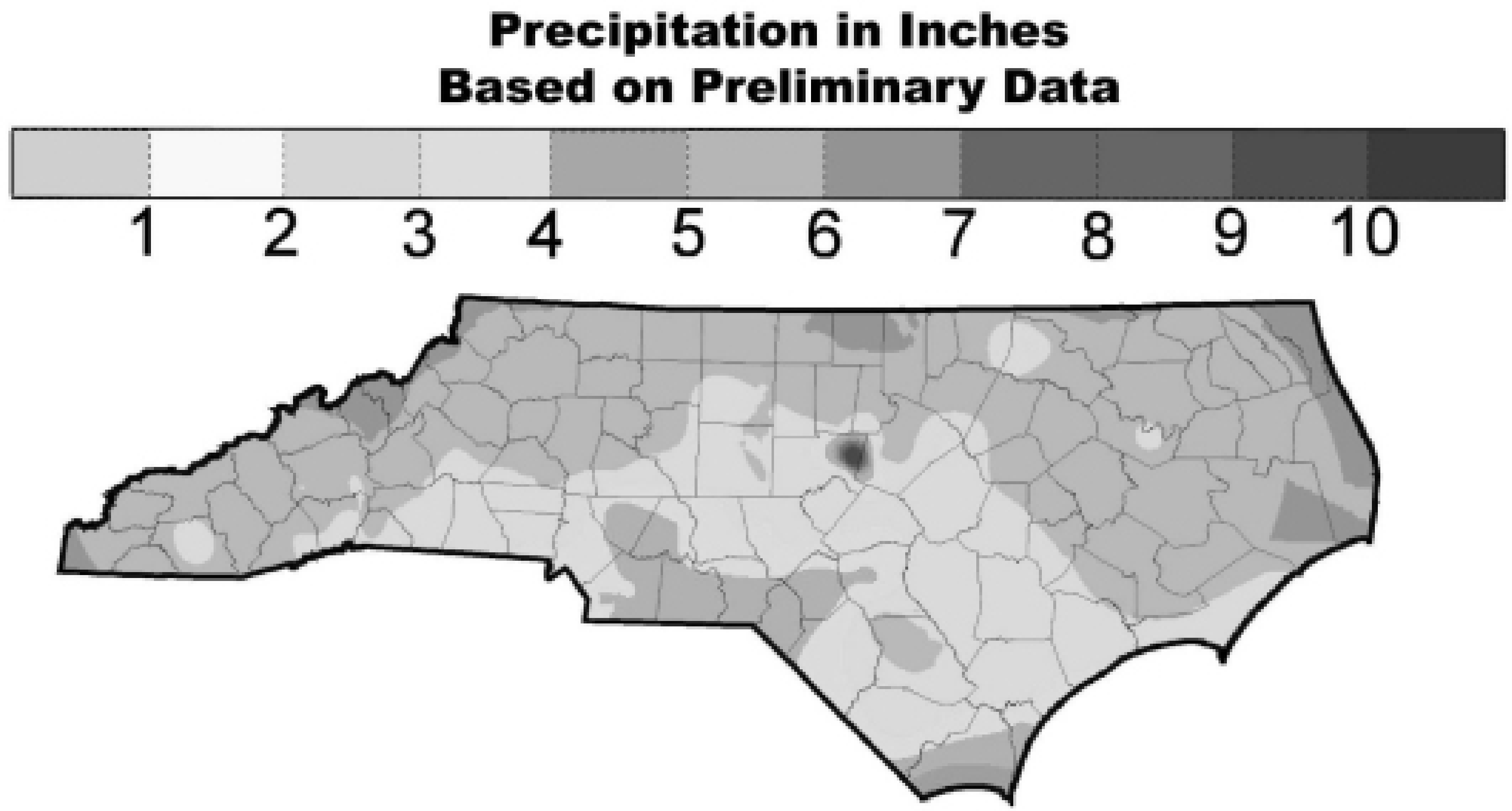

Figure 39. As in Fig. 4, except for Helene (September 2000).

