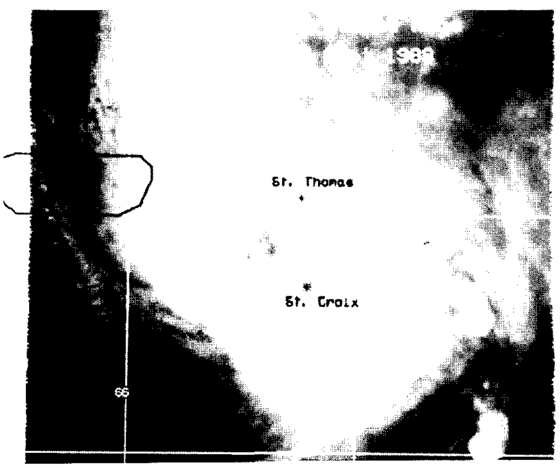
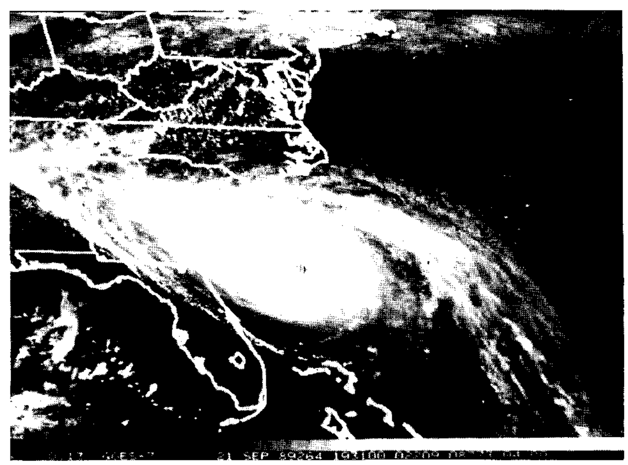
Natural Disaster Survey Report

Hurricane Hugo
September 10-22, 1989





U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service, Silver Spring, Maryland

Left: Enhanced infrared satellite imagery of Hurricane Hugo moving through the U.S. Virgin Islands, 2AM AST September 18.

Right: Visible spectra satellite imagery of Hurricane Hugo approaching South Carolina, 330PM EDT September 21.

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May 1990

U.S. DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary

National Oceanic and Atmospheric Administration
Dr. John A. Knauss, Administrator

National Weather Service
Dr. Elbert W. Friday, Jr., Assistant Administrator

"Mr. President, I have mentioned a number of organizations that have responded with great skill and dedication to this crisis. Certainly, the U.S. National Weather Service must be near the top of anyone's list. They have performed magnificently before, during and after Hugo. It was the Weather Service's accurate and timely forecasts that saved so many lives and allowed us to avoid even worse destruction. My hat is off to this superb outfit. It consistently does the Government proud."

Excerpt from a speech by Senator Ernest F. Hollings of South Carolina on the Senate floor -- October 2, 1989.

PREFACE

Hurricane Hugo, one of the most powerful storms of the century, proved to be a double catastrophe for the United States. Its course through the Caribbean and the Carolinas caused untold suffering and the largest economic loss that this country has ever experienced from a hurricane. Our thoughts and prayers reach out to those courageous individuals who suffered Hugo's fury and are now struggling to rebuild their lives. Furthermore, I congratulate all of those in NOAA and the National Weather Service who, in many instances, disregarded personal concerns to ensure that the warnings and the response to the storm were of the highest order. Their dedication and professionalism shall ever inspire us.

Elbert W. Friday Jr.

Dr. Elbert W. Friday, Jr.

May 1990

FOREWORD

This report on Hurricane Hugo was prepared by the disaster survey team after a week of interviews and visits to damaged areas with commonwealth, state, local and Federal officials in the U.S. Virgin Islands, Puerto Rico, Florida, South and North Carolina and the citizens who survived the storm's devastation.

The team is grateful to the many state and local officials and representatives of private relief agencies who took time from urgent duties in helping the injured and the homeless, as well as coping with Hugo's havoc, to share their impressions of events before and during the storm's onslaught. We appreciate the understanding and courtesy of the many citizens who consented to interviews while still trying to comprehend and deal with the appalling national disaster that struck their communities. The team was impressed by their courage, candor and graciousness under conditions of intense stress.

Where the team believed it would serve to clarify the report, we have attributed a specific action or comment to an identified person. We recognize that many individual acts of professional skill and judgment and, indeed, heroism are not recorded in this report. While this document is not intended to chronicle the entire history of the storm and its aftermath, it attempts to assess accurately the National Weather Service performance to determine whether improvements are possible in forecasting and preparing for severe storms.

In carrying out our assignment, we acknowledge -- with gratitude and admiration -- the many individuals who can be justly proud of what they accomplished in concert with others. We salute all whose participation made the response to Hurricane Hugo such a success.

The Disaster Survey Team

Alexander Hamilton Airport, St. Croix, U.S. Virgin Islands. Hugo's eye made landfall to the west of this area along the southwest coast. Over portions of the island, wind gusts were estimated near 160 mph. Photo courtesy of Jose Meitin.

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ACRONYMS

ABT	Auxiliary Backup Terminal
ADM	Alphanumeric Display Module
AFOS	Automation of Field Operations and Services
ALERT	Automated Local Evaluation in Real Time
AP	Associated Press
ART	Automatic Radiotheodolite
ASL	Above Mean Sea Level
ASOS	Automatic Surface Observing System
AWIPS	Advanced Weather Information Processing System
CD	Civil Defense
CLIPER	Climatological/Persistence Model
DLM	Deep Layer Mean
DoD	Department of Defense
EBS	Emergency Broadcast System
EOC	Emergency Operations Center
EPA	Environmental Protection Agency
EPD	Emergency Preparedness Division
ETV	Educational Television
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
GDM	Graphics Display Module
GOES	Geostationary Operational Environmental Satellite
HLS	Hurricane Local Statement
IFLOWS	Integrated Flood Observing and Warning System
MB	Millibar
MEOW	Maximum Envelopes of Water
MIC	Meteorologist in Charge
MLW	Mean Low Water
MMT	McEntire Air National Guard Base
NAWAS	National Warning System
NESDIS	National Environmental Satellite, Data and Information Service
NEXRAD	Next Generation Weather Radar
NGVD	National Geodetic Vertical Datum
NHC	National Hurricane Center
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NSSFC	National Severe Storms Forecast Center
NWR	NOAA Weather Radio
NWS	National Weather Service
NWWS	NOAA Weather Wire Service
OIC	Official in Charge
PNS	Public Information Statement
PPI	Plan Position Indicator
QLM	Quasi-Lagrangian Model
QPF	Quantitative Precipitation Forecast
RFC	River Forecast Center
SAB	Synoptic Analysis Branch
SLOSH	Sea, Lake and Overland Surges from Hurricanes
SPE	Satellite Precipitation Estimate

SSC	Shaw Air Force Base
SWIS	Satellite Weather Information System
UPI	United Press International
VAS	VISSR Atmospheric Sounder
VDUC	VAS Data Utilization Center
VISSR	Visual and Infrared Spin Scan Radiometer
VITEMA	Virgin Islands Territorial Emergency Management Agency
WPM	Warning Preparedness Meteorologist
WSFO	Weather Service Forecast Office
WSO	Weather Service Office
WSR	Weather Surveillance Radar

THE DISASTER SURVEY TEAM

After a severe weather event, such as a hurricane, a disaster survey team is assigned by the National Oceanic and Atmospheric Administration (NOAA) to evaluate the role played by the National Weather Service (NWS), provide an objective appraisal and make findings and recommendations. The Hurricane Hugo team was divided between the Caribbean and the Carolinas.

Team Members

Leader, James W. Brennan, Assistant Administrator for Fisheries, NOAA; currently Deputy General Counsel, NOAA

Coordinator, Linda Kremkau, Program Assistant, Warning and Forecast Branch, NWS

Puerto Rico/U.S. Virgin Islands:

R. Augustus Edwards III, Special Assistant to the Deputy Administrator, NOAA
Edward M. Gross, Chief, Constituent Affairs Office, NWS
Jose G. Meitin, Jr., Meteorologist, Environmental Research Laboratories, NOAA
Donald R. Wernly, Chief, Warning and Forecast Branch, NWS

The Carolinas:

Mr. Brennan
Gary Ellrod, Meteorologist, Satellite Applications Laboratory, NESDIS
Dr. Lee W. Larson, Central Regional Hydrologist, NWS
Robert E. Muller, Senior Meteorologist, Transition Program Office, NWS
Roy S. Popkin, Consultant
Mitchell A. Rosenfeld, Consultant
Dr. Wilson A. Shaffer, Chief, Marine Techniques Branch, NWS

Romain Retreat, Southeast Corner of Bulls Bay, South Carolina. This area received the strongest part of the storm and suffered estimated maximum winds of 135 mph and a storm surge of 20 feet. There were 43 homes in this development.
Photo courtesy of NHC.

EXECUTIVE SUMMARY

The Storm

NOAA pronounced 1989's Hurricane Hugo as the strongest storm to strike the United States in 20 years. The NWS, through its National Hurricane Center (NHC), reported that Hugo smashed into the Charleston, South Carolina, area minutes before midnight, September 22, with winds estimated at 135 MPH in Bulls Bay north of the city. Four days earlier, the storm crossed the U.S. Virgin Islands and Puerto Rico with equal force. See Appendix A for a summary of Hugo's recorded and estimated surface wind speeds.

During the hurricane's approach to the Leeward Islands, a NOAA research aircraft east of Guadeloupe measured winds of 160 MPH and a central pressure of 27.1 inches or 918 millibars (mb). This qualified Hugo as a Category 5 storm -- the highest -- on the Saffir-Simpson Scale (see Appendix B). The storm was rated as Category 4 when it pounded the Virgin Islands, Puerto Rico and South Carolina. Although rainfall was moderate in the Caribbean and on the U.S. mainland, Hugo produced record storm tides of up to 20 feet in South Carolina.

The hurricane was the Nation's costliest in terms of monetary losses but not in lives lost. Forty-nine directly-related storm fatalities were recorded, 26 in the U.S and its Caribbean islands. Twenty-three died in other Leeward Islands. NHC estimated more than $9 billion in damages and economic losses on the mainland, Puerto Rico and the Virgin Islands. The mainland alone accounted for $7 billion of the total.

Services and Benefits

Hugo's dangerous winds and storm surges had the potential of exacting a heavy death toll in the Carolinas and the Caribbean. Some 216,000 people evacuated from the coasts before the storm struck. The key to these evacuations, which undoubtedly saved hundreds of lives, was communications -- long before Hugo, in the days immediately before the storm and during the event.

Cooperation and coordination among NWS, state, county and local officials developed over the years provided the basis for the response to the hurricane. Working together, NWS and local officials conducted broad-based weather awareness programs highlighting hurricane preparedness. NOAA-produced print and electronic materials were used extensively.

Local relationships should continue to be encouraged. Programs on emergency preparedness and other educational activities should be expanded. Under conditions of budget constraints, NOAA and NWS should continue to emphasize public information programs as a very effective way to save lives. Their contributions in saving lives and protecting property are worthy of dollar and moral support.

Survey team members found that local officials from state to local governments relied primarily on local NWS personnel in making important decisions. Two striking examples are: the South Carolina Governor's decision to call for an early, voluntary evacuation of barrier islands and the Puerto Rico Governor's decision to take part in a radio broadcast to emphasize the need for early evacuations and other precautions as the storm approached. The NWS should encourage all local offices to build rapport with local emergency managers based on long-term, mutual respect.

