

HURRICANE BERTHA

*Carin Goodall-Gosnell, Dan Bartholf, John Elardo,
Bob Frederick, Cory Gates, Jim Hudgins, and Richard Thacker
NOAA/NEXRAD Weather Service Office
Newport, North Carolina*

1. INTRODUCTION

Around 2000 UTC 12 July 1996, Hurricane Bertha, a category 2 hurricane on the Saffir-Simpson Hurricane Scale (Table 1), made landfall south of Topsail Island, North Carolina (Fig. 1). The eye of Bertha passed within 40 n mi of NWSO MHX, located in Newport, NC, approximately 9 n mi west-northwest of Morehead City. This was the first hurricane to move inland over east-central North Carolina since the NEXRAD Weather Service Office (NWSO) Newport (MHX) and the collocated Doppler radar (KMHX) were put into service in January 1994. A close call occurred in August 1995, when the eye of Hurricane Felix appeared on the radar for two volume scans. The last major hurricane to make direct landfall over North Carolina was Hurricane Donna when her eye crossed Topsail Island in 1960.

Damage estimates from Bertha across the NWSO MHX County Warning Area (CWA) were around 500 million dollars. Most of the damage was a result of significant loss of crops away from the coast. Along the coast, major damage from storm surge flooding was reported from North Topsail Island north to around Emerald Isle. There was also significant flooding along the western sections of the Pamlico Sound from New Bern north to Washington and

Belhaven. Numerous trees and power lines were knocked down across all of eastern North Carolina, leaving many residents without electricity for several days.

Included here is a collection of studies made by the forecasters at NWSO MHX. A history of Bertha has been constructed using satellite and Doppler radar pictures. A non-standard Z-R relationship was used on the Weather Surveillance Radar - 1988 Doppler (WSR-88D), and its performance has been compared with ground truth from various rain gauges. The vulnerability of eastern North Carolina to flooding, the public's response to the hurricane threat, and the performance of various numerical weather prediction and storm surge models are also discussed.

Appendix I shows a comparison between Hurricane Bertha and some of the more memorable hurricanes in North Carolina history. Appendix II is a detailed description of the effects of Hurricane Bertha on eastern North Carolina. Appendix III shows the official positions and maximum sustained winds during Hurricane Bertha's lifetime. Appendix IV lists rainfall reports for several locations within 120 n mi of the KMHX radar.

2. HISTORY OF BERTHA

Hurricane Bertha was an unusual, early season Cape Verde storm. She formed as a depression off the coast of Africa on 5 July 1996, and moved on a west-northwest track (Fig. 2 and Appendix III) around the bottom side of a large anticyclone centered along 30°W in the North Atlantic. Bertha intensified into a category 3 storm by 0900 UTC 9 July 1996, with sustained winds of 100 kt and a central pressure of 960 mb.

On 10 July, a 500-mb trough moved through the northeastern United States, leaving in its wake a progressive zonal flow from the Great Lakes to New England. In response, Bertha shifted to a more northwest track.

During the afternoon and evening of 11 July, Bertha weakened as she moved to around 200 n mi east of the Georgia coast. Maximum sustained winds had decreased to 70 kt and the central pressure had risen to 980 mb. On the 2115 UTC 11 July visible satellite picture (Fig. 3), the low-level circulation was partially exposed and well west of the deep convection.

Examination of the 0000 UTC 12 July upper air data showed winds at the 300-mb level were from the west-northwest at between 20 and 25 kt along the southeast coast of the United States (Fig. 4). This would help to explain the shearing of the deep convection away from the low-level circulation. Bertha continued to weaken into the early morning hours of 12 July with the pressure rising to 991 mb by 0600 UTC as another weak short wave approached the mid-Atlantic region. This weak, but noticeable, disturbance was short-lived, and on the morning of the 12 July, Bertha had regained convection around her center, and was reorganizing.

The short wave pulled Bertha's track to a more

north-northwest direction and it appeared as though she would pull away from land. But instead of moving out to sea, landfall was further north than the expected Savannah, GA, to Charleston, SC, corridor.

Infrared satellite imagery indicated an increase in deep convection associated with Bertha between 0600 UTC and 0900 UTC (Fig. 5) and reconnaissance flights showed that the pressure had dropped to 985 mb by 0900 UTC.

Examination of the 1200 UTC 12 July upper air data (Fig. 6) showed that the weak short wave over the Tennessee Valley had moved east toward the coast. This backed the winds at 300 mb over the southeast North Carolina coast from west-northwest to south-southwest at 20 to 30 kt. As the upper level winds became more southerly, the shear that had been influencing Bertha decreased. Bertha also moved over the core of the Gulf Stream, where satellite data showed sea surface temperatures between 83 and 86 °F. These factors helped Bertha become better organized.

Reconnaissance flights reported that the pressure was down to 997 mb and the maximum sustained winds had increased to 80 kt by 1200 UTC 12 July. At 1236 UTC, an ill-defined eye became visible east of northern Georgia on the 1.1-n mi resolution base reflectivity product (Klazura and Imy 1993) of the KMHX WSR-88D.

By 1345 UTC, WSR-88D reflectivity data showed the eye becoming more organized, as the first spiral rain band moved ashore near Wilmington (Fig. 7). A visible satellite picture taken at 1400 UTC 12 July, indicated the low-level center was no longer exposed and was now under the deep convection just south of the North Carolina coast (Fig. 8).

Bertha continued to deepen during the morning of 12 July as she moved toward the coast at 10 to 15 kt, and was a strong category 2 storm by 1500 UTC. Sustained winds increased to 90 kt and the central pressure dropped to 974 mb. The first rain band moved over NWSO MHX around 1800 UTC as the eye approached Cape Fear (Fig. 9).

The Velocity Azimuth Display (VAD) Wind Profile (VWP) indicated winds at 1000 ft had increased to around 60 kt with the passage of this band (Fig. 10). The band moved over the office during the next hour, and as it moved away, winds dropped back to less than 50 kt. Bertha still had not made landfall by this time.

Bertha remained a category 2 storm with sustained winds of 90 kt as she made landfall around 2000 UTC between Wrightsville Beach and North Topsail Beach, about 2 h before high tide. Bertha had a classic hurricane appearance at landfall with distinct banding around the eye as seen on both radar and satellite imagery (Figs. 11 and 12).

Another rainband moved over NWSO MHX shortly after landfall, increasing the 1000-ft wind to 55 to 60 kt (Fig. 13). After the passage of this spiral band, 1000-ft winds dropped to a mere 15 kt. The eye of Hurricane Bertha passed about 34 n mi west of the KMHX radar a little less than 2 h after landfall.

The final rain band moved into the area around 2253 UTC (Fig. 14). One thousand foot winds increased to 65 kt from the south (Fig. 15) as the eye was almost due west of the office. The eye slowly lost definition over the next hour, but the storm still resembled a hurricane. Up until this time, rainfall over land was mostly stratiform.

However, by 2300 UTC, convection became evident east of the eye with the strongest convection occurring around 2330 UTC.

Around 0200 UTC, the final rain band was still in the area (Fig. 16), but the convection had diminished. One thousand foot wind speeds were still around 50 kt. At 0300 UTC, Bertha's eye was completely filled with precipitation; however, heavy rains continued over the northeastern North Carolina counties. One thousand foot wind speeds over NWSO MHX dropped to around 45 kt and continued to drop throughout the remainder of the night.

An exciting day at NWSO MHX had come to an end!

3. FLOODING

North Carolina is unique in that it not only has an expansive coastline with low, flat topography across the adjoining coastal plain, but it also has an extensive series of sounds and tidal rivers. This makes much of eastern North Carolina vulnerable to significant flooding, and particularly susceptible to flooding from tropical cyclones.

Hurricane Bertha demonstrated the impact on eastern North Carolina due to flooding from a moderate hurricane. The worst flooding in nearly 40 years was experienced in this area causing significant property damage and devastating beach erosion. Emergency management officials reported that nearly every pier and dock located on the Neuse and Pamlico Rivers was damaged or destroyed during the storm.

The approach of Hurricane Bertha from the south-southeast exposed eastern North Carolina to a prolonged period of east to southeast flow. The persistent winds began

to pile up water on east-facing beaches and inlets along the Atlantic Ocean. The downwind areas of the Pamlico and Albemarle Sounds, as well as the Neuse and Pamlico Rivers, experienced increasing water levels as much as 36 h in advance of landfall, as the pressure gradient between Bertha and an anticyclone to the north tightened.

The hurricane's landfall was about 2 h before high tide. The increasing water levels on top of the incoming tide contributed to a high coastal storm surge, especially over Onslow County and western Carteret Counties, between Topsail Beach and Emerald Isle.

a. Inland Storm Surge Flooding

Inland, the most serious flooding occurred in the communities of Belhaven, Washington, and New Bern. Belhaven, located adjacent to the Pamlico River in Beaufort County, had the record 6.6-ft storm surge associated with the Hurricane of 1913 eclipsed by Bertha's surge of around 7 ft (Fig. 17). Elsewhere, Washington on the Pamlico River in Beaufort County and New Bern on the Neuse River in Craven County also experienced significant flooding with storm surges of around 7 ft, but remained under record levels.

b. Coastal Storm Surge Flooding

Hurricane Bertha's landfall over southeast North Carolina put the NWSO MHX CWA in the dangerous northeast quadrant of the storm. Significant storm surges of 8 to 10 ft above normal were experienced from Topsail Beach north to Emerald Isle. On the beaches, many sand dunes were seriously eroded or destroyed during the storm. Extensive property damage due to the combination of strong winds and storm surge was reported in these areas, especially

along the barrier islands and immediate coast.

North of Emerald Isle, the storm surge was generally 4 to 6 ft above normal with serious beach erosion, but much less flood and wind damage than was recorded in North Topsail Beach, Swansboro, and Emerald Isle.

Minor flooding occurred along the Morehead City waterfront due to Bogue Sound overwash. Eastern sections of Carteret County experienced minor to moderate flooding from the Pamlico Sound with portions of Route 12 inundated near Cedar Island.

The Outer Banks experienced some overwash on Route 12, but since Bertha moved well south and west of the area, this overwash was minor.

c. Seiching

Coastal flooding from a storm surge associated with a land-falling hurricane is always a concern. However, with the complex sound and river system over eastern North Carolina, flooding due to seiching effects is also a major problem. An example of this phenomenon occurred when the sustained northerly winds from Hurricane Gloria emptied the Pamlico Sound from the north, and water was not visible as far as the naked eye could see. After the winds let up, the water returned, and there was massive flooding from Manteo to Elizabeth City.

The persistent, strong wind flow associated with slow moving Hurricane Bertha allowed water to pile up rapidly on the downwind sides of the relatively shallow inland waterways. The onshore wind trajectory pushed high water levels onto the western side of the Pamlico Sound, while eastern portions near the central Outer Banks in the

vicinity of Cape Hatteras were blown dry up to 200 yards from shore.

The high water levels on the western Pamlico Sound were pushed upstream on the Neuse and Pamlico Rivers where significant flooding ensued. Water levels had risen 5 to 7 ft above normal by the evening of 12 July, causing extensive damage in the communities of New Bern, Bath, Washington and Belhaven.

As the hurricane moved inland and continued north, the prevailing flow veered to the south and southwest and allowed water to accumulate on the northern portion of the Pamlico and Albemarle Sounds. Some minor flooding was reported on Roanoke Island, with more significant flooding on the northern reaches of the Albemarle Sound, where water levels reached up to 6 ft above normal by the early morning hours of 13 July.

Often, after a strong storm moves by, winds abruptly back to the opposite direction, allowing the water that was piled up on the northern and western sides of the sounds to quickly return, flooding the adjacent southern and eastern land areas. This type of seiching happened most recently with the March 1993 "Storm of the Century." However, with slow-moving Hurricane Bertha, the winds turned around and diminished more slowly, allowing the water to return at a slower rate. Residents on Hatteras Island were reportedly surprised that they didn't catch the backlash of water.

d. Storm Surge Models

The staff at NWSO MHX used output from three storm surge models to help them forecast oceanic and inland water levels during the storm. The primary model used was the well-known Sea, Lake, and Overland Surges from Hurricanes (SLOSH)

model (Jelesnianski et al. 1992) developed by the NWS Office of Systems Development Techniques Development Laboratory. The other two models were produced by local universities. The Croatan-Albemarle-Pamlico Estuary System (CAPES) model was engineered by the North Carolina State University (Neuherz et al. 1997) while the Advanced Circulation (ADCIRC) model was developed at the University of North Carolina (Luettich et al. 1992).