Appendix A

North Carolina Fatalities Directly Related to Hurricane Floyd

Decedent	**Age**	**County**	**Description**
1. George Jefferson	43	Bertie	Drowned - stepped out of a truck and was swept away in flood waters.
2. Badger Chandler	76	Craven	Drowned in vehicle - drove around a barricade.
3. Reiford Nichols	55	Craven	Drowned - fell out of a boat on a flooded street in Grifton on the Pitt County Line.
4. Ransom Cole	70	Duplin	Drowned - found in roadside ditch between hurricane shelter and his home.
5. Mitchell Piner	42	Duplin	Drowned - vehicle related - truck was washed off the road in flood waters.
6. Larry Summerlin	63	Duplin	Drowned - vehicle related - DOT Employee drowned while trying to cross high water on way to work. Rescue workers tried to throw a rope to him, he got out of the truck but was swept under.
7. Chris Brown	75	Edgecombe	Drowned - fell into a ditch of high water and could not get out or swim. Ditch was in front of home.
8. Cabrina Flowers	5	Edgecombe	Drowned - part of 6 deaths of people that fell from a boat overloaded with 13 people in a neighborhood rescue attempt to bring people off rooftops.
9. Destiny Flowers	3	Edgecombe	
10. Ben Mayo	50	Edgecombe	
11. Vivian Mayo	45	Edgecombe	
12. Teshika Vines	5	Edgecombe	
13. Chiquita Mayo	23	Edgecombe	
14. Otis Reid	51	Edgecombe	Drowned - found in flooded trailer.

15. James Stokes	64	Halifax	Drowned - vehicle related - car swept away in flood waters that he had driven into. Got out of car and tried to swim.
16. Carrie Poythress	47	Halifax	Drowned - vehicle related - passenger in car that was washed off a flooded road.
17. Eusebio Maldonado	30	Johnston	Drowned - vehicle related - vehicle swept into creek. He was the driver of the car.
18. Paul Mobley	31	Johnston	Drowned - vehicle related - Part of a father/daughter group that died when their vehicle was washed into a creek.
19. Emily Mobley	5	Johnston	These two were on their way to rescue others from the flood.
20. James Wilder	63	Jones	Drowned - vehicle related - DOT worker found in auto - died during rescue operations.
21. William Gooding	54	Lenoir	Drowned - vehicle related - last seen driving toWork at Dupont Plant. Found in vehicle when Waters receded.
22. Eulalia Aldridge	87	Nash	Drowned - vehicle related - brother and sister in a pickup truck were washed off Highway 64 overpass north of Nashville.
23. David Mills	79	Nash	
24. Richard Phillips	40	Nash	Drowned - vehicle related - car was being swept away and he got out of the car and tried to swim. Off Highway 921 in Rocky Mount.
25. Artemus Westry	46	Nash	Drowned - vehicle related - washed off road at a low spot on Highway 64 into the river.
26. Paul Buco	78	Pender	Drowned - vehicle related - trying to cross a flooded roadway section of I-40, swept into ditch.
27. William Nixon	47	Pender	Drowned - vehicle related - trying to cross a flooded roadway. Got out of car and tried to swim.
28. Aaron Child	19	Pitt	Drowned - vehicle related - ECU student found in car after flood waters receded. Was on the way to a hurricane party at his brother's house.
29. Mario Gomez	26	Pitt	Drowned - vehicle related - one of two in the same auto that went into flooded waters. Decided

30. Silberio Gomez	27	Pitt	not to go forward into flood waters and instead backed into them.
31. Ronald Russell	43	Pitt	Drowned - vehicle related - drove onto flooded road with a bridge out and was swept away, got out of car and tried to swim.
32. Lou Giggets Hendrick	55	Warren	Drowned - vehicle related - part of two that drove into flood waters and was swept away off secondary road 1600 near Warrenton.
33. George Clinton Jones	72	Warren	
34. Kenneth Denning	51	Wayne	Drowned - vehicle related - Driving to work attempted to cross a road that was washed away.
35. Cheryl Whitley	42	Wayne	Drowned - vehicle related - drove onto a washed out road.

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