Timely, reliable information from the NWS and NHC contributed greatly to the emergency management and public response. In the crucial hours before the storm's arrival, local officials said access to local NWS meteorologists was critical. Despite overloaded telephone circuits, power outages and difficult working conditions, Weather Service Forecast Offices (WSFOs) and Weather Service Offices (WSOs) were able, for the most part, to meet local needs. The media also responded well in using NWS and NHC storm information.

Hugo tested NWS's aging equipment to the utmost. NWS radar is late 1950s technology. It cannot measure wind velocity or integrate information horizontally and vertically in storms. Such information was inferred or missing in warning processes. NWS should continue to develop and implement Next Generation Weather Radar (NEXRAD) Doppler Radar as planned.

Low density of surface observations in the Caribbean and the Carolinas proved troubling during Hugo and after the storm in trying to reconstruct the hurricane's movement and intensity. As part of modernization and restructuring, Automatic Surface Observing Systems (ASOS) should be implemented as soon as possible.

The hurricane revealed a deficiency in buildings housing WSFOs and WSOs. Strong winds and rain caused damage and exposed important equipment to the elements. Emergency generators, supplied to provide short-run power during outages, were operated in some cases until they failed with other NWS offices forced to provide backup support. Spare parts, in other instances, were unavailable.

In the midst of these problems, NWS personnel whose families and properties were threatened by the storm worked under adverse conditions. Toilets failed. Only minimum refrigeration, cooking and resting facilities were provided. No sleeping or shower facilities were available. Yet, personnel worked 12-hour shifts and longer.

All new construction in hurricane-vulnerable locations should include hardened hurricane-proof areas for safety. Provision for amenities, such as cots, limited shower and kitchen facilities, refrigerators, emergency food supplies and backup toilets, should also be considered.

Communications' deficiencies must be corrected. The National Warning System (NAWAS) is vital to coordination with external agencies, emergency managers and other NWS offices. In Puerto Rico and the Virgin Islands, there is no NAWAS. Coordination was accomplished by telephone. In the Carolinas, lack of sufficient NAWAS drops made communication between neighboring states difficult. The NWS and the Federal Emergency Management Agency (FEMA) should investigate the possibility of a system that allows communications within and without states among NWS and emergency management agencies.

In Puerto Rico and the Virgin Islands, limited NOAA Weather Wire Service (NWWS) drops resulted in few emergency managers having hard copies of NWS products. The upgraded weather wire should be implemented in Puerto Rico and the Virgin Islands as soon as practical. The NWS should explore with FEMA the funding of critical outlets.

Hugo's experience showed that aircraft reconnaissance will remain a necessary tool in forecasting hurricanes until other sensing platforms can provide data fields of equal accuracy.

A potentially disastrous error in base elevation was discovered when a high school shelter at a South Carolina coastal community was inundated by a storm surge. One evacuation document showed the shelter elevation to be 11 feet higher than it was. Base information on shelters and evacuation routes should be verified before becoming final. NWS coastal offices should encourage local emergency management officials to verify shelters' structural soundness periodically, preferably before the hurricane season.

Another problem revealed was the difficulty in communicating the threat of hurricane winds to emergency managers and the public in inland areas. The NWS should develop policy and provide guidance to NHC and field offices on how to deal with this situation.

Despite deficiencies noted in existing facilities and equipment, the survey team concluded that Senator Hollings' speech on the Senate floor accurately portrayed the NWS role. Employees of NWS did perform "magnificently before, during and after Hugo." Those in the path of the storm merit special praise. They performed coolly and professionally in the face of personal danger.

Cooperation among state, local and Weather Service personnel, coupled with a mutual commitment to continuing public education, was the key to minimizing loss of life. The coordination between local Weather Service employees and emergency preparedness people at all levels in the affected communities and the cooperation of the citizenry could well serve as a model of disaster awareness, preparedness and execution for all areas of the country. The survey team found extraordinary levels of mutual respect, trust and ultimately reliance between local and state professionals, on the one hand, and the professionals at the WSOs and the WSFOs on the other.

The report makes a series of recommendations grounded on the concept that full communication is the key to maintaining that mutual respect and confidence. With that in mind, it includes recommendations to recognize and further strengthen the existing cooperation. Even in times of constrained resources (and perhaps because of constrained resources) the survey team recommends that NWS continue to dedicate sufficient time and monies to public education and preparedness. Based upon what the team heard in the Carolinas and Puerto Rico, public education and preparedness will provide significant payoffs in future weather emergencies.

Charleston, South Carolina. Photo courtesy of NHC.

Chapter I

HURRICANE HUGO: THE EVENT AND ITS IMPACT

Hurricane Hugo was the strongest storm to strike the United States since Camille pounded the Louisiana and Mississippi coasts in 1969. At one point east of Guadeloupe, a NOAA research aircraft measured winds of 160 MPH and a central pressure of 27.1 inches (918 mb) which rated Hugo as a Category 5 -- the highest -- storm on the Saffir-Simpson Scale. When Hugo struck the Virgin Islands, Puerto Rico and the Carolinas, it was classified as a Category 4. Storm tides of approximately 20 feet were experienced along part of the South Carolina coast. These are record storm tide heights for the East Coast. Although the highest surges struck sparsely populated areas north of Charleston, South Carolina, damage was extensive and lives were lost.

The History of the Storm

Hurricane Hugo began as a cluster of thunderstorms which was first detected on satellite imagery as it moved off the coast of Africa. It became a tropical depression on September 10, 1989, about 125 miles south of the Cape Verde Islands. The tropical storm traveled due west over the eastern Atlantic Ocean along 12 degrees north latitude for several days. Late on September 13, the circulation had gained sufficient strength and organization to be classified as a full hurricane by NHC. At this time, the storm was located 1,100 miles east of the Leeward Islands and was continuing due west at 20 MPH.

By Thursday, September 14, Hugo had slowed its westward movement to 16 MPH while its winds increased to 115 MPH. The storm was 650 miles east of the Leeward Islands. (See Fig. 1-1.) The next day, reconnaissance aircraft measured winds of 150 MPH making Hugo a strong Category 4 storm on the Saffir-Simpson Scale. The eye was positioned 400 miles east of Guadeloupe. A hurricane watch was posted for Puerto Rico and the U.S. Virgin Islands. On Saturday, September 16, the hurricane aimed for Guadeloupe and Dominica with wind speeds reaching 140 MPH. That afternoon, hurricane warnings were raised for Puerto Rico and the Virgin Islands. At midnight, Hugo's eye passed over Guadeloupe where a surface pressure of 27.8 inches (941 mb) was reported.

The hurricane approached the Virgin Islands the next evening when its forward speed began to slow (Fig. 1-2). This had the effect of prolonging Hugo's fury. A couple hours after midnight Monday, September 18, the hurricane's eye crossed the southwestern coastline of St. Croix near Frederiksted severely damaging this Dutch-style town. Maintaining 140 MPH maximum winds, the hurricane destroyed or damaged more than 90 percent of the buildings on St. Croix leaving the island without power, telephone service or water. No official wind velocities were recorded on the island. Weather observers had abandoned the exposed airport site.

Based on the Fujita Tornado Intensity Scale (see Appendix C), damage surveys indicated that there was widespread upper (F1) and (F2) straightline wind damage. Thus, wind speeds as high as 161 MPH were estimated. Some localized damage appeared to be (F3) but might have been caused by topographic channel effects or microbursts.

With Hugo's forward speed slowing to 9 MPH over the 12-hour period, St. Croix experienced strong winds both before and after the passage of the eye. From the lie of downed power poles and from the entire island's vegetation, which was literally stripped bare, it was deduced that all of St. Croix experienced the storm's maximum winds.

The eye missed the island of St. Thomas as it continued through the channel between Puerto Rico and the Virgin Islands. Although St. Thomas was buffeted by hurricane-force winds, it fared far better than St. Croix. Even so, St. Thomas experienced extensive damage to structures, utilities and vegetation. Maximum wind readings were unavailable for St. Thomas. Two days after Hugo's passage, St. Thomas sustained additional flooding from rainbands associated with Tropical Storm Iris.

Subsequent to its Virgin Islands course, Hugo shifted slightly northward. After sunrise Monday, September 18, the hurricane increased its forward speed as it crossed over the Puerto Rican islands of Vieques and Culebra and skirted the northeast tip of Puerto Rico near Fajardo. As the eye passed over Vieques, maximum winds were estimated at 132 MPH. At Culebra just north of Vieques, an unofficial gust of 170 MPH was reported by the

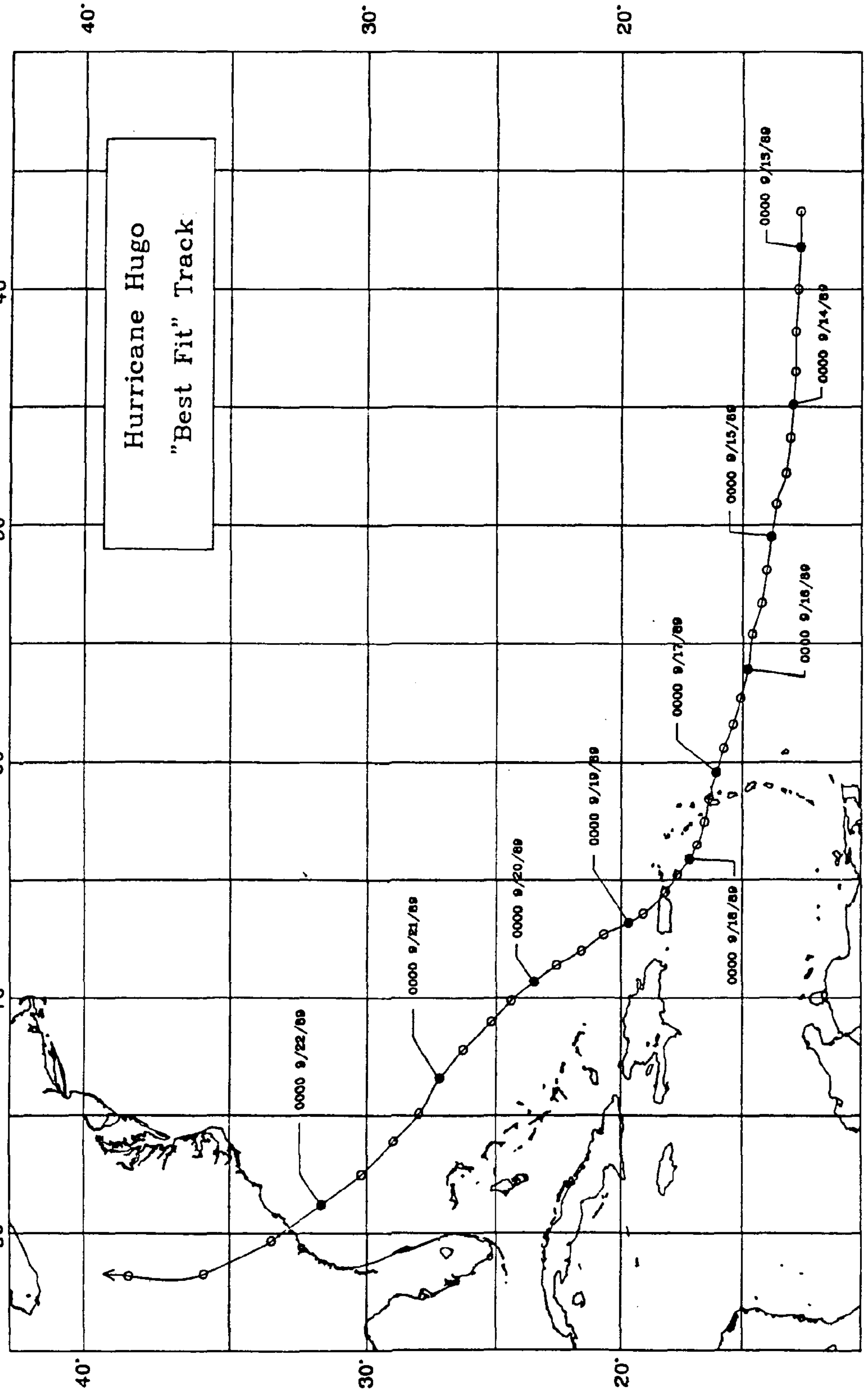
Hurricane Hugo
"Best Fit" Track
0000 9/13/89
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Figure 1-1