SLOSH - For this event, the SLOSH model indicated the best results (National Weather Service 1996). The model accurately predicted a 7 ft storm surge along the Neuse and Pamlico Rivers (Fig. 18) for a category 2 hurricane moving slowly NNE.

CAPES - The CAPES model was run at North Carolina State University on the night prior to the hurricane's landfall and produced results comparable to SLOSH. The 2100 UTC advisory from the TPC was used to input the predicted track, wind radii and minimum pressure information. A downward adjustment to the winds of 25% was made to account for the expected weakening of the storm upon landfall.

The model handled the high water levels on the western end of the Pamlico Sound extremely well (Table 2). The model not only forecast the areas that would receive significant flooding, but it's water level forecasts of 7 to 8 ft over the western Pamlico Sound were very accurate. On a negative note, the model overforecast sound-side flooding along the Outer Banks on the east side of the hurricane's circulation. This poor handling of the flooding on the eastern end of the basin was caused by the model's inability to deal with time-dependent winds and the asymmetry of Bertha's wind field.

ADCIRC - This model accurately forecast the areas that would receive major flooding (Fig. 19). However, the model significantly underforecasted water levels from Bath to Belhaven. This was a result of the model using an internally generated hurricane wind field based solely on the barometric pressure. The model assumed the hurricane to be a symmetric, uniform storm while in actuality, the strongest winds were primarily confined to the northeast and east portions of the storm.

Forecast surges along the beaches were less than half of the observed values (Fig. 20). This appeared to be a result of limitations associated with the projected track of Bertha. It is important to note that this model was specifically developed for non-tropical storm surges, and while it is capable of using wind fields, only pressure was input in this instance since real-time wind information was unavailable.

4. NCEP NUMERICAL MODEL SUITE

The ensemble of hurricane forecast models used by the Tropical Prediction Center (TPC; formerly the National Hurricane Center) can be complemented by output from the daily synoptic numerical models: the Eta model, the Nested Grid Model (NGM), and the Aviation (AVN) model. The performance of these three models will be discussed. While the individual model solutions differed slightly from one another, their overall performance with respect to Bertha was reasonably accurate.

Approximately 60 h prior to landfall, at 1200 UTC 10 July, Hurricane Bertha was located at 25.4°N and 75.4°W, or about 55 mi east of Eleuthera Island in the Central Bahamas. Bertha was moving to the northwest at 16 kt at this time. The 1200

UTC runs of the Eta, NGM, and AVN were consistent in showing that Bertha would take a gradual turn to the north, bypassing Florida and possibly making landfall somewhere from Wilmington (ILM) to Cape Hatteras, North Carolina (HAT).

A comparison of the three models showed variable results from run to run. The Eta model seemed to perform the best overall. It was the most consistent model from run to run, but occasionally overestimated the storm's forward motion and was a bit to the left of the actual track. In addition, the Eta model initialized better than the other models at 0000 UTC 13 July, when the decaying center of Bertha was over the central coastal plain of North Carolina. The NGM had some problems at the 60- and 48-h projections, but performed well from 36 h to landfall. The AVN model solutions were consistently to the left of the actual track and often overpredicted the storm's forward motion. The 1200 UTC 10 July (60-h forecast) run was an exception, as the forecast position was well to the right of the storm's actual location at landfall.

a. Eta

At 1200 UTC 10 July, the Eta model showed remarkable geographical accuracy by placing Bertha near ILM at landfall. Unfortunately, it predicted the storm's arrival about 12 h ahead of schedule. This run of the model handled the 500-mb features almost flawlessly. For the 0000 UTC 11 July run, the Eta track shifted a bit to the left (Fig. 21), with landfall forecasted between Charleston (CHS) and Myrtle Beach (MYR), South Carolina. The timing was once again about 12 h too fast, and this run seemed to downplay the strength of the short wave (Fig. 22) approaching the mid Atlantic area. The 1200 UTC 11 July Eta

run was nearly identical to the previous run, and still 12 h too fast.

For the 0000 UTC 12 July model run, the Eta forecast was very similar to the prior two runs, but with a slight shift to the right, showing landfall along the northern South Carolina coast (Fig. 23). The timing of this forecast was also improved with landfall predicted closer to the time of the actual landfall.

Only 8 h before landfall, the 1200 UTC 12 July forecast track (Fig. 24) was 50 mi to the left of the actual observed path of the storm. For the 0000 UTC 13 July run, the center of Bertha was initialized very close to the actual location of the hurricane at the surface (Fig. 25).

b. NGM

The 1200 UTC 10 July NGM run (not shown) was inaccurate in its handling of the 500-mb and surface features. Bertha was reflected as an open weak short wave at 500 mb, and the timing was almost 36 h too fast. The 0000 UTC 11 July run more accurately predicted the building ridge to the north of Bertha, but still underforecasted the strength of the approaching short wave. There was a large shift to the left with landfall predicted near CHS. However, for this projection, the NGM was the best of all three models with respect to the timing of Bertha's landfall.

There was tremendous improvement in the 1200 UTC 11 July NGM run. The surface forecast showed landfall near ILM, but 14 to 16 h ahead of schedule. By the 0000 UTC 12 July forecast, the NGM also showed improved timing.

The 1200 UTC 12 July NGM run, less than 12 h prior to the storm's landfall, was excellent. The surface features were nearly

perfect. However the timing was still just a bit fast.

It is interesting to note that, for the 0000 UTC 13 July NGM run, the model was initialized with Bertha centered about 50 mi south of the actual position 4 h after landfall.

c. AVN

The 1200 UTC 10 July AVN forecast was similar to the NGM for this run, 60 h prior to landfall. The timing was around 24 h too fast as the model put the center of the hurricane near HAT at 0000 UTC 12 July. The model overpredicted the speed of the approaching short wave and failed to adequately depict the strength of the ridging just north of the system. For the 0000 UTC 11 July AVN forecast, the model was similar to the NGM in depicting a large shift to the left of its previous forecast track. Landfall was now projected to occur near MYR and the timing was 12 h too fast. At 500 mb, the model seemed to have a better handle on both the ridge to the north of the system and the short wave in the Tennessee Valley.

At 1200 UTC 11 July, there was another large shift to the left in the forecast track of Bertha. The AVN now depicted landfall between CHS and Beaufort, South Carolina. The model now overpredicted the strength of the 500-mb ridge to the north of Bertha. The effects of the short wave to the north were minimal on this run. The AVN deviated from both the Eta and the NGM solutions and would have a hard time recovering in the two subsequent runs.

Less than 24 h prior to landfall, at 0000 UTC 12 July, the AVN was still depicting a landfall south of CHS. The surface low was displaced too far west. The 1200 UTC 12 July forecast from the AVN continued to

project landfall well to the left of the actual track as the hurricane was forecast to make landfall between CHS and MYR. The model had slowed the system down and was now about 6 h too slow. Once again, the 500-mb features appeared reasonable, but the surface low position was incorrectly initialized.

There was a questionable initialization on the 0000 UTC 13 July AVN run as the center of the surface low was placed near Newport/Morehead City, North Carolina, or about 60 mi to the right of the actual center of Bertha at that time.

5. WSR-88D PRECIPITATION ESTIMATES

Prior to Hurricane Bertha, the default Z-R relationship used by the KMHX WSR-88D was replaced by the tropical equation. Rainfall estimates from the radar were obtained for the entire time that tropical rains affected eastern North Carolina. The tropical Z-R relationship was examined to assess the radar's performance. Unfortunately, Archive Level II data are unavailable, so testing other relationships based on data from this case was not possible.

The Z-R relationship was changed from $Z=300R^{1.4}$ to $Z=250R^{1.2}$ at 2148 UTC 11 July. Only a few very light showers had fallen up to this point so continuity between the Storm Total Precipitation (STP) product and the rain gauge data was maintained. At this point, Hurricane Bertha was still well to the south of North Carolina, but her large tropical circulation was beginning to impinge on the region as more concentrated showers were advancing onshore.

Fifty rainfall reports (Appendix IV) were gathered from various sources, such as local airports, NWS cooperative observers, NWS personnel, and trained spotters. Data from the 50 rain gauges were compared to STP totals (Fig. 26) for the 30-h period from 2148 UTC 11 July to 0332 UTC 13 July, using several different techniques (Gates 1996). Mid-point precipitation estimates between each STP threshold were used. For example, if the STP bin had an estimate of 2.50 inches, it was recorded as 2.75 inches, the mid-point between 2.50 and 3.00 inches on the STP accumulation legend. For this report, only the bin closest to the gauge was used, and only Mean Radar Bias (Eq. 1) and Average Difference (Eq. 2) are discussed for three geographic areas: the entire 124-n mi radius KMHX radar umbrella, the MHX CWA, and longer ranges (75-124 n mi).

$$\frac{1}{N} \sum_{i=1}^N \frac{G_i}{R_i} \quad (1)$$

$$\frac{1}{N} \sum_{i=1}^N |(G_i - R_i) / G_i| * 100\% \quad (2)$$

(Note: For both equations, G is the gauge measurement, R is the radar STP estimate, and N is the total number of gauge reports.)

Table 3 shows that the mean radar bias for the entire 124-n mi range was 1.47 with an average difference of 29.4%. The WSR-88D precipitation processing algorithms underestimated rainfall amounts as compared to gauge reports. (A bias of 1 and an average difference of 0% are considered perfect.)

When the analysis was limited to the NWSO MHX CWA, the radar's performance with the new Z-R relationship was quite

respectable, with a mean radar bias of 1.38, and an average difference of 25.7%. The MHX CWA is relatively small, with 90% of the area within 75 n mi of the radar. The results represent an objective view of how the radar performed at the close and medium ranges.

Results for the longer ranges were not as favorable with a bias of 1.61 and an average difference of 34.9%. This is reasonable given that the beam height increases from 8,000 ft to 17,000 ft as range increases from 75 n mi to 124 n mi when the radar is scanning at the 0.5° elevation angle. The height of the beam at longer ranges is likely overshooting the heavy rain cores, especially in tropical situations where the highest reflectivities are typically located at relatively low altitudes.

An average difference of 29.4% does not produce significant errors for lighter rainfall amounts of 1 to 2 inches. However, rainfall amounts between 4 and 6 inches would result in estimates that would be off by about 1.2 to 1.8 inches. With excessive rains of greater than 10 inches, estimates would be off by 3 inches or more.

These figures are encouraging, especially when compared to the radar's performance during Hurricane Gordon in November 1994. A local study involving radar-gauge comparisons during Hurricane Gordon showed that WSR-88D rainfall estimates were underestimated by 50% to 70% (Thacker 1996). Another study (Choy et al. 1996) at the NWS office in Melbourne, Florida, indicated a 46% underestimation of rainfall during tropical rains. During both of these events, the default Z-R relationship was used.

6. EVACUATION AND PUBLIC AWARENESS

Hurricane Bertha came at the peak of the tourism season. The Coastal County Emergency Management coordinators have a copy of the HURREVAC computer program (Townsend 1984) that helps them make evacuation decisions for hurricanes. They compare the output from HURREVAC to the information contained in a comprehensive hurricane evacuation study (U.S. Army Corps of Engineers 1987). A strike probability of 30% is a critical threshold in the evacuation decision making process. A tourist occupancy of MEDIUM was used in HURREVAC, which corresponds to landfall during a summer work week. An evacuee response of MEDIUM was input because of the wet roads from rainfall prior to the storm. With these conditions, it was estimated that it would take around 9 1/4 h to evacuate Dare County (Hatteras Island) and around 20 h to evacuate the Outer Banks of Hyde County (Ocracoke Island). Given the same conditions, Carteret County could be evacuated in 9 1/2 h, and Onslow County in about 10 h.