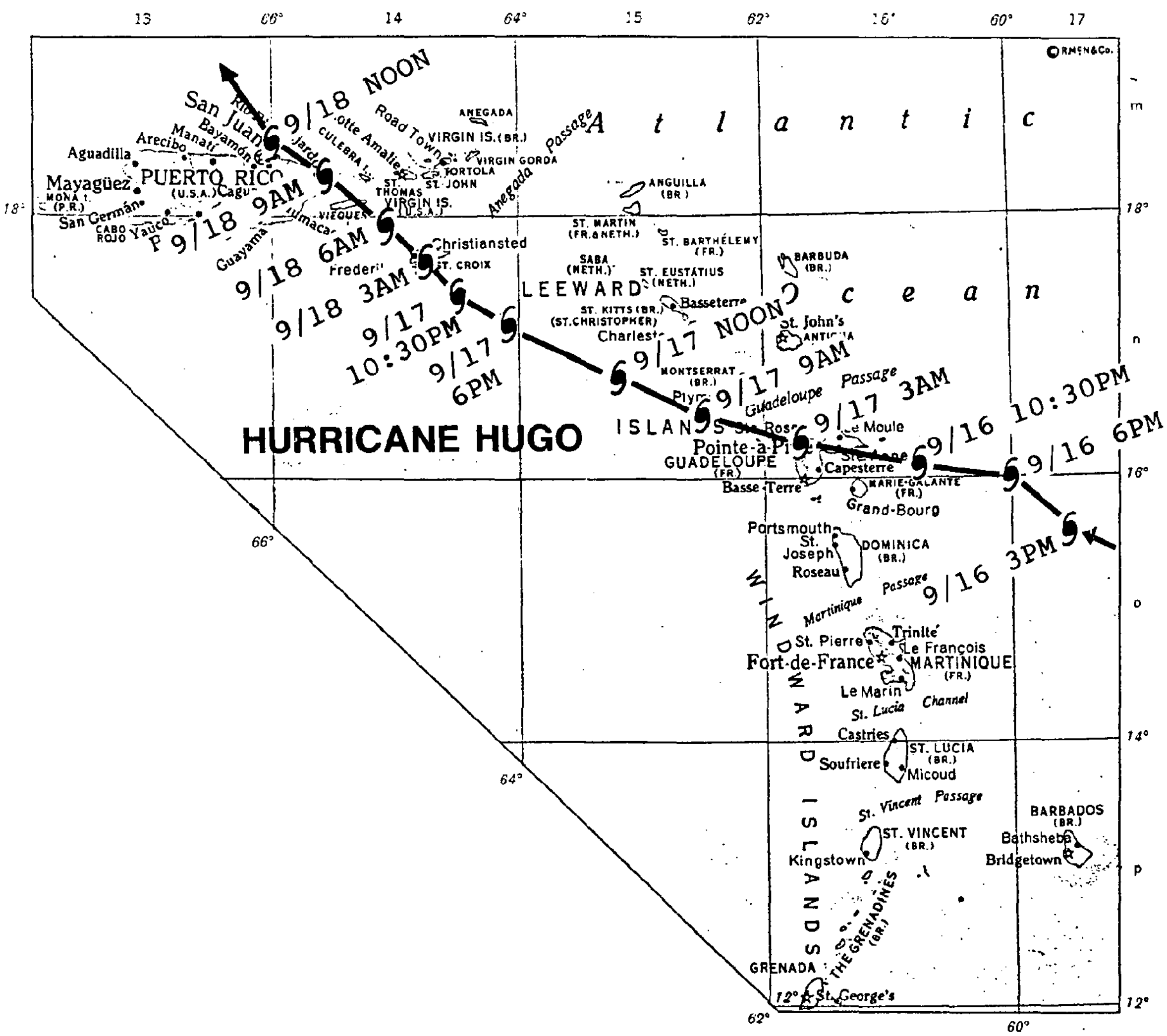

HURRICANE HUGO
9/16 3PM
9/16 6PM
9/16 10:30PM
9/17 3AM
9/17 9AM
9/17 NOON
9/17 6PM
9/17 10:30PM
9/18 3AM
9/18 6AM
9/18 9AM
9/18 NOON
PUERTO RICO
San Juan
Mayagüez
Aguadilla
Arecibo
Christiansted
ST. CROIX
VIRGIN IS.
ANEGADA
ANGUILLA
ST. MARTIN
BARBUDA
LEEWARD
ISLANDS
GUADELOUPE
Pointe-à-Pitre
Basse-Terre
Capesterre
Grand-Bourg
DOMINICA
Roseau
Portsmouth
MARTINIQUE
Fort-de-France
St. Pierre
Trinité
Le François
Le Marin
ST. LUCIA
Castries
Soufriere
Micoud
ST. VINCENT
Kingstown
BARBADOS
Bridgetown
Bathsheba
GRENADA
St. George's
WINDWARD ISLANDS
Atlantic Ocean

Figure 1-2

yacht, Night Cap. Storm surges of 7- to 8-feet were estimated. Culebra Island sustained major damage. Structures, as well as many boats which sought refuge, were destroyed.

On Puerto Rico proper, peak gusts at Roosevelt Roads Naval Air Station, 10 miles south of Fajardo, were recorded at 120 MPH. Sustained winds hit 98 MPH. The hardest hit areas were Fajardo and Luquillo Beach on the northeast coast where damage paralleled that of St. Croix. The larger ships at Roosevelt Roads left well before conditions worsened. Smaller vessels, which remained in port, were piled against the seawall.

By noon Monday, the eye was positioned north of San Juan moving to the northwest at 15 MPH. San Juan International Airport reported wind gusts of 92 MPH around 8 AM[1] that day. Sustained winds of 77 MPH were clocked. San Juan, including the "old city," fared well although power and water were out in many areas for more than a week. The lowest surface pressure reading from Puerto Rico was 27.94 inches (946 mb) at Roosevelt Roads.

Hugo weakened after its encounter with Puerto Rico. By the morning of September 19, the eye of the storm had become poorly defined in satellite images (Fig. 1-3) and the strongest sustained winds had diminished to 100 MPH. As it continued to move out over the open Atlantic, however, the storm slowly began to regain strength. Hurricane warnings were in effect for the southern Bahamas as Hugo resumed a northwestward track at 12 MPH.

On September 20, Hugo had become better organized with a well-defined eye once more. By late in the day, forward speed increased to 18 MPH. The storm was entering a strong southeasterly current of air which was sandwiched between an upper level high centered north of Bermuda and an upper low in the northeastern Gulf of Mexico. Hugo appeared to be taking aim at the southeastern United States. Hurricane watches were issued for the coast from Fernandina Beach, Florida, to Cape Hatteras, North Carolina. Meanwhile, the threat to the Bahamas and south Florida had diminished.

On September 21, Hugo reached the Gulf Stream current. Air Force reconnaissance and NOAA research aircraft reported falling central pressures throughout the day. Maximum sustained winds increased to 138 MPH by evening which qualified Hugo again as a Category 4 storm. Hugo developed an enormous eye (Fig. 1-3) more than 40 miles in diameter. Hurricane warnings were issued at 6 AM from Fernandina Beach to Cape Lookout, North Carolina.

State and local governments ordered evacuation of barrier islands and beach areas from Georgia to southern North Carolina. Hugo continued to move relentlessly toward the northwest with its forward speed increasing to 25 MPH. Landfall of the eye was expected by late night or early morning along the South Carolina coast close to the time of normal high tide. NHC bulletins alerted coastal residents of tides 12 to 17 feet above normal and rainfall of 5 to 10 inches in the path of the storm.

The eye crossed the coast near Charleston minutes before midnight, September 22, at a forward speed of nearly 30 MPH. Winds increased rapidly as the eye wall moved over land. Maximum sustained winds were estimated at 135 MPH in Bulls Bay north of Charleston while wind gusts to 137 MPH were recorded on the 118 foot anemometer at the Charleston Naval Station. Gusts to 125 MPH were observed by Navy ships in Charleston Harbor. An unofficial observer reported a minimum pressure of 27.68 inches (937 mb) in the eye. Hurricane-force winds extended nearly 100 miles to the northeast along the coast and 50 miles to the southwest. Myrtle Beach Air Force Base reported gusts to 76 MPH with unofficial reports of 110 MPH gusts at the oceanfront.

Electrical power was lost in most areas as uprooted trees, broken limbs or debris severed power lines. Roofs were peeled off many buildings and homes. The Ben Sawyer swivel-bridge connecting Sullivans Island to the mainland near Charleston was severely damaged and became stuck in the open position

[1] Atlantic Standard and Eastern Daylight Times coincide.

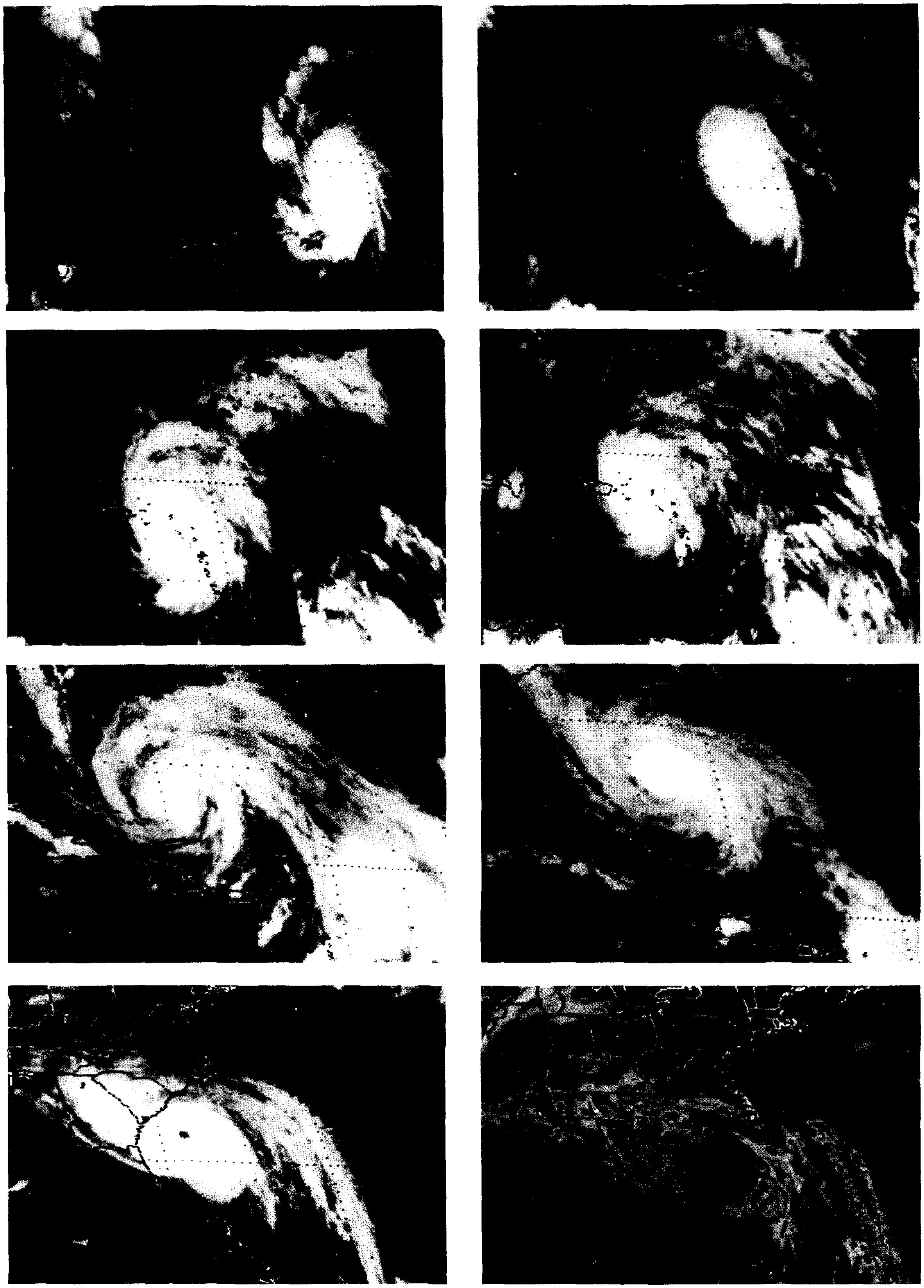


Figure 1-3. Composite history of Hurricane Hugo shown by GOES-7 infrared satellite images. Times are Universal Coordinated Times (UTC). Subtract 4 hours to convert to EDT. Image at landfall (0401, 22 Sept) is enhanced with "MB curve".

A storm tide of up to 20 feet inundated coastal sections from around Charleston northward to Myrtle Beach. In McClellanville, a small fishing village 35 miles northeast of Charleston, residents taking shelter in a school had to clamber on top of tables and chairs to escape the rising waters.

The eye of Hugo passed just to the east of Columbia, 100 miles inland, shortly after 3 AM, September 22. At Shaw Air Force Base near Sumter, 30 miles east of Columbia, winds gusted to 109 MPH. The minimum pressure of 28.73 inches (972.9 mb) set an all-time record for Columbia.

By sunrise the same day, Hugo was downgraded to a tropical storm after it had passed just west of Charlotte, North Carolina. Peak winds at the Charlotte Airport had reached 87 MPH a few hours earlier. High winds resulted in a nearly 50-mile-wide swath of downed trees and power lines in this portion of North Carolina. Pleasure boats on Lake Norman, north of Charlotte, were piled into a heap like toys.

Hugo then swept northward across southwest Virginia reaching Charleston, West Virginia, by midday. The Appalachian Mountains began to weaken the storm rapidly but not before winds in excess of 60 MPH and locally-heavy rains pounded southwest Virginia. By that evening, the remnants of Hugo turned northeastward across western New York and exited the United States less than 25 hours and 600 miles from where it had come onshore.

Hurricane-induced Tornadoes

No tornadoes were observed in the Virgin Islands or Puerto Rico although damage surveys suggested possible microbursts on St. Croix, Culebra and Vieques. Residents, including personnel at the Roosevelt Roads Naval Air Station, believed that some tornadoes did occur although none could be confirmed.

The National Severe Storms Forecast Center (NSSFC) received several unconfirmed reports of tornadoes in the interior of South Carolina and west-central North Carolina. The most likely tornado events occurred near Florence and Sumter about 2 hours after landfall and northwest of Hickory, North Carolina, after sunrise, September 22. Other tornadoes were suspected in Georgetown and Cherokee Counties in South Carolina and Union and Mecklenburg Counties near Charlotte. Aerial surveys in South Carolina could not observe tornado-like damage signatures with any certainty since there was such widespread destruction resulting from straightline winds.

Rainfall with Hugo

The rapid forward movement of Hugo greatly reduced the maximum rainfall potential and thus the threat of severe flooding other than from the storm surge. Rainfall of 5 to 9 inches was reported in Puerto Rico and the Virgin Islands with a maximum of 13.55 inches recorded at the Lower Rio Blanco rain gauge in the mountains of northeastern Puerto Rico. Some flash flooding occurred at Luquillo in northeast Puerto Rico.

Rainfall of 4 to 6 inches was common along coastal sections of South Carolina diminishing to 2 to 4 inches inland. On the coast at Edisto Beach, a maximum of 10.28 inches was observed. Some small stream flooding occurred as far north as southwest Virginia and western North Carolina where orographic effects caused by the Appalachians produced local rainfall totals of more than 6 inches.

Casualty and Damage Statistics

Hugo was the Nation's costliest hurricane in terms of monetary damage but not in lives lost. NHC estimated more than $9 billion in damages and economic losses to the mainland, Puerto Rico and the Virgin Islands. The mainland accounted for $7 billion of the total.

Although the death toll was kept low by excellent weather information, planning and evacuations, Hugo's ferocity resulted in 49 directly-related fatalities; 26 in the U.S. and its Caribbean islands and 23 in other Leeward Islands. (Directly-related deaths are those actually resulting from weather conditions as opposed to fatalities, such as electrocutions and automobile accidents which are considered indirectly related to the storm's effects.)

Hard-hit South Carolina suffered the greatest toll with 13 lives lost. Other fatalities included: Puerto Rico, 2; Virgin Islands, 3; Virginia, 6; North Carolina, 1; and New York, 1. In comparison, a total of 256 hurricane-related deaths were recorded in 1969 when Camille struck the mainland.

The American Red Cross Disaster Services reported 79 hurricane-related deaths in the Carolinas, Puerto Rico and the Virgin Islands. Fifty deaths were recorded in the Carolinas, most in South Carolina. No separate records were kept on the individual Carolinas or states where the Red Cross did not establish disaster operations. Of the 29 deaths in the U.S. Caribbean islands, 22 were recorded on Puerto Rico. Five died on St. Croix; two deaths were reported from St. Thomas and St. John.

The Red Cross totaled more than 200,000 families that were affected by the hurricane with homes destroyed or damaged. The figure was expected to rise as new tallies were reported from Puerto Rico and the Virgin Islands. In the Carolinas, initial reports showed 129,687 families were affected while in Puerto Rico and the Virgin Islands, the total reached 87,700.

Northeastern Puerto Rico near Fajardo. Photo courtesy of Joseph Golden.

Chapter II

SUMMARY OF PREPAREDNESS ACTIONS, INFORMATION AND WARNING SERVICES

PREPAREDNESS ACTIONS

The true measure of a warning program's effectiveness is the degree of response that the warning elicits from the public and local officials. Social scientists repeatedly point out that individuals must be able to assess adequately their risk before they are willing to take action. To do this, a timely stream of credible and consistent information must flow from the Weather Service, emergency management community and the media.

The NWS must work closely with emergency managers, officials and the media to gain their trust and to ensure that their needs for technical information are met. Similarly, active public awareness campaigns conducted with the media and local officials foster heightened awareness of local weather hazards in the general population. Local weather office personnel thus have a critical role to play. They are recognized by local decision-makers as part of the local community, providers of local information and as an educational resource on technical matters.

Puerto Rico/Virgin Islands

WSFO San Juan has a dedicated warning and preparedness individual assigned to the station. This office conducted comprehensive warning coordination and hazard awareness programs. Almost 100 preparedness meetings were conducted in May, June and July by the office staff including Meteorologist in Charge (MIC) Israel Matos and the Warning and Preparedness Focal Point, Francisco Torres. During the first 6 months of the year, meetings and office tours reached upwards of 2,000 people. For the Virgin Islands, hurricane preparedness conferences were held for local government officials at St. Thomas and St. Croix in May. During that month, a hurricane drill was conducted by the Commonwealth of Puerto Rico using materials prepared by WSFO San Juan. The Virgin Islands Territorial Emergency Management Agency (VITEMA) participated as an observer.

In June, the Puerto Rican Department of Natural Resources held its annual Hurricane Conference that included a presentation on the hurricane season by Matos as well as an explanation on the use of hurricane probabilities. Media covered this session that was attended by more than 100 persons. In July, three hurricane workshops were conducted for radio station managers and Civil Defense (CD) personnel at San Juan, Ponce and Quebradillas, all in Puerto Rico.

Also in June, MIC Matos critically reviewed the evacuation plan for San Juan that had been developed by the U.S. Army Corps of Engineers for FEMA. The WSFO staff used this plan and its "decision arc" (see Fig. 2-1) methodology to advise Commonwealth CD personnel on times necessary to begin evacuation to ensure an effective public response.

In July, WAPA-TV, Channel 4, one of Puerto Rico's major television stations, began allocating 15 minutes each Wednesday morning to the WSFO San Juan staff for presentations on hurricane awareness through the end of the most active portion of the hurricane season.

This effort on the part of the San Juan office to improve coordination and awareness resulted in a high level of community preparedness and culminated in one of the largest evacuations, 30,000 people, ever experienced in Puerto Rico.

North and South Carolina

Extensive preparedness and drill activities also had been conducted by all coastal offices in both Carolinas prior to the hurricane season. In addition, an active public awareness campaign was orchestrated in both states.

The Raleigh and Columbia Management Areas each has a Warning Preparedness Meteorologist (WPM) assigned to its station. Both of these individuals conducted Hurricane Awareness Weeks for the

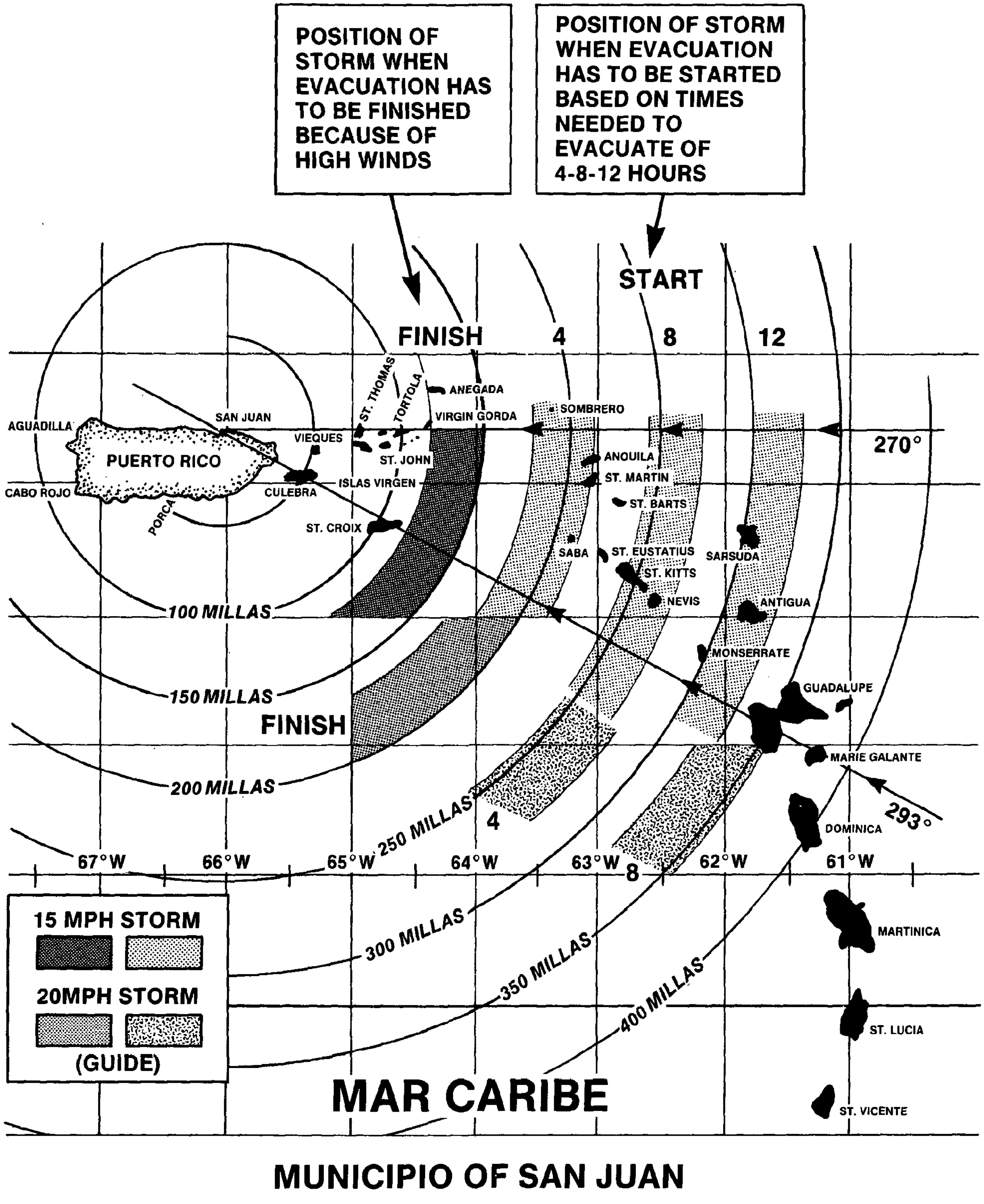


Figure 2-1. Decision arc methodology for evacuation planning in Puerto Rico.