A mandatory evacuation of Ocracoke Island began at 1230 UTC 10 July. Hatteras Island was ordered to begin evacuating at 1400 UTC. Shelters were opened in Virginia, and in North Carolina at Greenville and Williamston. The policy of the Emergency Managers in this area is to open up the distant shelters first and save the closer ones for any last-minute evacuees.

The decision was made late on 10 July to begin evacuation of the Bogue Banks (Carteret County's southern shore) beginning at 1000 UTC 11 July. Residents in mobile homes and low lying areas in the remainder of the county were also urged to

evacuate. Carteret County also opened up shelters.

Onslow County issued a voluntary evacuation order for North Topsail Beach, Surf City, and all low-lying areas and mobile homes at 1300 UTC 11 July. Craven County recommended evacuation of residents living in flood prone areas near the Neuse and Trent Rivers and those in mobile homes. A mandatory evacuation of the remainder of Dare and Hyde Counties, including the mainland areas, began in the morning of 12 July.

When the hurricane struck, NWSO MHX kept residents informed through live interviews with WKOO radio station in Jacksonville, NOAA Weather Radio broadcasts, statements to the Weather Channel and other media outlets, and by amateur radio. The NWSO MHX Bulletin Board Service for emergency managers, which contains all the latest hurricane watches/warnings, advisory statements, tornado watches/warnings, etc., was accessed many times during the event.

During Hurricane Bertha, more than 20 telephone conference calls were held with county emergency managers and the area coordinator. The purpose of the calls was to keep local officials apprised of the developing situation and to supplement information provided by the TPC. In addition, the latest Hurricane Hotline information was relayed. At times, conference calls were held every hour, but for the most part took place at 3-h intervals.

Ironically, North Carolina's Hurricane Awareness Week was scheduled for the week of 14-20 July. Needless to say, it was canceled.

7. THE REMAINDER OF THE 1996 HURRICANE SEASON

On 5 September 1996, Hurricane Fran struck eastern North Carolina at nearly the same place that Hurricane Bertha did in July, but continued inland instead of recurving back out to sea. Personal observations indicated that damage from Fran was less widespread than with Bertha, but the destruction that did occur was more severe. Bertha had already cleared out the weak trees, power lines, roofs, houses and foliage. Thus, although Fran was more powerful than Bertha, the area was much less susceptible to the extent of damage that was seen with Bertha.

Tropical Storm Josephine moved from the Gulf of Mexico into eastern North Carolina on 8 October 1996. This storm was considerably weakened by her long track over land. However, rainfall amounts from Josephine were higher in some areas than during either Bertha or Fran. Road flooding from Bertha and Fran had just subsided when Josephine moved over the area, causing water levels to rise once again.

8. CONCLUSION

Hurricane Bertha, a category 2 storm on the Saffir-Simpson scale, made landfall between North Topsail Beach and Wrightsville Beach at 2000 UTC 12 July 1996. The tropical system moved rapidly through Eastern North Carolina, becoming extratropical before exiting off the coast of the northeastern United States.

Several factors combined to create record to near record flooding across eastern North Carolina: the location of Bertha's landfall, which placed NWSO MHX, and our CWA, in the dangerous northeast quadrant of the

storm; the relatively slow movement of the storm; her arrival near high tide; high water levels from previous heavy rains; and, the large water volume, and shallow nature of the Albemarle and Pamlico Sound drainage basins. In fact, the flooding associated with Bertha was the most significant in east-central North Carolina in nearly 40 years, and in some locations reached record levels of 7 to 10 ft.

A comparison of three numerical models showed variable results from run to run. The AVN model was consistently to the left of the actual track and greatly overestimated the forward speed of the storm. The NGM had its problems as well at the 60- and 48-h projections, but performed well from 36 h to landfall. The Eta model seemed to be the best overall performer. It was less variable from run to run, but occasionally overestimated the forward speed of the storm and was a bit to the left of the actual track.

Of the three storm surge models available, the SLOSH model provided the best information for forecasters, but the CAPES model also did well. The ADCIRC model, a non-tropical storm surge model, had the poorest results.

The default WSR-88D Z-R equation was changed to a more tropical relationship and resultant rainfall estimates were underdone by about 30%. This is encouraging considering previous studies using the default Z-R relationship showed that precipitation amounts were underestimated by between 50% and 70%.

Maximum reported sustained winds were 81 mph with gusts reported as high as 108 mph. The highest rainfall amount reported was 8.06 inches and storm tides reached as high as 10 ft. Many areas were flooded, while

sand dunes and piers along the beaches and many inland crops were destroyed. Only two people died in North Carolina during Hurricane Bertha, both as an indirect consequence of the hurricane.

ACKNOWLEDGMENTS

The authors wish to thank Tim Obannon (OSF), Dan Berowitz (OSF), Central Wills (DAPM, NWSO MHX), Tom Addington (DAPM, NWSO ILM), Deborah Money penny (DAPM, NWSFO RAH) and Fay Crossley (DAPM, NWSO AKQ) for supplying numerous NWS cooperative observer rainfall reports and to Julie Adolphson (COMET) for providing some Eta model output. Thanks also go to Bonnie Terrizzi, James Ireland and Tom Kriehn for their help and suggestions.

REFERENCES

- Choy, B. K., L. Mazarowski, and P. Glitto, 1996: Tropical Storm Gordon: 72-hr rainfall totals over east central Florida and WSR-88D comparisons. *NOAA Technical Memorandum NWS SR-174*, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 99 pp.
- Gates, C., 1997: Hurricane Bertha: radar-gauge comparisons and changing the Z-R relationship. *Eastern Region WSR-88D Operations Note*, No. 10, National Weather Service, NOAA, U.S. Department of Commerce, 12 pp.
- Jelesnianski, C. P., J. Chen, and W. A. Shaffer, 1992: SLOSH-Sea, lake and overland surges from hurricanes.

- NOAA Technical Report NWS-48*, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 71 pp.
- Klazura, G. E., and D. A. Imy, 1993: A description of the initial set of analysis products available from the NEXRAD WSR-88D system. *Bull. Amer. Meteor. Soc.*, **74**, 1293-1311.
- Luetlich, R. A. , J. J. Westerink, and N. W. Scheffner, 1992: ADCIRC: An advanced three dimensional circulation model for shelves, coasts and estuaries. Report 1: theory and methodology of ADCIRC-2DDI and ADCIRC-3DL. *DRP Technical Report* DRP-92-6, U.S. Army Corp of Engineers, 137 pp.
- National Weather Service, 1996: A new storm surge atlas for the Pamlico Sound, North Carolina area. National Oceanic and Atmospheric Administration, U.S. Dept. of Commerce, 167 pp.
- Neuherz, R. A., L. Xie, L. J. Pietrafesa, and K. K. Keeter, 1997: Forecasting storm surge in the Albemarle and Pamlico Sounds induced by hurricanes during the 1996 hurricane season. *Preprints 22nd Conference on Hurricanes and Tropical Meteorology*, Fort Collins, Amer. Meteor. Soc., 6 pp.
- Thacker, R., 1996: A subjective comparison of the WSR-88D storm total precipitation products and rain gauge measurements for hurricane Gordon in North Carolina on November 16-18, 1994. Unpublished local report, 9 pp. Available from National Weather Service Office, Newport/Morehead City, North Carolina.
- Townsend, J. F., 1984: A computer calculation and display system for SLOSH hurricane surge model data. NOAA Technical Memorandum NWS ER-67, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 19 pp.
- U.S. Army Corps of Engineers, Wilmington District, 1987: Eastern North Carolina hurricane evacuation study. North Carolina Division of Emergency Management. Federal Emergency Management Agency.

Table 1. The Saffir-Simpson hurricane scale and the amount of damage that can be expected from storms within each category. Some recent storms (and their location of landfall) are also listed for each category.

Category	Winds (mph)	Damage	Examples
1	74-95	minimal	Florence 1988 (LA) Charly 1988 (NC)
2	96-110	moderate	Kate 1985 (FL) Bob 1991 (RI)
3	111-130	extensive	Alicia 1983 (N TX) Emily 1993 (NC Outer Banks)
4	131-155	extreme	Andrew 1992 (S FL) Hugo 1989 (SC)
5	>156	catastrophic	Camille 1969 (LA/MS) Labor Day Hurricane 1935 (FL Keys)

Table 2. Storm surge forecasts from the CAPES model as compared to observed values during Hurricane Bertha.

	Western Albemarle Sound	Western Pamlico Sound
Forecast	5-6 ft	7-8 ft
Observed	4-5 ft	6-7 ft

Table 3. Mean radar bias and average difference for Hurricane Bertha using the tropical Z-R relationship, $Z=250R^{1.2}$. Values are calculated for three geographic regions: the entire 124-n mi radius KMHX radar umbrella, the MHX CWA, and longer ranges (75-124 n mi).

	0-124 n mi	CWA	75-124 n mi
Mean Radar Bias (Eq. 1)	1.47	1.38	1.61
Average Difference (Eq. 2)	29.4%	25.7%	34.9%

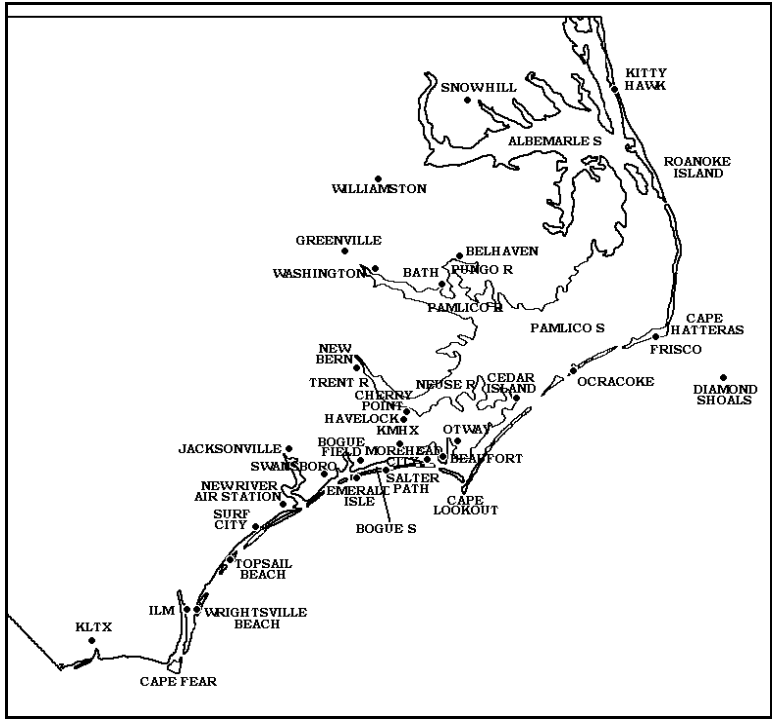


Figure 1. Map of eastern North Carolina with sites of interest indicated.

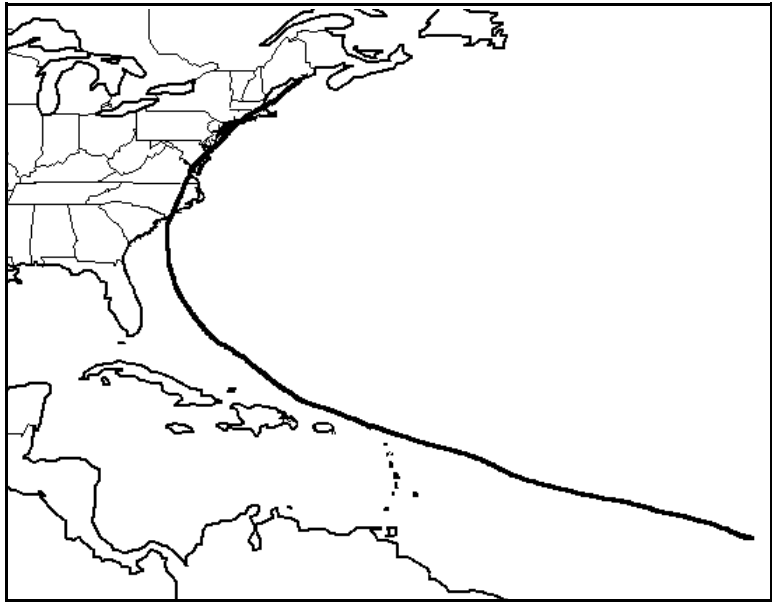


Figure 2. Track of Hurricane Bertha. See Appendix III for a list of official 3-h positions along this track.