public. They also worked closely with state, county and local coastal emergency management coordinators as well as their respective state government offices. In addition, a number of workshops and discussions took place that were led by the MIC at Charleston, Richard Shenot; the MIC at Wilmington, Albert Hinn; the Official in Charge (OIC) at Cape Hatteras, Wallace DeMaurice; and the two Warning Preparedness Meteorologists -- Dennis Decker, WSFO Raleigh, and Mary Jo Parker, WSFO Columbia. Participating were the media, private industry, local decision-makers, state, city and county officials, law enforcement officers from coastal areas, voluntary relief agencies and the public.

During Hurricane Awareness Weeks conducted at the beginning of the hurricane season, all offices in the eastern Carolinas, including the forecast offices at Raleigh and Columbia, provided public information releases on the NWWS and NOAA Weather Radio (NWR) dealing with hurricane safety, hurricane climatology and historical facts and information for local areas.

Mailings were made to the media and others. Print media releases in the two-state area during Hurricane Awareness Week included articles dealing with the potential dangers of hurricanes to the areas and historical storms. Some newspapers included evacuation routes and maps showing shelter areas designated by the respective governments. NWS offices in the Carolinas participated extensively with on-air interviews with local television and radio stations including a number of on-site television interviews from weather offices.

An extensive 2-day hurricane conference was held in June for all coastal law enforcement agencies, local and county decision-makers and the Emergency Preparedness Division (EPD) of South Carolina. Representatives from the FEMA regional office at Atlanta, Georgia, were among the 150 persons who attended. During the conference a scenario type of hurricane exercise was conducted. Decision-makers used a computer program to assist them in deciding what actions would be needed following receipt of locally prepared hurricane drill bulletins.

In July, a Coastal Zone Conference was conducted in Charleston. Attendees included representatives of NOAA, Department of the Interior, Sea Grant organizations, the Environmental Protection Agency (EPA), NWS offices in South Carolina and Emergency Preparedness Directors from the coastal counties. Presentations were made by the WSFO Columbia MIC, Bernard Palmer; NHC Director, Dr. Robert Sheets; NWS Techniques Development Laboratory Scientist, Dr. Wilson Shaffer; and the Beaufort County Emergency Preparedness Director, William Winn. This conference was aimed at coastal management issues and addressed the Sea, Lake and Overland Surges from Hurricanes (SLOSH) (see Appendix D) model that had been prepared for the Charleston basin.

Furthermore, local decision-makers were apprised of how the Maximum Envelopes of Water (MEOWs) could be factored into evacuation planning. SLOSH results allowed the local officials of the five coastal South Carolina counties to design suitable evacuation zones from the various storm scenarios and to study potential storm surge effects on evacuation routes and emergency shelters.

Similarly, North Carolina had just completed its comprehensive hurricane evacuation plan. This plan was a cooperative effort by the North Carolina Division of Emergency Management, FEMA, the Corps of Engineers, NHC, WSFO Raleigh and the 19 coastal counties in the state. During the plan's formulation, there were numerous meetings with state, county and local officials; the NHC Director or hurricane forecasters and SLOSH experts; state emergency management coordinators and planners; and personnel from the NWS offices at Raleigh, Wilmington and Cape Hatteras. These were conducted to train officials on the use of the SLOSH model and to show them examples of damage in their areas from various record storms. Vulnerable areas were located, shelters defined and evacuation routes developed for the entire eastern areas of the state.

North Carolina state, county and local officials were taught to use the "decision arc" and hurricane strike probabilities to aid them in making evacuation decisions. This comprehensive evacuation plan and the technique were also tested thoroughly in a full-scale, 2-day exercise conducted by NWS and the state of North Carolina in June. It involved the 19 coastal counties and the inland counties that would be involved in providing evacuation routes and shelters.

The Hugo evacuation was successful due in large part to the thorough planning and testing that had been done in both of the Carolinas. More than 90,000 people were moved to 400-plus shelters in the two states, and another 96,000 found shelter with families or friends.

NWS REGIONAL OFFICES

At the start of the hurricane season, the NWS Eastern and Southern Regional Headquarters assessed their coastal offices to determine staffing patterns, critical equipment needs and facilities. When it became apparent that Hugo would pose a threat to the islands and the mainland, both regional offices put their contingency plans into effect to ensure that offices in vulnerable areas had the resources necessary to meet responsibilities. Personnel were detailed to offices in the Carolinas, Georgia and northern Florida to augment staffs where necessary. Similarly, Eastern Region dispatched a needed part for the aging radar at Cape Hatteras to guarantee its continued operation.

STORM SURGE MODELING AND EVACUATION PLANNING

In the early 1980's, the NWS embarked on an effort to apply the SLOSH model to the entire U.S. Gulf and Atlantic coastlines. The SLOSH model takes into account an area's bathymetry and terrain features in a manner commensurate with the model's resolution for that area. The model aids forecasters in making real-time forecasts of hurricane storm surge and is useful for determining areas that could flood in various hurricane scenarios. Such information is the first step in developing a comprehensive hurricane evacuation plan for an area.

The Carolinas

The Charleston area was among the first areas modeled by SLOSH. An 80 x 100 grid (Fig. 2-2) extends over South Carolina from Hilton Head Island in the south to Myrtle Beach in the north. The geography of the area includes coastal barrier islands, extensive areas of marshland, rising terrain from the edge of the marsh inland and complex river/sound systems. Later in the SLOSH modeling effort, the Myrtle Beach/Wilmington and Hilton Head areas were covered with additional basins.

MIC Shenot, together with the Coastal Council of South Carolina, encouraged NHC to do a SLOSH simulation study for the Charleston area with funding from South Carolina and various Federal agencies. The result was an atlas containing predicted flooding from each of the simulated storms to assist in making evacuation decisions. From that study a comprehensive hurricane evacuation plan was completed for the Charleston area in 1986. The plan details the evacuation procedures to follow preceding a hurricane and gives recommended evacuation routes and designated shelter locations. Each of the area's emergency managers and many local officials have copies of this document.

In the village of McClellanville, the Lincoln High School was used as an evacuation shelter. The evacuation plan listed the base elevation of the school as 20.53 feet National Geodetic Vertical Datum (NGVD). Many of the residents took shelter in this school. During the height of the storm, water rose outside the school and eventually broke through one of the doors. Water rushed in and continued to rise inside the school reaching a depth of 6 feet within the building. A resident with a videocassette recorder documented people climbing on tables and bleachers to escape the rising water. As the water reached its maximum height, children were lifted onto the school's rafters. Fortunately, everyone survived the event although not without considerable anxiety.

Later examination revealed that the base elevation of the school was 10 feet, not the 20.53 feet listed on the evacuation plan. This school should not have been used as a shelter for any storm greater than a Category 1 hurricane.

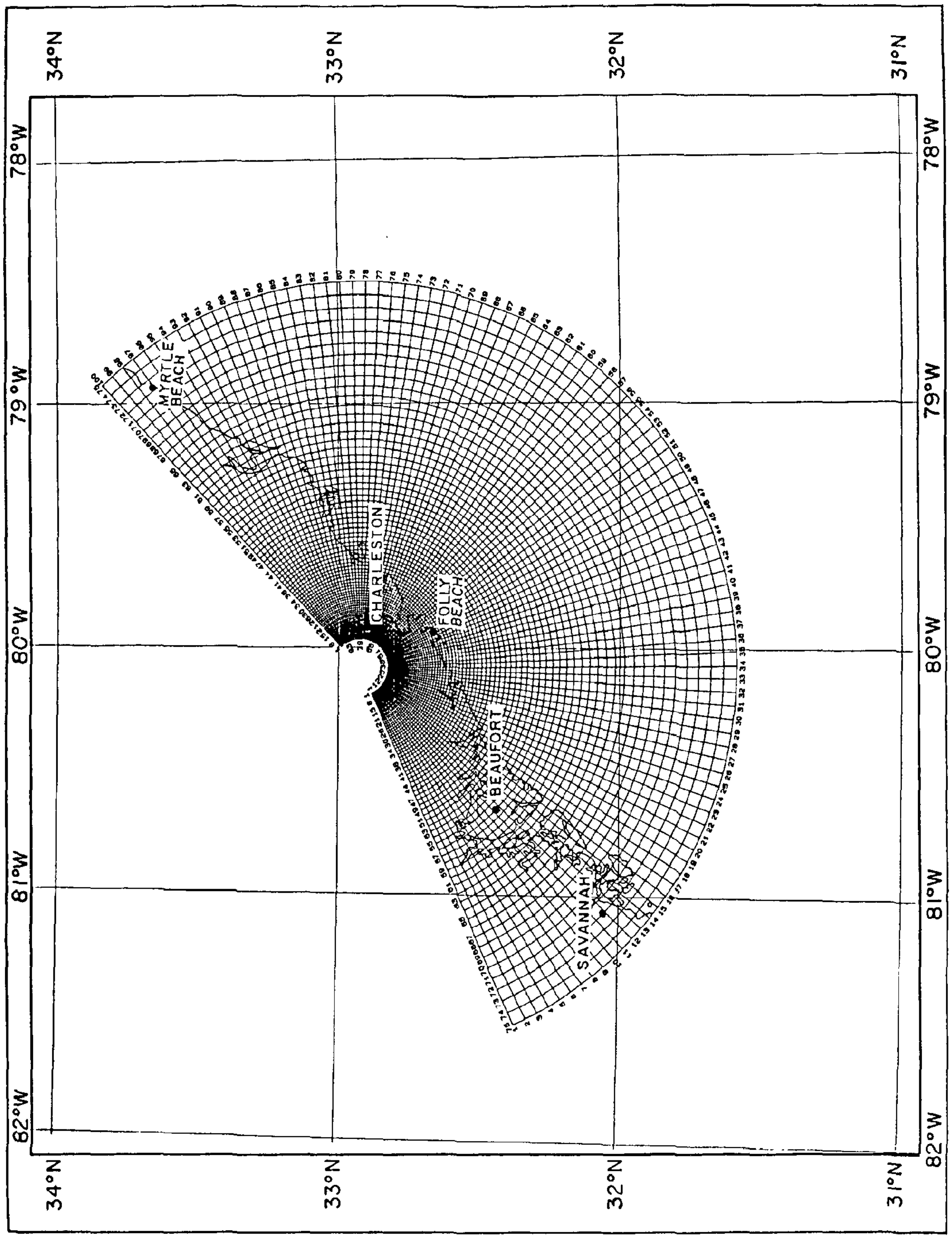


Figure 2-2. 80 x 100 grid point SLOSH model for the Charleston, South Carolina, basin.

Puerto Rico and Virgin Islands

A coarse mesh SLOSH model was developed in 1982 to cover Puerto Rico. Dr. Aurelio Mercado of the University of Puerto Rico, Mayaguez, under contract with FEMA for the Department of Natural Resources, has modified the model to run on the university's computer. Dr. Mercado has run many simulation studies; however, they are not of the magnitude of simulation studies done on the mainland and have not been folded into a comprehensive evacuation study. On the Saturday before Hugo struck, Dr. Mercado provided WSFO San Juan a copy of the only simulation study pertinent to a landfalling storm of Hugo's characteristics. This study predicted a surge of 8 to 9 feet for the southeast coast. Information from this study was shared with emergency managers and was instrumental in the evacuation of affected persons along Puerto Rico's southeast coast.

FINDING 2.1: Errors in base elevation information on shelters or evacuation routes could result in loss of life as evacuees move to unsafe shelters or through unsafe evacuation routes.

FINDING 2.2: A comprehensive evacuation study has not been undertaken for Puerto Rico and the Virgin Islands.

WARNING SERVICES

Puerto Rico/Virgin Islands

NHC's goal is to issue a watch approximately 36 hours before a hurricane's eye makes landfall and a warning about 24 hours before the eye crosses the coast. Hurricane watches were issued for the Virgin Islands and all of Puerto Rico at 6 PM Friday, September 15. Hurricane warnings were posted for the Virgin Islands and all of Puerto Rico at 3 PM Saturday, September 16. Partly as a result of the slowing of Hugo's forward motion, lead times for the hurricane watches were 56 hours for St. Croix, 62 hours for the Puerto Rican island of Vieques and 63 hours for the big island of Puerto Rico. Similarly, the hurricane warning lead times were 35 hours for St. Croix, 41 hours for Vieques and 42 hours for the big island. (See Fig. 2-3.) Although lead times of this magnitude helped local decision-makers and the public in taking adequate precautions, it did pose some problems for the Red Cross which was required to provide shelters for longer periods of time than ordinarily planned for hurricanes.

NHC is also responsible for issuing forecast storm positions out to 72 hours as well as hurricane strike probabilities. As in all forecasts, the forecast storm position has an associated error for each forecast period. The NHC average 24-hour forecast position error is approximately 100 miles. Position error is the distance between the forecast position and the actual observed position.

Due to the uncertainties involved in hurricane forecast positions, emergency managers and the media have been advised not to focus their sole attention on the forecast track. Hurricane probabilities were developed to assist in interpreting the forecast track by including the average forecast position errors. Hurricane probabilities give the probability in percent of a storm center passing within 75 nautical miles to the left or 50 nautical miles to the right (looking out from the beach) of the coastal location within the forecast period. Decision-makers are urged to use both the forecast track and the probabilities to assist in defining the coastal areas most at risk.

During much of Sunday, the storm's forecast track suggested a landfall on Puerto Rico's southeastern coast. By 6 PM, the track suggested the southwest coast but targeted the southeast coast by midnight. Six hours before landfall, the track focused on eastern Puerto Rico. The island of Puerto Rico is only about 40 miles wide and a little over 100 miles long which is approximately the size of NHC's 24-hour average hurricane forecast error. NHC advisories through this whole period indicated that Hugo would move over the island of Puerto Rico implying that all areas were equally at risk. WSFO San Juan's Hurricane Local Statements

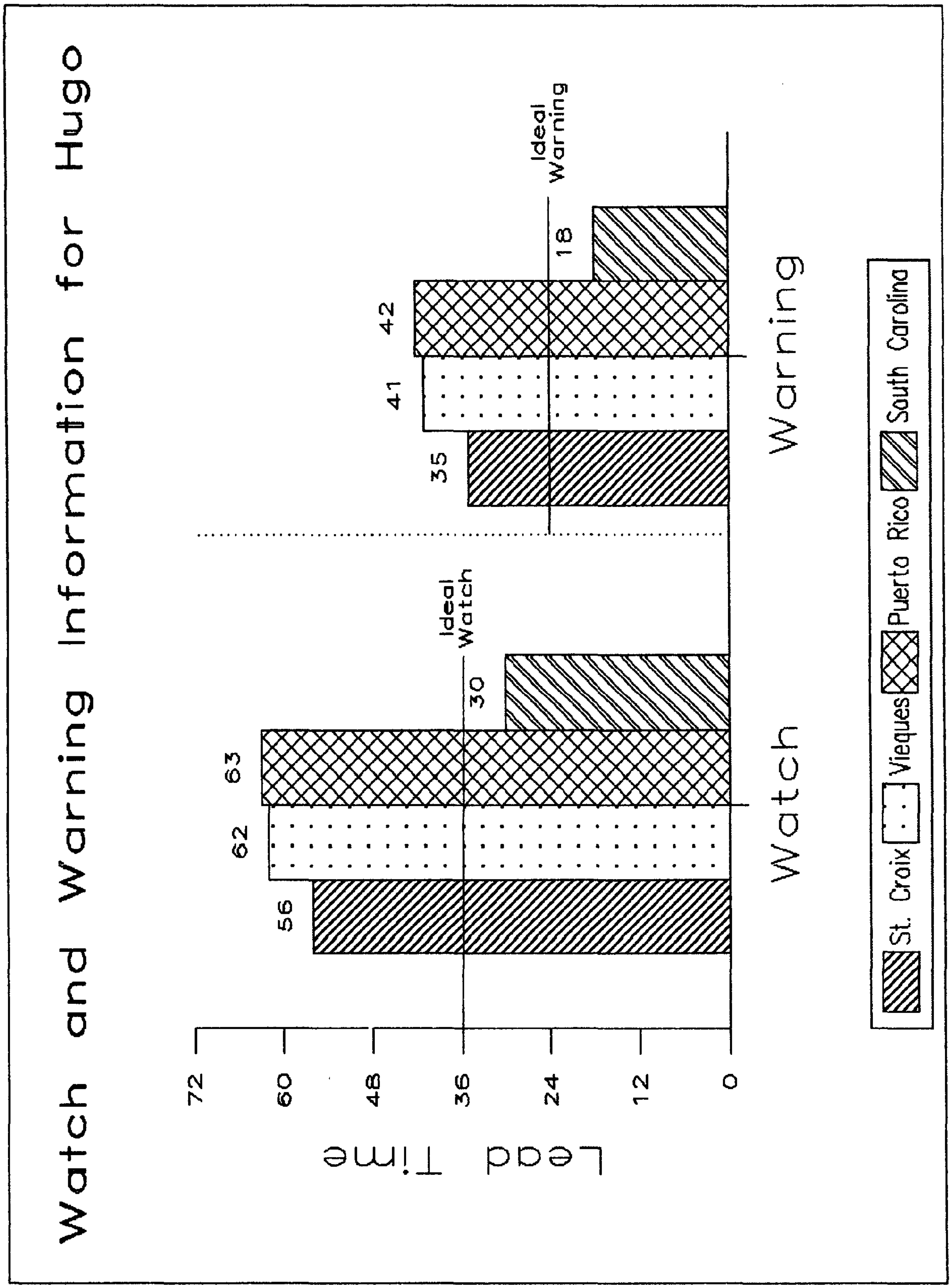

Watch and Warning Information for Hugo
Lead Time
0
12
24
36
48
60
72
56
62
63
30
Ideal Watch
35
41
42
18
Ideal Warning
Watch
Warning
St. Croix
Vieques
Puerto Rico
South Carolina

Figure 2-3

(HLSs), however, mentioned the potential landfall positions as suggested by the forecast tracks.

This could have posed problems for evacuation decisions by CD officials. In coordination calls to the emergency managers, WSFO San Juan emphasized the uncertainty in track predictions and stressed that the forecast tracks could be off as much as 60 miles. Interviews with CD directors of the Virgin Islands, the Commonwealth of Puerto Rico and San Juan, and the Mayor of San Juan indicate that the changes in potential landfall locations were not that significant to their planning. They essentially prepared for a direct hit.

Hurricane strike probabilities for Puerto Rico were always higher at San Juan than at Ponce. That landfall probabilities were so close, usually with differences of 10 percent or less, reflected the fact that chances for landfall on the northeast or south coasts were practically the same. Local officials and media representatives interviewed mentioned that they used hurricane probabilities and did not concentrate on the forecast track. Survey team members were left with the impression that frequent coordination with the WSFO served to encourage that tendency.

Emergency managers and the Governor of Puerto Rico were concerned that the public's response to evacuation might be negatively influenced by recent memories of Hurricane Dean. This did not appear to be the case. In August, Dean aimed directly for Puerto Rico when at the last minute it stalled and made an abrupt turn to the north missing the island.

The constant coordination between WSFO San Juan, the emergency managers and elected officials ensured that all decision-makers kept current with the evolving scenario. This resulted in the Governor of Puerto Rico taking a lead role along with the Commonwealth CD Director and the WSFO MIC in a critical Sunday night broadcast to the entire island over the Emergency Broadcast System (EBS) Network. As a result, 30,000 persons were evacuated. This included the impoverished northern coastal community of La Perla which evacuated for literally the first time in memory. Government officials claim that this was one of the best evacuation responses ever. Similar actions occurred in the Virgin Islands where EBS was activated and live broadcasts were made by the Governor and the Civil Defense Director.

The Carolinas

After passing over Puerto Rico, Hugo continued on a west-northwest to northwest track and maintained a steady course for the next 4 days. A hurricane watch was issued at 6 PM Wednesday, September 20, from St. Augustine, Florida, to Cape Hatteras. At 6 AM Thursday, a hurricane warning was posted from Fernandina Beach, Florida, to Cape Lookout. This afforded a lead time of 30 hours for the watch and 18 hours for the warning. This is somewhat less than the ideal but approximated the NHC average (see Fig. 2-3).

The potential for a hurricane watch being posted along a portion of the East Coast was mentioned in the NHC advisories 3 hours before the watch went into effect. Similarly, the potential for upgrading the watch to a warning was highlighted 12 hours before the warning was issued. This heightened awareness in the threatened areas and was a critical factor in the consultations between WSFO Columbia's MIC Palmer and the Governor of South Carolina. The Governor's highly successful voluntary evacuation order, issued in anticipation of the warning, resulted from his discussions with Palmer.

In the hurricane advisory issued at 3 PM Thursday, NHC extended the hurricane warning from Cape Lookout to Oregon Inlet, North Carolina. The advisory also stated that Hugo was expected to make a gradual turn to the north within the next 12 hours.

The barrier islands require more than 12 hours to evacuate, and by mid-afternoon Thursday when the warning was extended, surface winds had increased to a point that precluded ferry boat operations. This extension of the warning posed a dilemma to emergency managers. Furthermore, the advisory gave no reason for the gradual turn to the north so that emergency managers and the media did not know and could not share with the public the reasons for the forecast change.

The extension of the warning to the north and the forecast of a gradual turn to the north were linked by some local officials and residents. Concern was heightened when a local television station stressed the turn to the north.