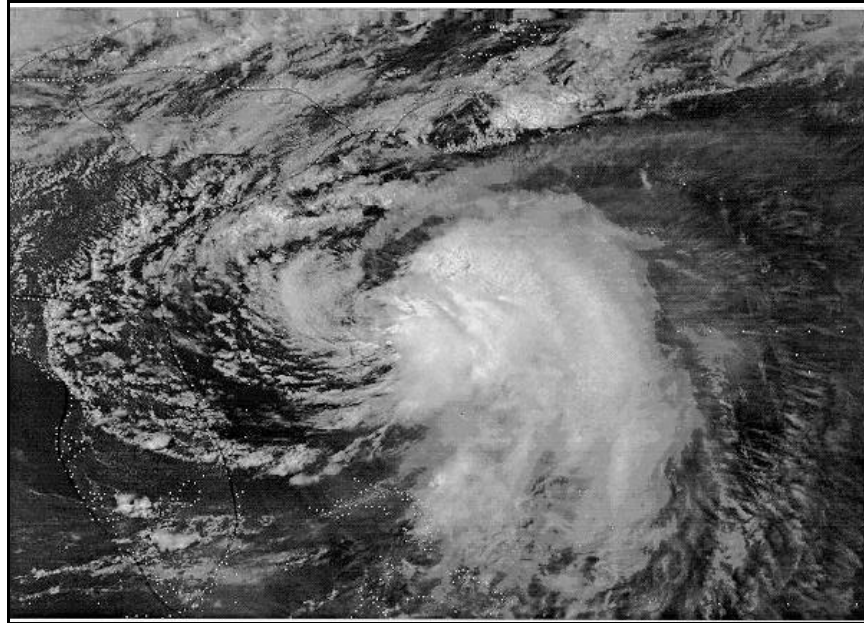


Figure 3. Visible satellite picture from 2115 UTC 11 July 1996.

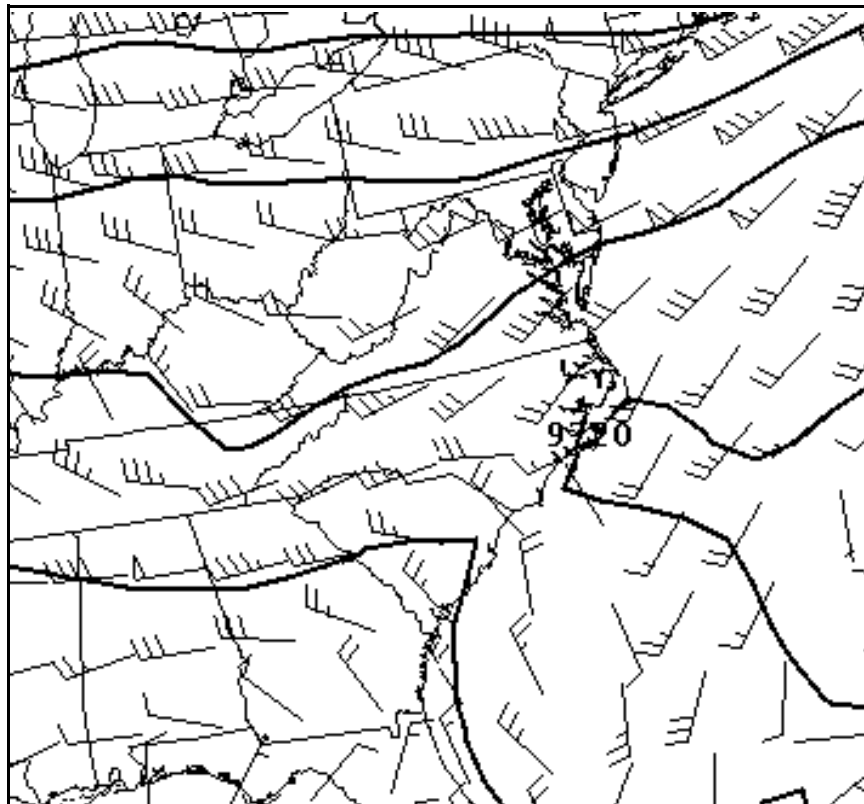


Figure 4. 0000 UTC 12 July 1996, 300-mb heights (dm) and winds (kt). Contours are drawn every 60 dm.

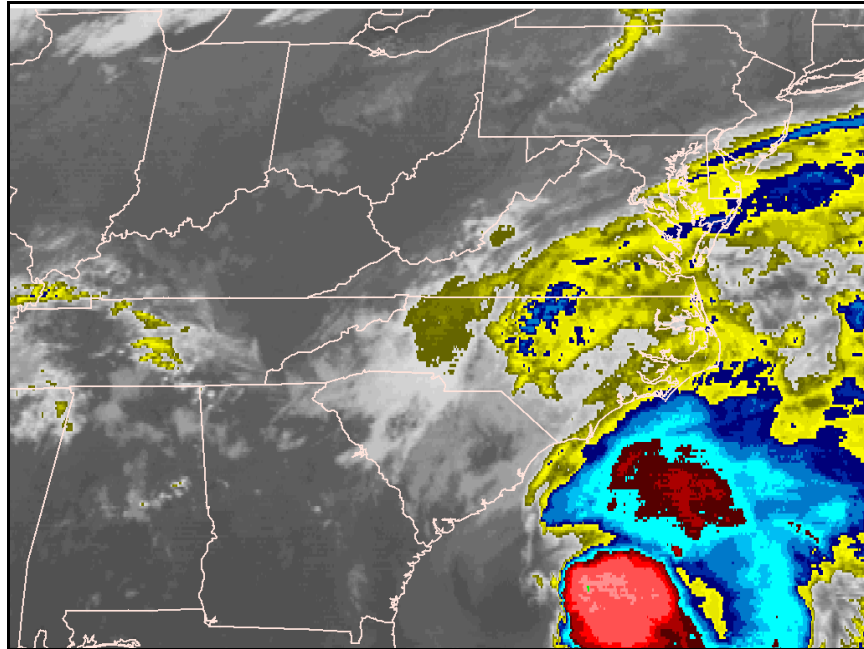


Figure 5. Infrared satellite picture from 0915 UTC 12 July 1996.

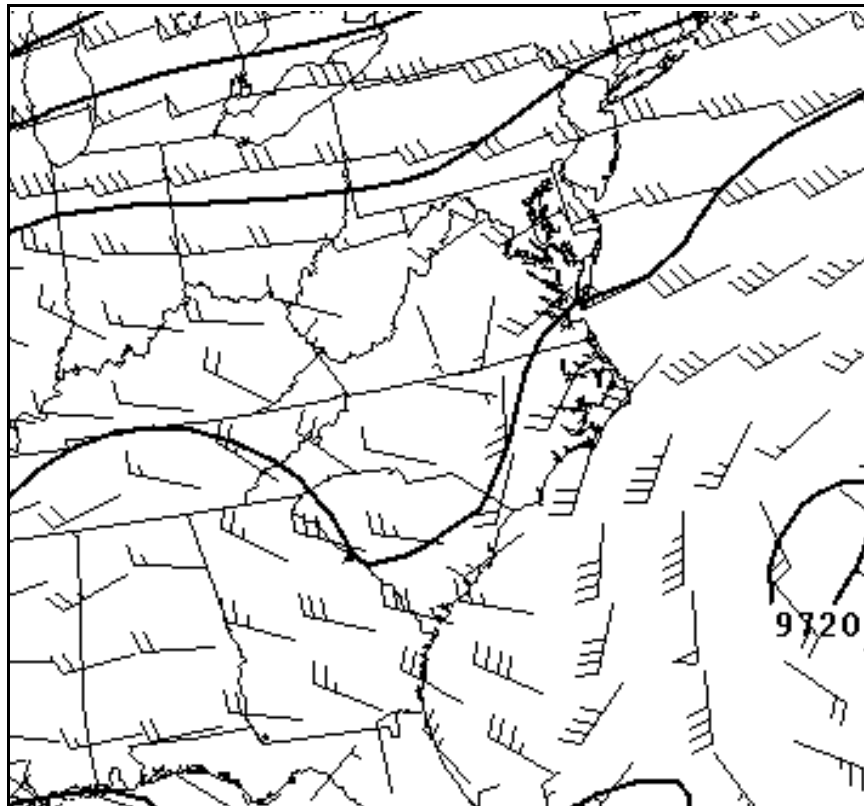


Figure 6. As in Figure 4, except for 1200 UTC 12 July 1996.

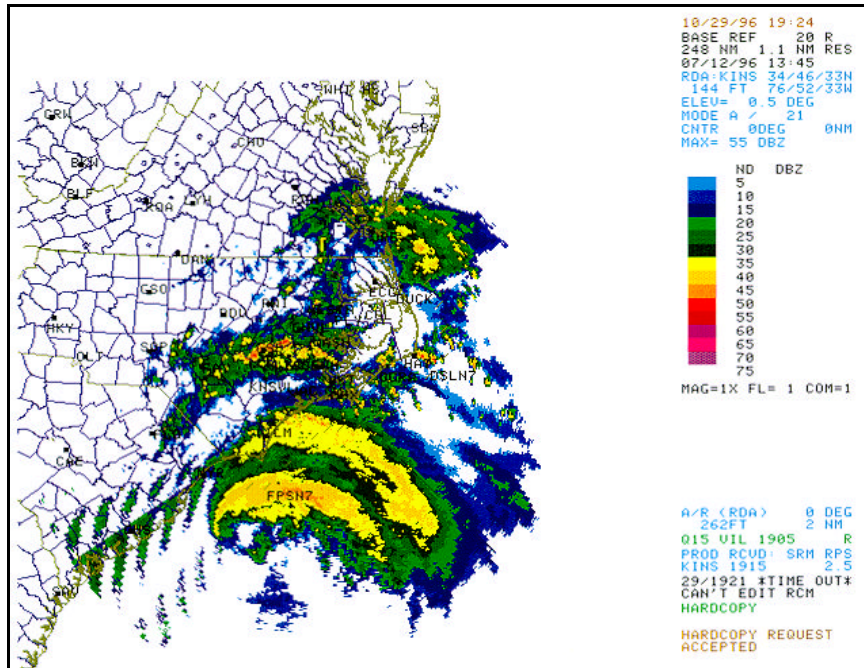


Figure 7. Newport/Morehead City, North Carolina, WSR-88D (KMHX) base reflectivity product at 1345 UTC 12 July 1996. The color table on the right depicts the intervals of reflectivity in units of dBZ. The elevation angle is 0.5° , range of coverage is 248 n mi (460 km), and resolution is $1^\circ \times 1.1$ n mi (2km). The maximum reflectivity is 55 dBZ.

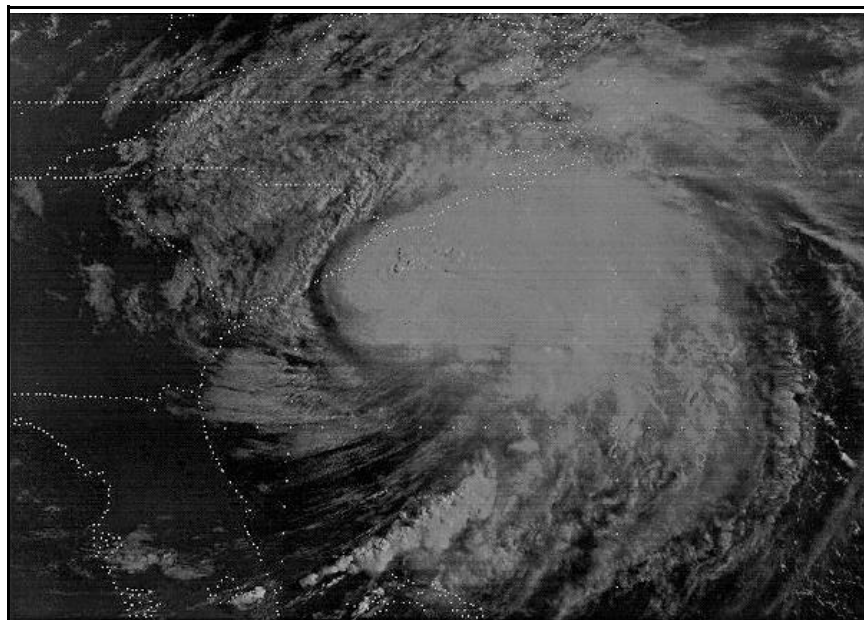


Figure 8. Visible satellite picture from 1400 UTC 12 July 1996.