The reasoning behind the extension of the warning and the forecast turn to the north was discussed by NHC with local NWS offices over the Hurricane Hotline. When the local offices shared this information with the emergency managers, it was apparent to them that the area would be on the fringe of the hurricane and that evacuations would not be required. To assuage public concerns, however, North Carolina officials opened three shelters on the coast even though they were convinced that evacuations were not necessary.

Table 2-1 lists the probabilities for the southeast coast Thursday afternoon and evening. The segment of the coast from Morehead City to Cape Hatteras corresponds to the area where the warning was extended at 3 PM. The probabilities show a change in forecast track to the north at 3 PM although the magnitude of the values still suggest that the area of greatest threat was between Wilmington and Charleston.

TABLE 2-1

HURRICANE HUGO PROBABILITIES THURSDAY, SEPTEMBER 21

	Noon	3 PM	6 PM	8 PM
Savannah, GA	37	10	7	25
Charleston, SC	48	56	69	99
Myrtle Beach, SC	35	63	69	62
Wilmington, NC	17	48	53	6
Morehead City, NC	5	20	24	X
Cape Hatteras, NC	1	5	6	X

The storm's track, after Hugo made landfall, was further west than the NHC forecast 24 hours before landfall. Later forecasts adjusted the track to the west.

Hurricane-force winds were forecast well inland with this strong storm. Marine advisory #41, issued about 24 hours before the storm crossed the coast, forecast sustained winds of near 60 MPH with gusts to 75 MPH as far inland as Charlotte. Marine advisory #46, issued at 11 PM Thursday when the eye was near the South Carolina coast, forecast the storm center to move within 30 miles of Charlotte and to reach southwestern Virginia by 7 PM Friday with wind gusts to 86 MPH. The extent to which hurricane-force winds would extend inland was not emphasized in the public advisories, and many inland residents were surprised to be awakened by hurricane-force winds as far inland as 200 miles from the point of landfall of the storm.

Because the public advisories did not highlight the extent of high winds inland, it was left to the local NWS offices to emphasize the threat to emergency managers in vulnerable areas. On Thursday, September 21, Ronald Kuhn, OIC of WSO Charlotte, discussed with the local emergency coordinator, Wayne Broome, the possibility that Charlotte might suffer high winds, flooding and perhaps tornadoes particularly if the gradual turn to the north did not materialize. Kuhn advised him that if these possibilities matured into probabilities, the appropriate response would be to close schools, alert power companies and set up traffic control and road clearance procedures. In short, respond as though it were a winter storm.

At 3 AM, September 22, the WSO advised the local emergency coordinator of imminent high winds. The official issued emergency orders immediately. High winds struck at 4 AM and continued through the morning. Wind gusts of 90 MPH were reported at the control tower in Charlotte before it was evacuated. Wind damage exceeded $500 million in all of Mecklenburg County, North Carolina. Closer to the coast, wind gusts of nearly 110 MPH destroyed 200 homes and heavily damaged 1,000 others at the Air Force Base in Sumter.

Taken all together, this illustrates how important it is that NHC communicate fully as possible on a level understood by the public. When updating advisories, NHC must ensure that all language is clear and all information properly conveys its true intent. Furthermore, NHC cannot assume that the public has knowledge of all previously released information.

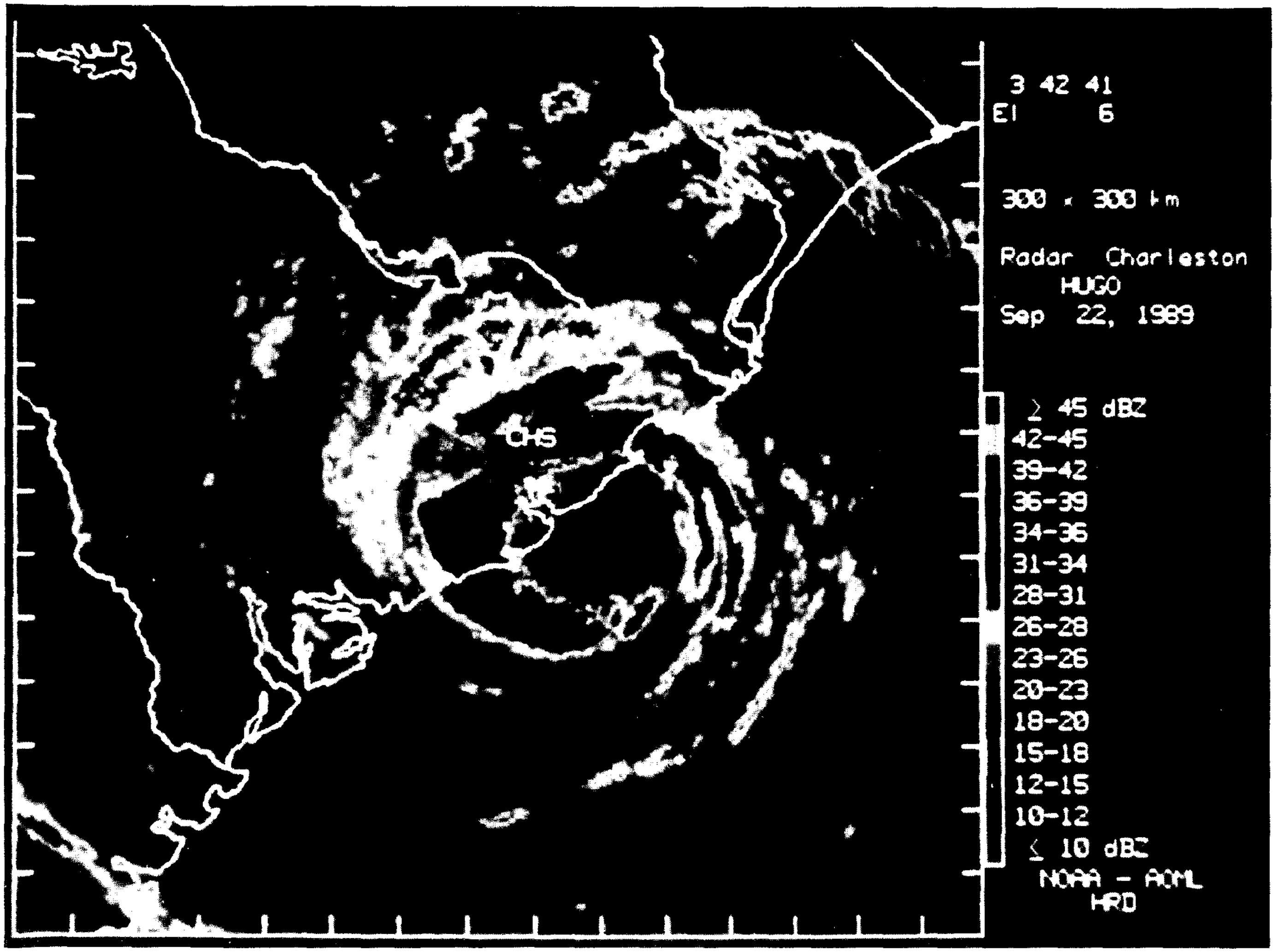
The timing of NHC bulletins sometimes posed problems for local NWS offices in keeping all forecast and warning products current and consistent. One example was when the hurricane watch was posted at 6 PM Wednesday. Public forecasts for the East Coast are issued between 3 and 4 PM. This meant that all forecast products had to be reworded and reissued following the posting of the warning. Although all offices were apprised of this possibility from an earlier Hurricane Hotline conference call, it still required considerable work. The need for frequent updates is unavoidable. Unfortunately, local offices do not have the interactive product formatting (word processing) capability which would expedite rapid revisions of forecasts.

FINDING 2.3: In its HLSs, WSFO San Juan referenced potential landfall sites with a degree of specificity that was greater than current forecast capabilities allow. Frequent coordination calls with users kept decision-makers from overly focusing on the forecast track.

FINDING 2.4: In both the Caribbean and the Carolinas, hurricane probabilities were used in varying degrees by decision-makers to incorporate forecast uncertainties in their planning efforts.

FINDING 2.5: In two hurricane advisories, the addition of two significant changes without reasons for these changes created some problems for emergency managers and the media.

FINDING 2.6: The lack of emphasis in NHC public advisories for the Carolinas on inland high winds left the media and local officials with little guidance on how to respond.



Digitized representation of the Charleston, South Carolina radar image of Hugo crossing the coast near Charleston.
Photo courtesy of Peter Dodge, Hurricane Research Division, ERL.

Chapter III

DATA COLLECTION AND COMMUNICATIONS

DATA COLLECTION

Puerto Rico and Virgin Islands

Surface observations throughout the Caribbean are sparse. WSFO San Juan takes hourly observations at the International Airport and receives hourly observations from three additional sites in Puerto Rico and one each from St. Croix and St. Thomas. During the height of the storm, observations were only available from the WSFO and the Navy base at Roosevelt Roads. Attempts to assess peak winds in the islands have been seriously hampered by the lack of surface observational data.

WSFO San Juan radar is a WSR-74S band system that is located on the International Airport grounds. The radar signal is partially blocked from the east through the southwest by a mountain range that extends east to west across Puerto Rico. WSFO San Juan does not have a drop on the Roosevelt Roads radar. Blocking, however, was not a problem during Hugo.

The radar was in operation throughout the storm even when air conditioning was lost. Fans were positioned to keep the console cool enough to operate.

Upper air observations were taken twice a day until Sunday afternoon, September 17, when conditions deteriorated to a point where balloon launching was too difficult. As the storm swept across the northeastern portion of the island, the radome was damaged and the doors were blown off the inflation shelter. Fortunately, the automatic radiotheodolite (ART) was not damaged. Launchings were resumed Tuesday evening following recalibration of the equipment and installation of a barrier created from a carport to keep winds away from the inflation area.

Geostationary Operational Environmental Satellite (GOES) information is available to WSFO San Juan through the Satellite Weather Information System (SWIS). Up to 200 of these images can be displayed on the SWIS which has animation and color enhancement capability. WSFO San Juan received infrared, water vapor and daylight visible images with few interruptions during Hurricane Hugo.

Water vapor imagery is a relatively new tool. When animated, water vapor images show mid-tropospheric motion which affects the steering of tropical storms even in cloud-free areas. No images were transmitted from 1 to 2 AM each day because of the "eclipse" period in which the GOES is unable to recharge its solar cells. This system functioned well throughout the storm. After the storm was over, however, the SWIS had to be cycled on and off to prevent overheating. This meant that continuous satellite imagery was not available after Hugo when Tropical Storm Iris threatened heavy rains.

A series of satellite precipitation estimates (SPEs) produced at the Synoptic Analysis Branch (SAB) of the National Environmental Satellite, Data and Information Service (NESDIS) in Camp Springs, Maryland, were transmitted on Automation of Field Operations and Services (AFOS) while Hugo was over Puerto Rico. SPEs are rainfall estimates for periods of an hour or more based on satellite-observed cloud-top temperatures, cooling rates and movements of convective cells.

WSFO San Juan has access to an automatic rain gauge network known as Automated Local Evaluation in Real Time (ALERT) system. The system consists of 31 automated rainfall gauges strategically located around the island with information sent by radio to four base stations periodically on demand. Two of the gauges also are equipped with wind and temperature sensors.

These gauges are located at Puerto Rico's highest peak, La Punta, and at Maricao where the NWR transmitter for western Puerto Rico is sited. In addition to WSFO San Juan, the other three base stations are located at the Commonwealth Office, the Department of Natural Resources and the U.S. Geological Survey.