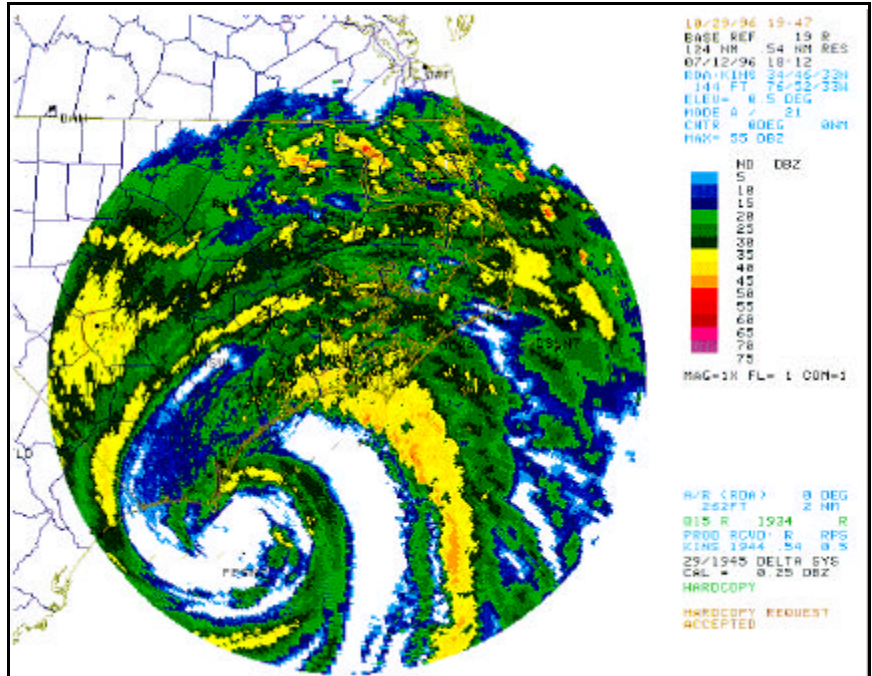


Figure 9. As in Figure 7, except for 1812 UTC 12 July 1996. The range of coverage is 124 n mi (230 km) and the resolution is 1° x .54 n mi (1 km).

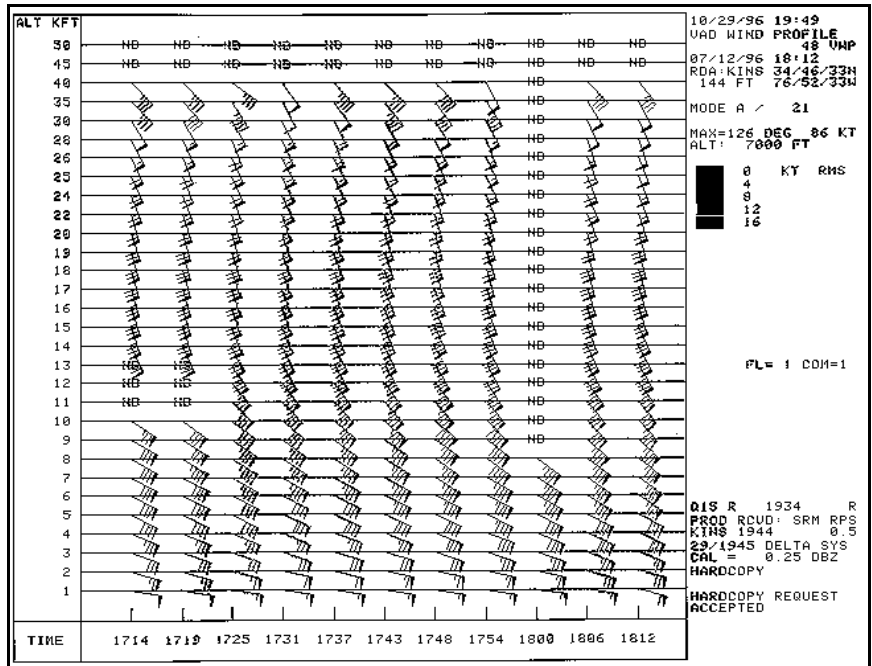


Figure 10. KMHX Velocity Azimuth Display Wind Profile product for 1714 UTC to 1812 UTC 12 July 1996. Vertical axis is altitude in thousands of feet. ND indicates no data. Wind barbs follow standard meteorological convention.

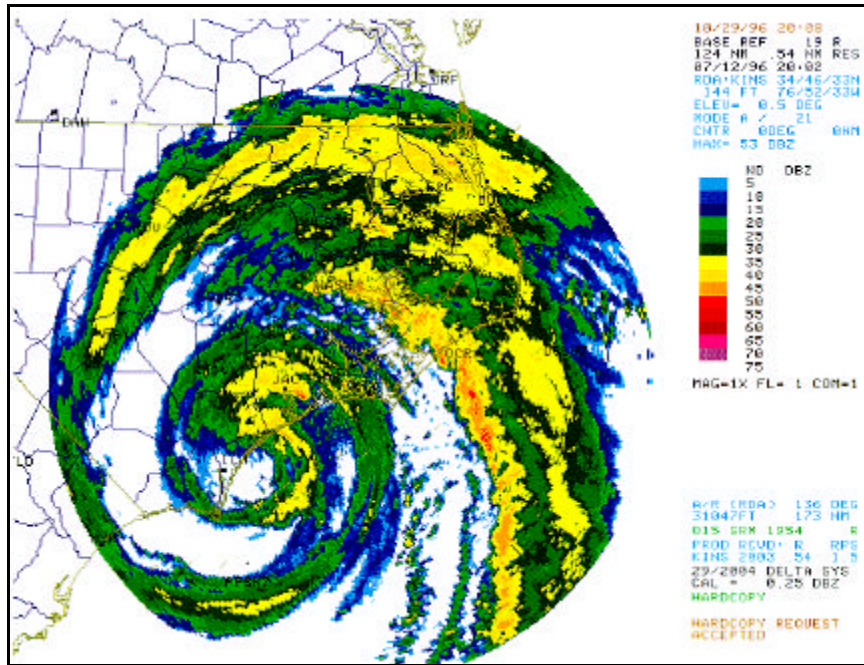


Figure 11. As in Figure 9, except for 2002 UTC. The maximum reflectivity is 53 dBZ.

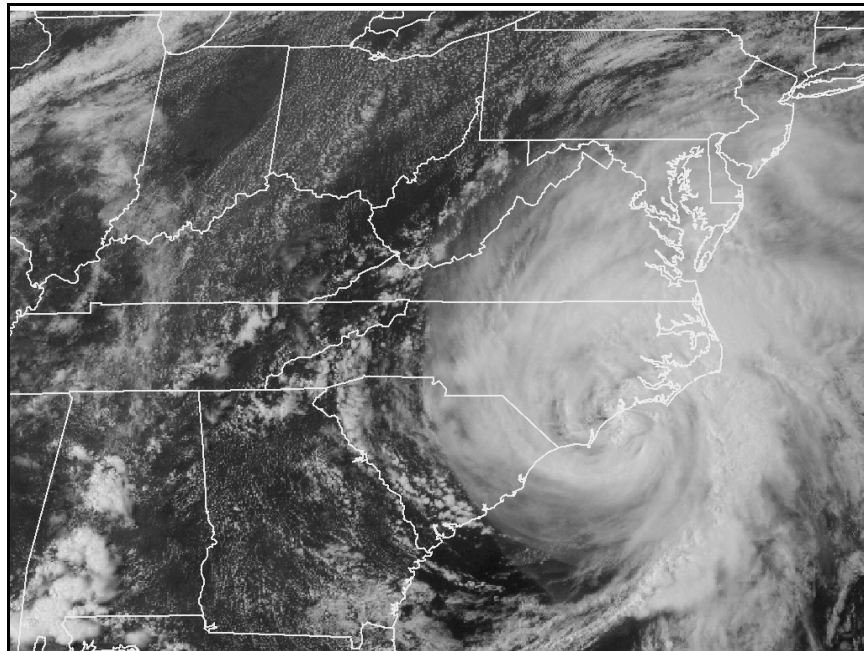


Figure 12. As in Figure 8, except for 2000 UTC.

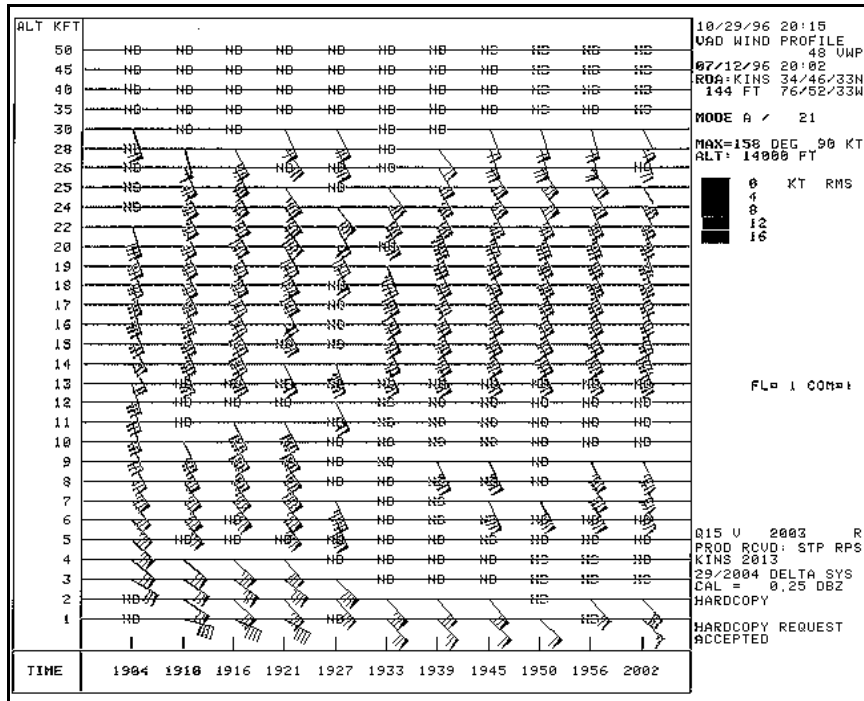


Figure 13. As in Figure 10, except for 1904 to 2002 UTC.

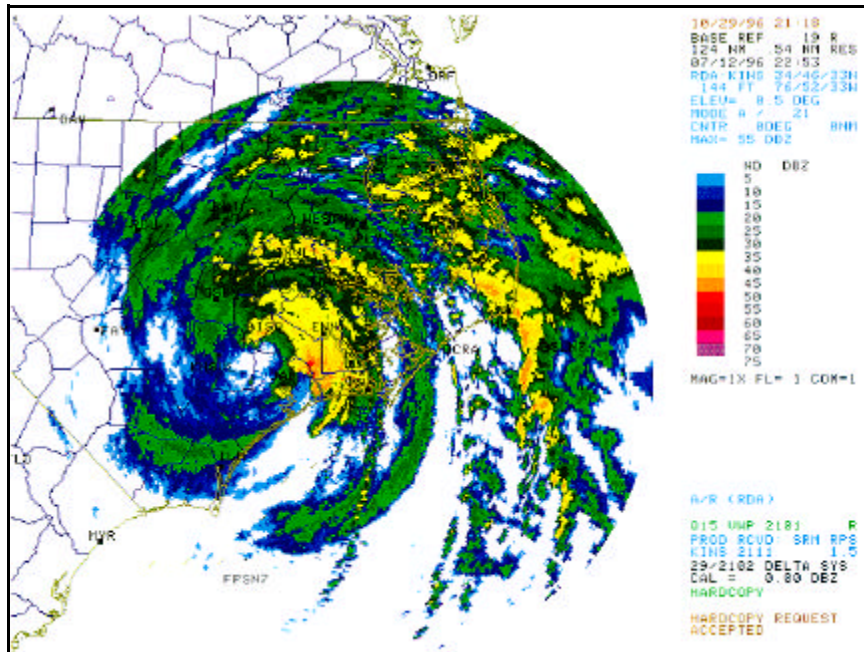


Figure 14. As in Figure 9, except for 2253 UTC.

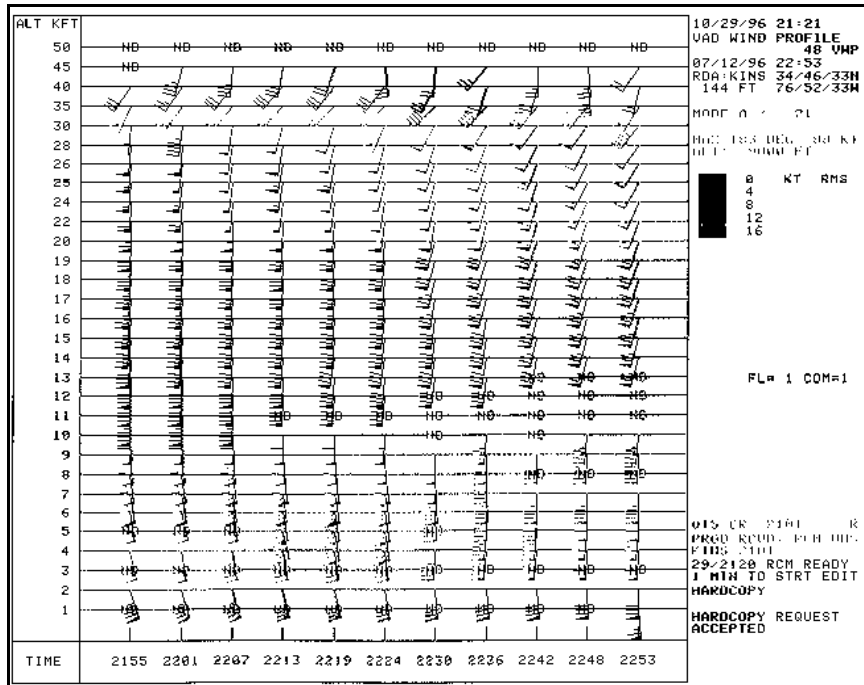


Figure 15. As in Figure 10, except for 2155 to 2253 UTC.

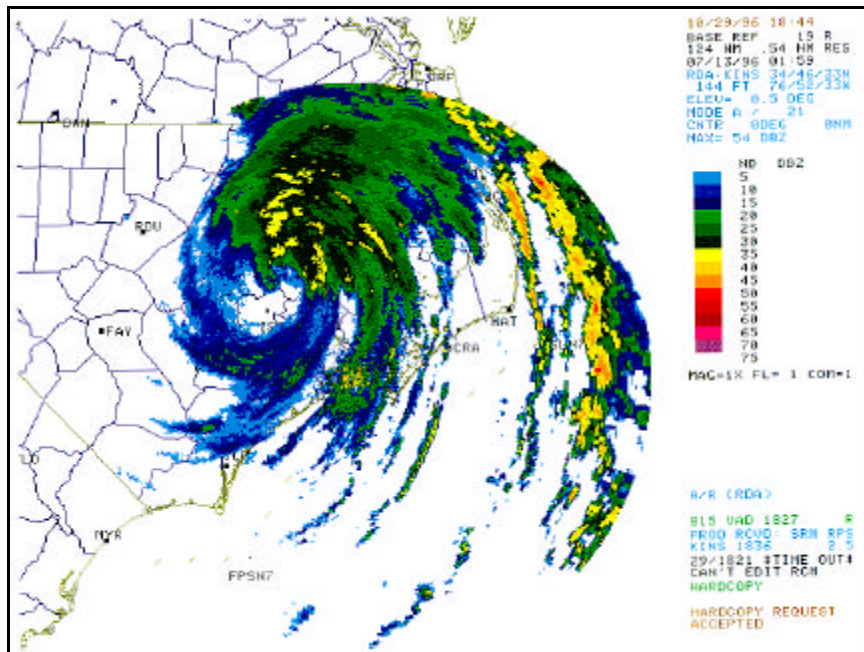


Figure 16. As in Figure 9, except for 0159 UTC 13 July 1996. The maximum reflectivity is 54 dBZ.

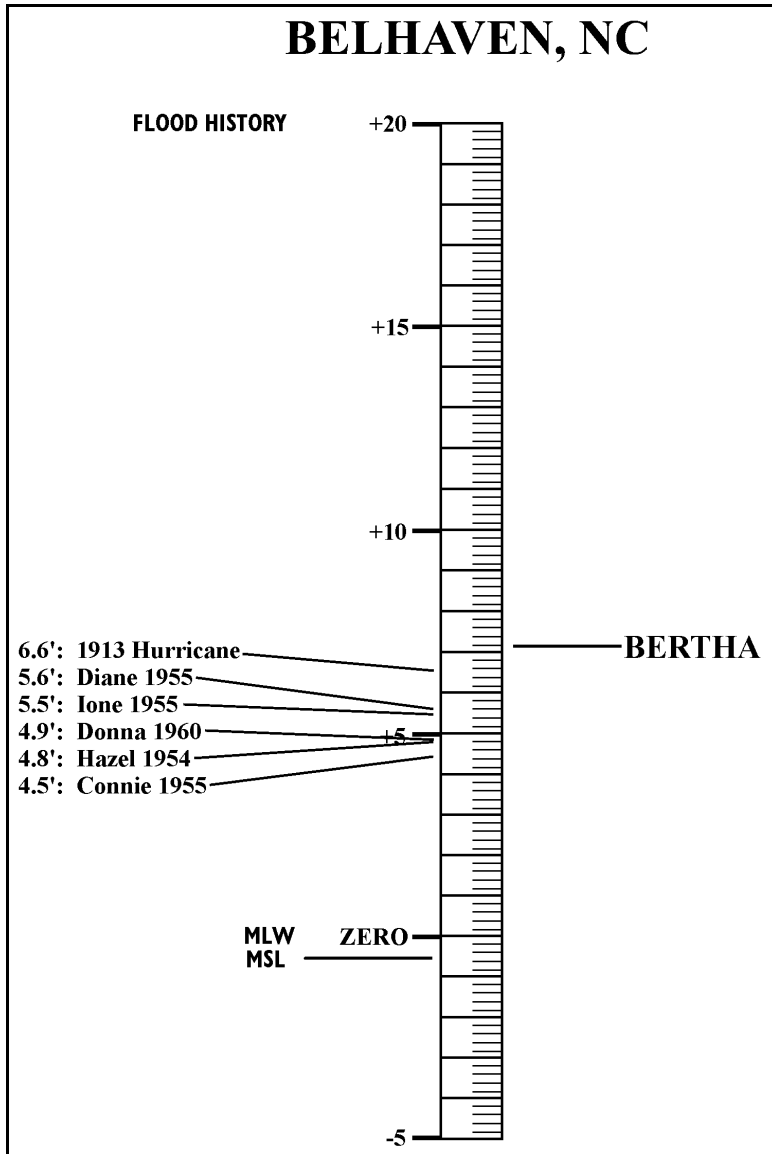


Figure 17. Storm surge flooding from Hurricane Bertha at Belhaven, North Carolina, as compared to historical storms.

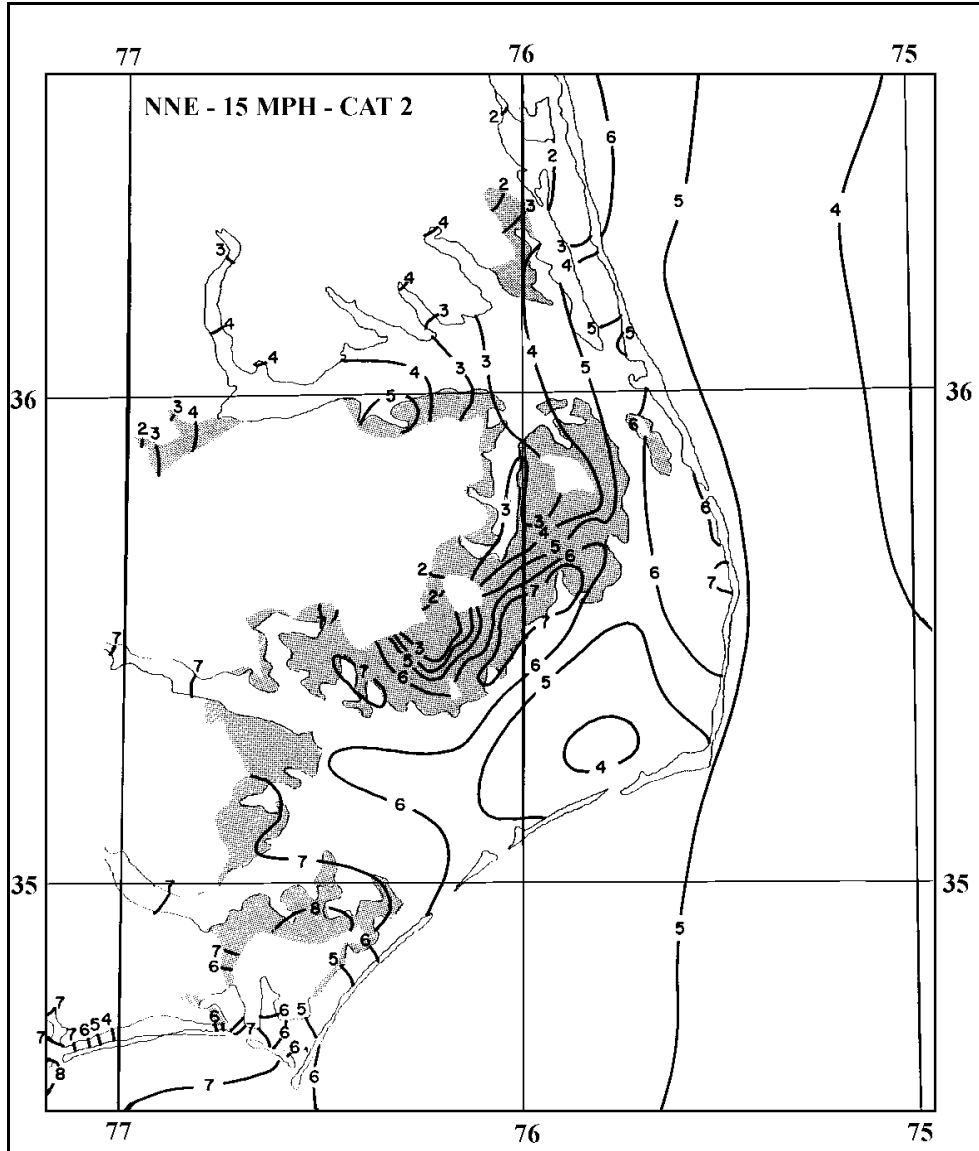


Figure 18. Storm surge forecast from the SLOSH model for a category 2 hurricane moving north-northeast at 15 mph. Contours are drawn every 1 ft. Shaded areas indicate inundated land areas.

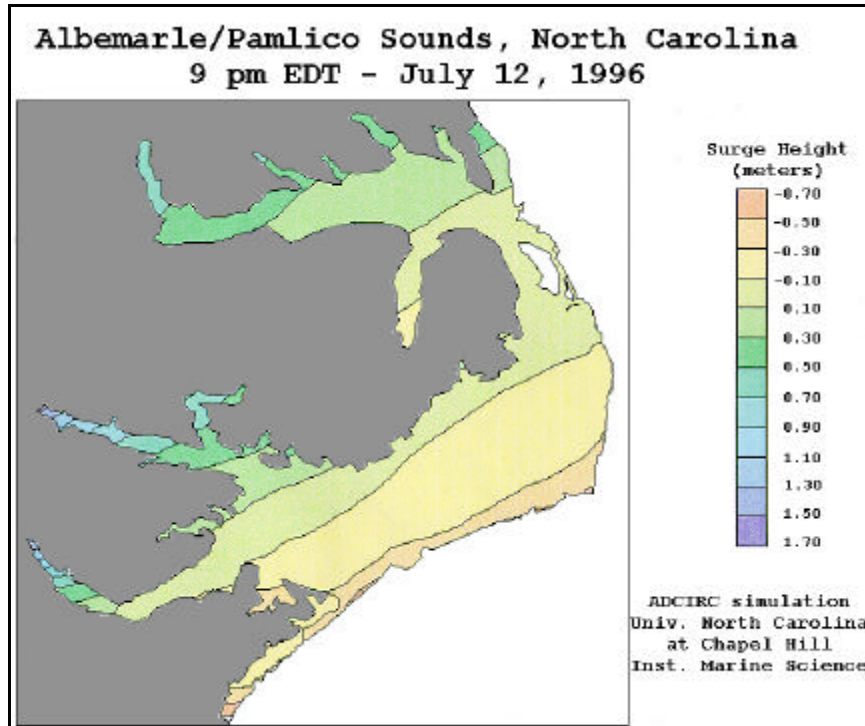


Figure 19. Storm surge forecasts from the ADCIRC model for the Albemarle and Pamlico Sounds valid 0100 UTC 13 July 1996. Surge heights are contoured every 0.2 m.

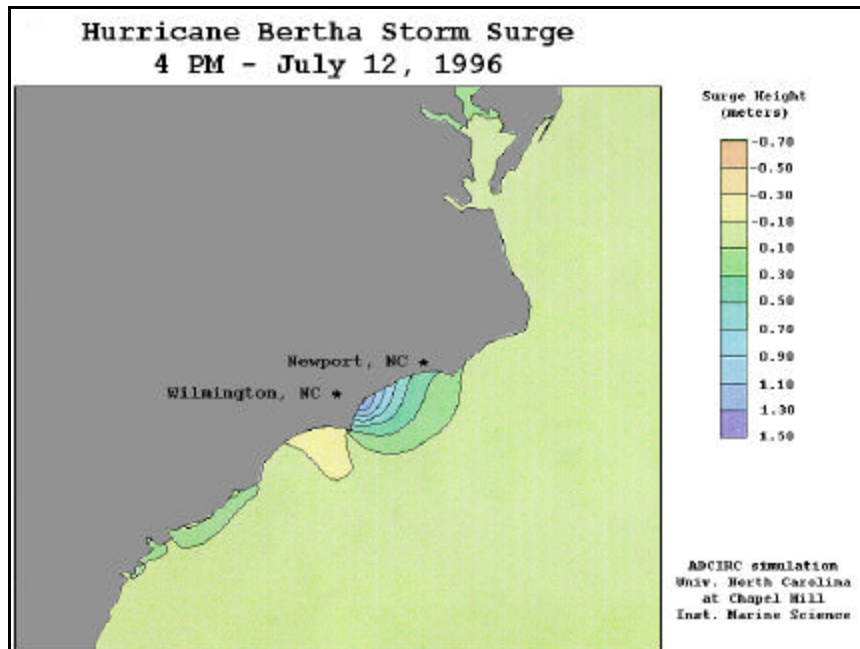


Figure 20. As in Figure 19, except for the Atlantic Basin valid 2000 UTC 12 July 1996.

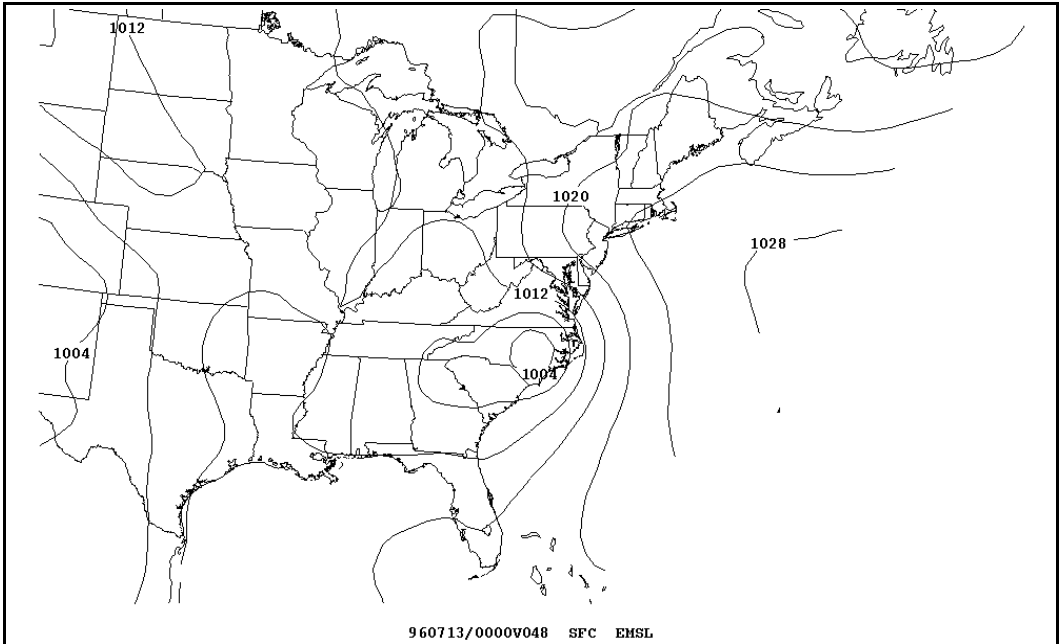


Figure 21. Eta model 48-h surface pressure forecast valid 0000 UTC 13 July 1996. The contour interval is 4 mb.

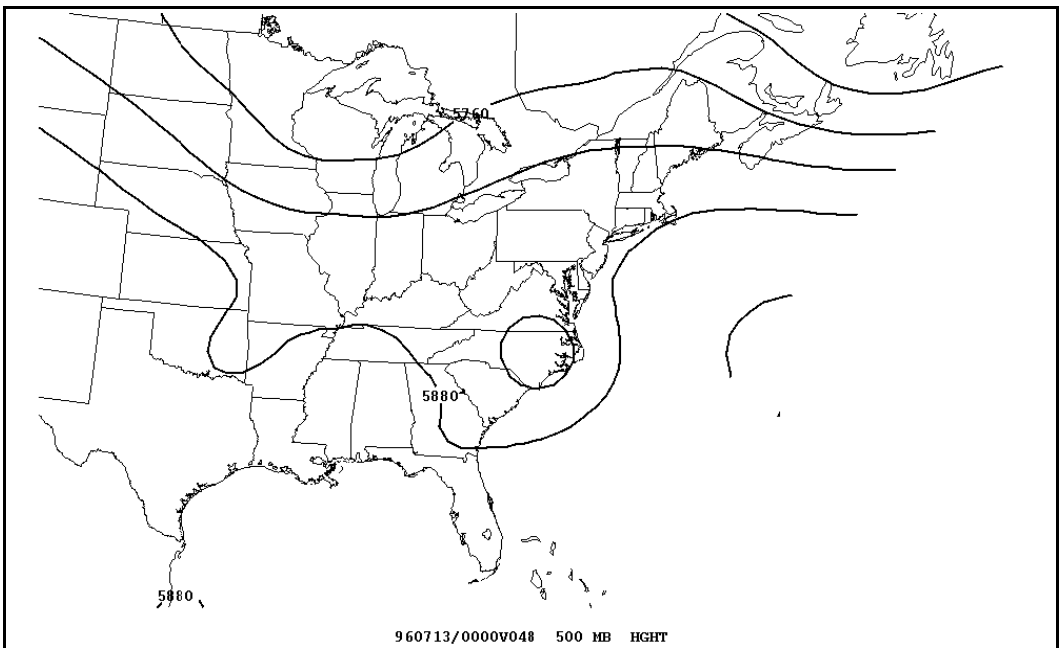


Figure 22. Eta model 48-h forecast of 500-mb heights valid 0000 UTC 13 July 1996. The contour interval is 60 m.

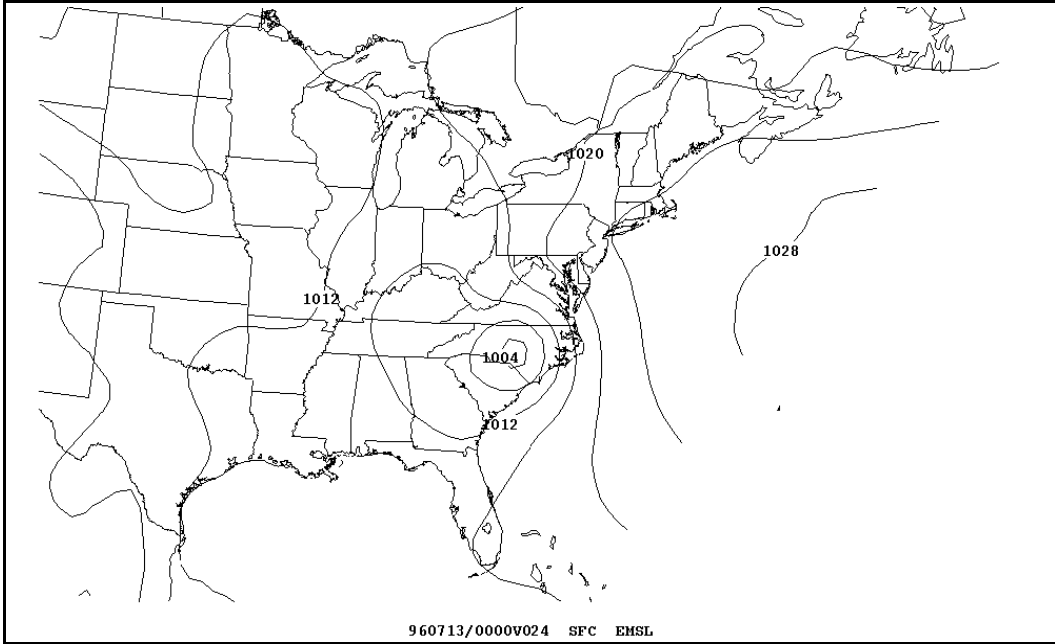


Figure 23. As in Figure 21, except for the 24-h forecast.

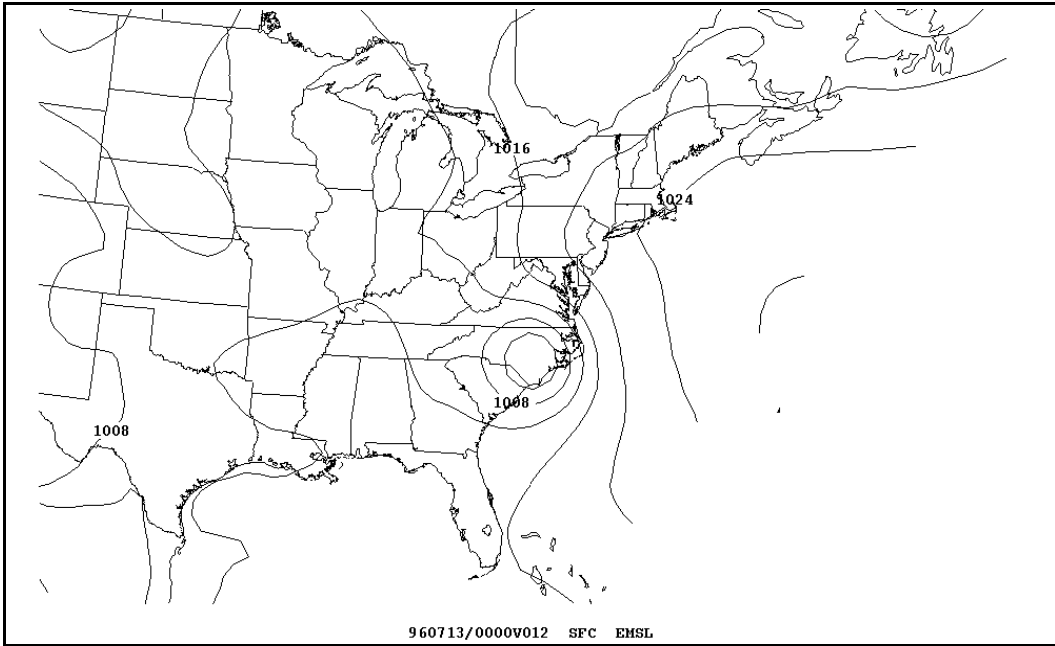


Figure 24. As in Figure 21, except for the 12-h forecast.

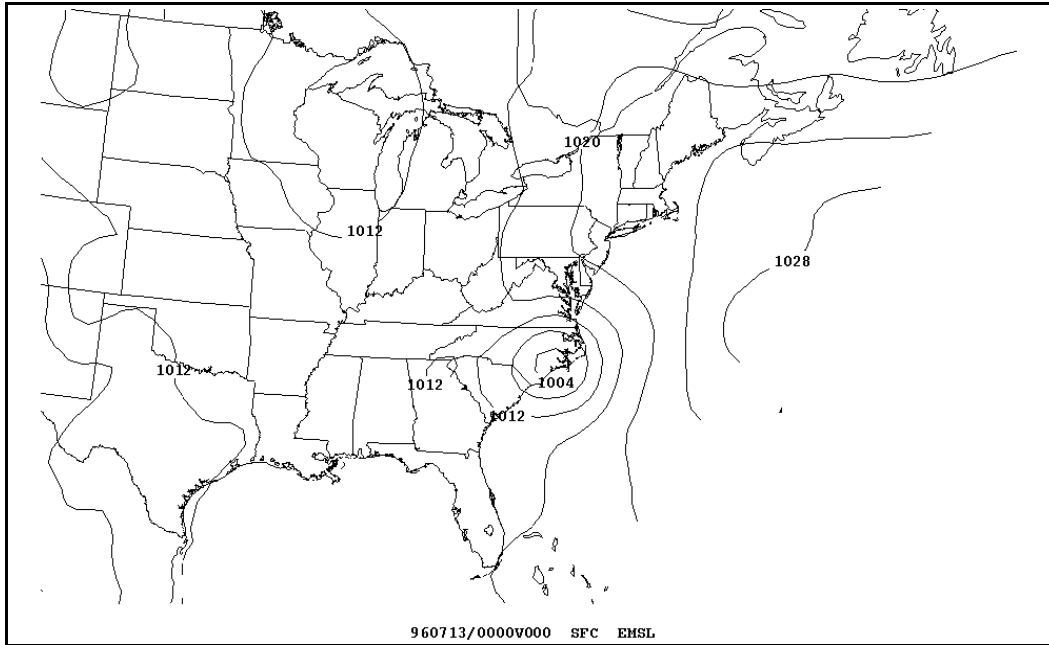


Figure 25. As in Figure 21, except for the 00-h forecast.

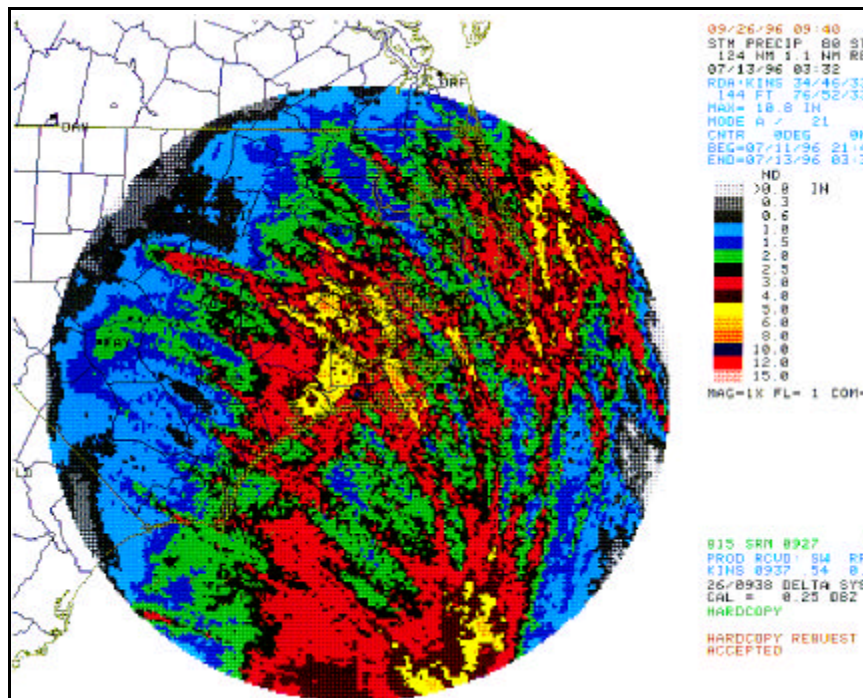


Figure 26. KMHX Storm Total Precipitation product for the time interval from 2143 UTC 11 July 1996 to 0332 UTC 13 July 1996. Range of coverage is 124 n mi (230 km) and resolution is 1.1 n mi x 1.1 n mi (2 km x 2 km). The color table on the right depicts the intervals of estimated precipitation accumulation in inches. The maximum accumulation is 10.8 inches.

APPENDIX I

Comparison Between Bertha and Other Memorable Hurricanes in North Carolina History

Storm Name	Date of Landfall	Location of Landfall	Highest Winds (mph)	Fatalities	Highest Storm Surge (ft)
	8 August 1879		138		
	September 1883			53	
	16 September 1933			21	7
Hazel	15 October 1954	Little River	150	19	
Ione	19 September 1955	Salter Path	125	5	11
Donna	1 September 1960	Topsail Island	100	8	8
Diana	14 September 1984	Brunswick City	92G100		6
Gloria	20 September 1985	Cape Hatteras	74G86		8
Bertha	12 July 1996	N. Topsail Island	108	2	10

APPENDIX II

Damage and Effects From Hurricane Bertha

Highest Sustained Wind	81 mph	New River (NCA), Jacksonville 1621E
Highest Wind Gusts	108 mph	(NCA) 1621E
	100 mph	Swansboro
	100 mph	Broad Creek (Salty Shores) 1800-1830E
	90 mph	Newport
	89 mph	Caspers Marina, Swansboro 1730E
	87 mph	Greenville Utilities
	82 mph	Diamond Shoals 2200E
	82 mph	Bogue Field ASOS 2107E
	77 mph	Duke Marine Lab, Beaufort 1900E
	74 mph	Cherry Point (NKT) 1842E
	72 mph	Hatteras Ferry Office 2100E
	71 mph	Cape Lookout Buoy 1900E
	64 mph	Beaufort 1725E
62 mph	New Bern 1808E	
Lowest Reported Pressure	995.3 mb (29.35")	Newport
Rainfall Amounts	6.50"	Broad Creek
	5.44"	Snow Hill
	5.09"	Cherry Branch (5 mi east of Havelock)
	4.56"+	Havelock (top cap of rain gauge blew off and "a lot of rain was sucked out")
	4.11"	Greenville
	4.10"	Williamston
	2.95"	Newport
	8"+	estimated by radar over northern Craven and eastern Carteret Counties
Storm Tides	8 ft	Swansboro
	8 to 10 ft	Emerald Isle
	7 ft	Belhaven and Washington
	6 ft	Bath
	4.5 ft	Pungo River
		S. Pamlico River 3 ft above normal
Beach Erosion	Sand dunes were breached in Emerald Isle and North Topsail Beach.	

Flooding	Swansboro had 5-6 ft of water inside businesses on water front. Queens Creek Bridge just outside of town out. In Otway, Wards Creek bridge was washed out. Water flowed through Belhaven with knee deep water in the town hall. Washington waterfront under water...water came within 1 ft of going over Route 17 drawbridge. Ocean overwash on northern end of Ocracoke, Hatteras Island north of Buxton, and in Frisco.
Tornadoes	One reported on highway 24 in Newport, another on highway 17, 6 mi southeast of New Bern, and a third in the western portion of the Albemarle Sound.
Damage	Heavy damage to tobacco and corn crops in at least 12 eastern NC counties. The storm demolished fishing piers and stripped roofs from homes. In Onslow county, 33 single family homes, 87 mobile homes, 10 apartment buildings and 13 businesses were destroyed. Damage in Onslow County alone exceeded \$100 million. In New Bern, numerous boats were sunk and damaged at 3 private marinas. Trees and power lines were downed all across area. An estimated 186,000 customers were without power or phone service.
Deaths	Two people died, one in a traffic accident in Kitty Hawk, the other while working on a generator the day after the storm struck (electrocuted).
Evacuation	The North Carolina Division of Emergency Management estimated 250,000 people evacuated ahead of the hurricane.
Transportation	Amtrak briefly curtailed service on a number of trains that travel through North Carolina. No alternate transportation was provided. All operational Coast Guard aircraft normally stationed at Elizabeth City, North Carolina were relocated pending the passage of the storm.

APPENDIX III

Three-Hourly Positions Of Hurricane Bertha And Maximum Sustained Winds

Date/Time (UTC)	Latitude	Longitude	Maximum Wind (kt)
05/0300	10.2N	35.1W	30
05/0900	10.2N	37.6W	30
05/1500	11.1N	40.2W	35
05/2100	12.3N	42.0W	35
06/0300	13.2N	44.9W	35
06/0900	13.4N	47.8W	40
06/1500	13.9N	50.2W	40
06/2100	14.4N	52.3W	45
07/0300	15.1N	53.9W	60
07/0900	16.0N	55.0W	60
07/1200	16.2N	56.7W	60
07/1500	16.5N	58.0W	60
07/2100	17.0N	59.6W	60
08/0000	17.1N	60.5W	60
08/0900	17.7N	62.8W	70
08/1500	18.2N	64.1W	75
08/2100	18.9N	65.4W	80
09/0300	19.7N	66.8W	80
09/0700	20.2N	67.9W	100
09/0900	20.7N	68.4W	100
09/1500	22.0N	70.1W	100
09/2100	23.0N	71.6W	100
10/0300	24.3N	73.4W	90
10/0900	25.0N	74.7W	90
10/1500	25.9N	76.0W	90
10/2100	26.8N	76.1W	90
11/0300	27.9N	76.6W	85
11/0900	28.8N	77.0W	85
11/1500	29.8N	77.6W	85
11/2100	30.6N	78.3W	70
12/0300	31.1N	78.5W	70
12/0900	31.6N	78.7W	70
12/1500	32.8N	78.4W	90
12/2100	34.3N	77.7W	90
13/0300	35.8N	77.4W	65
13/0900	37.4N	75.6W (INLAND)	50
13/1500	39.3N	74.7W	45

13/2100	41.0N	73.1W	40
14/0300	42.8N	70.0W	45
14/0900	44.7N	67.5W	45

APPENDIX IV

Rainfall Reports (inches) From Hurricane Bertha And Distance (n mi) From KMHX RDA

<u>Station</u>	<u>Amount</u>	<u>Distance</u>	<u>Station</u>	<u>Amount</u>	<u>Distance</u>
Broad Creek	6.50	6	Landfall	4.8	58
Cherry Point	5.39	8	Willard	1.80	58
Lands End	4.62	9	Williamston	4.34	66
Morehead City	3.87	9	Gum Neck	2.59	67
Cherry Branch	5.09	10	Plymouth	3.77	67
5NW Havelock	6.25	11	Clinton	3.01	71
New Bern FAA	4.74	19	Columbia	2.59	75
Trent Woods	5.90	20	Tarboro	4.27	75
Hoffman Forest	8.06	21	Wilson	2.64	77
Trenton	4.84	29	Edenton	3.05	79
Cedar Island	1.71	31	Rocky Mount	2.06	84
Hobucken	2.80	32	Lock Dam	1.81	85
Aurora	4.24	37	Scotland Neck	3.32	86
5 SE Kinston	4.79	42	Manteo	2.59	90
Belhaven	4.0	47	Longwood	3.27	95
1 E Washington	5.5	47	Zebvin	2.18	96
Kinston Ag R	4.88	49	Whiteville	2.12	98
New Holland	3.03	53	Elizabeth	3.36	98
Nr ILM AP	4.7	57	Jackson	3.23	101
LaGrange	4.75	56	Lumberton	1.45	105
Snow Hill	5.72	57	4 SW Raleigh	2.94	106
Snow Hill	5.44	57	FBG WT	2.13	108
Greenville	4.86	57	Red Springs	2.13	114
Greenville	4.36	57	RDU	1.94	114
5 SE Warsaw	3.45	58	Samford	1.36	117