Several weeks before September 18, personnel of the Department of Natural Resources were performing field maintenance on the ALERT equipment. Three of eight rain gauges had been inoperative in the Rio Grande de Loiza Basin. Out of 30 ALERT gauges across the island of Puerto Rico, 25 were operational.

The ALERT system functioned throughout the storm although the repeater for the Loiza River basin failed on Sunday night, September 17.

WSFO San Juan previously attempted to set up a similar ALERT system in the Virgin Islands with financial support from FEMA. The Virgin Islands CD was unable to support the system so the project was never implemented.

Fifty-three river and rainfall gauges are available to the WSFO through the GOES system. These functioned normally throughout the event. A number of amateur radio operators on the KP4 HAM net provided rainfall reports to a base station at 7 PM daily. The reports were telephoned to WSFO San Juan.

The Carolinas

Stations reporting surface weather conditions over the southeastern United States are shown by the map (Fig. 3-1). Most of these stations operate on a 24-hour basis staffed by personnel of the NWS, Federal Aviation Administration (FAA) or Department of Defense (DoD). Some of the stations with limited operating hours, such as McEntire Air National Guard Base (MMT), South Carolina, provided supplementary observations during Hurricane Hugo. MMT was directly in the path of the storm and estimated sustained winds of 58 MPH with a peak gust to 79 MPH. There are no stations between Charleston and Myrtle Beach, a distance of 90 miles, the segment of the coastline most severely affected by Hugo. The data-void region extends inland 50-100 miles. During the height of the storm, several observations from Charleston were not transmitted due to a problem with the auxiliary backup terminal (ABT) which was being used in lieu of the AFOS system. Otherwise, no significant data losses were reported for any stations.

The upper air station at Charleston sustained damage to the inflation shelter during the storm and was not able to perform the normal radiosonde release at 8 AM, September 22. The Cape Hatteras site was unable to repair an electronics problem that resulted in manual rawinsonde operation that contained no wind data. Other upper air stations operated normally.

In the southeastern mainland areas most affected by Hugo, NWS operates network radars (10 centimeter (cm) wavelength WSR-57S) at Charleston, Wilmington and Cape Hatteras, and inland at Athens, Georgia. Local warning radars (5 cm wavelength WSR-74S) are located at Columbia, Charlotte, and Augusta, Georgia. The radar systems performed well during the storm and were invaluable in tracking the storm inland during the early morning hours.

The plan position indicator (PPI) scope at Hatteras was inoperative beginning at 8 PM, September 20. A spare part from Wilmington was shuttled to Cape Hatteras by North Carolina Highway Patrol vehicles, and the radar was functional by 4 PM, September 21. The Charleston radar was out briefly when rain began leaking through the roof during the height of the storm.

WSFOs Raleigh and Columbia both had access to SWIS and satellite products, such as satellite precipitation estimates, throughout the storm. WSOs Charleston and Charlotte do not have any satellite image display capabilities.

A variety of river and rain gauges are available in the Carolinas. These include gauges from cooperative programs with other Federal and state agencies as well as automated systems, such as the Integrated Flood Observing and Warning System (IFLOWS), in western North Carolina and NWS gauges over the state. There were no significant outages of these gauges during the storm.

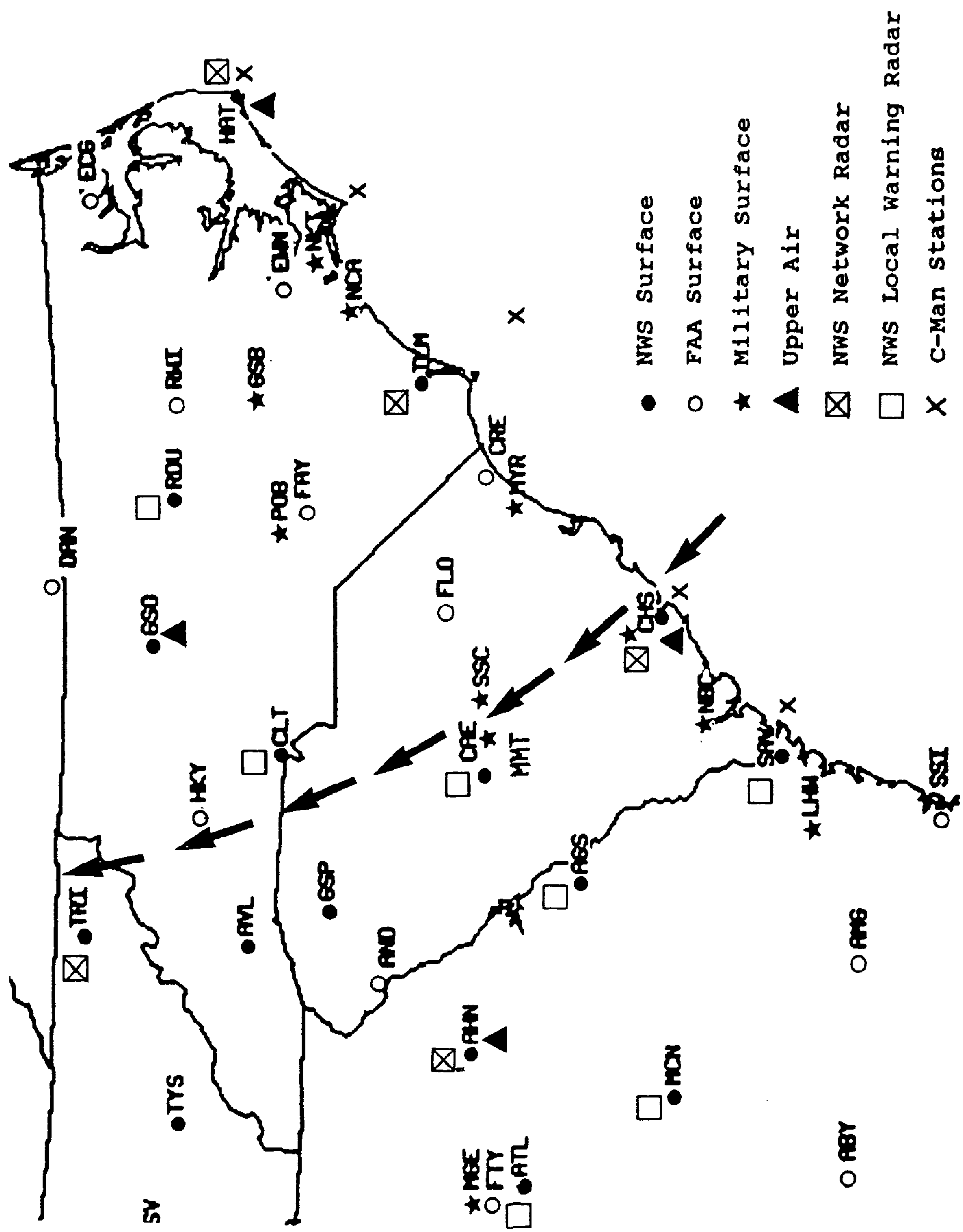


Figure 3-1. Locations and types of data reporting stations available to NWS in area affected by Hurricane Hugo. Arrows show the track of the storm center.

FINDING 3.1: The density of surface observations in the Caribbean and the Carolinas is extremely low. This posed a significant problem to forecasters trying to obtain information during the storm.

FINDING 3.2: A dedicated connection to the Roosevelt Roads radar would ensure full radar coverage for WSFO San Juan.

FINDING 3.3: A fully operational ALERT system for the Virgin Islands would assist the WSFO staff in preparing flood related warnings and assist VITEMA in responding to flood situations.

COMMUNICATIONS

Automation of Field Operations and Services (AFOS)

The main communications system for National Weather Service offices is the AFOS system.

Puerto Rico

Basically, AFOS functioned well during the storm with only a minor loss late Friday evening, September 15, when the system went down for 2 hours. This resulted in WSFO San Juan missing the 9 PM NHC hurricane advisory. Problems with AFOS became pronounced after the storm due to excessive heat build-up in the office. Fans were placed throughout the work area and directed at graphic display modules (GDMs) which generated most of the heat.

Finally, the GDMs were turned off to reduce heat build-up and the alphanumeric display modules (ADMs), which are used for message composition, were cycled on and off to keep operating temperatures at acceptable levels. Although these actions were taken, the hard disks developed problems that required an exhaustive software rebuilding effort over 3 days.

The Carolinas

In South Carolina, AFOS at both Columbia and Charleston operated throughout the storm, but the communications data line between the two offices was out for 6 hours beginning about 11:45 PM, September 21. During that period, HLSs normally issued by the Charleston office were provided by Columbia. No serious AFOS problems were reported at WSO Charlotte.

NOAA Weather Wire Service (NWWS)

The primary external dissemination system for National Weather Service products is NOAA Weather Wire. A national program is underway to upgrade the system to utilize satellite transmission capabilities for all NWWS products. Puerto Rico and the Virgin Islands, however, still are served by the old weather wire, a land line system. Raleigh and Columbia drive a NOAA Weather Wire for their respective states and both systems have been upgraded to a satellite system. Both states are also served by a land line system until the full national upgrade is completed. NWS offices in the Carolinas can transmit directly onto the NOAA Weather Wire through AFOS.

The San Juan NOAA Weather Wire consists of two separate circuits. The first circuit is bilingual and goes to the Puerto Rican Communications Authority which distributes it to the media and to the Commonwealth CD. Only one television station in Puerto Rico, Channel 11, has NOAA Weather Wire as does WKAQ radio (the EBS station) and the San Juan CD. The Commonwealth CD fans out weather information to the 78 principal CDs.

The other NOAA Weather Wire circuit to the Virgin Islands is in English. Primary customers are VITEMA and marine radio station WAH in St. Thomas. The NOAA Weather Wire functioned throughout the storm in Puerto Rico and until shortly before landfall in the Virgin Islands.

NOAA Weather Radio (NWR)

NWR is the other primary means of distributing NWS products to emergency managers and the general public. NWR transmitters normally serve an area within 40 miles of the antenna.

In San Juan one console drives two transmitters that essentially cover the island. Broadcasts are bilingual.

The transmitter for eastern Puerto Rico, including the islands of Vieques and Culebra as well as portions of the Virgin Islands, remained operational throughout the storm. The Maricao transmitter, which covers western Puerto Rico, failed at 9:22 PM Sunday and fluctuated in operation after the storm until early October.

The NWS has been working with marine radio station WAH in St. Thomas to begin broadcasts of NWR in English to the Virgin Islands. Software problems at WAH have slowed implementation efforts. WAH was not broadcasting NWR information over the NWR frequency allotted to it during the storm.

In South Carolina, the network was exposed to extensive outages that began about midnight Friday, September 22, and lasted from 6 hours to a week. The transmitter at Mount Pleasant, South Carolina, which repeats WSO Charleston broadcasts, was destroyed. Other transmitters experiencing outages were Florence, Columbia, Sumter, Green Pond and Conway.

NWR broadcasts from WSFO Columbia were interrupted only Friday from 2 to 6 AM. These interruptions resulted from sporadic failure of the WSFO emergency generator and the failure of commercial power at the transmitter site which is collocated with South Carolina Educational Television (ETV) station. A 2 to 4 AM interruption resulted from failures of power and the emergency generator at the WSFO. The ETV station has an emergency generator, but personnel must activate the generator manually. This was not done until 6 AM, September 22, when ETV staff returned to work. WSFO Columbia was not made aware that there was no automatic switchover to backup power for NWR, an important requirement during a weather emergency.

North Carolina escaped with no major interruptions and the NWR system performed well.

Hurricane Hotline Internal Coordination System

The NWS uses a dedicated land line telephone system in the eastern and southern U.S. for conference calls. The system accommodates most WSFOs in these areas plus, NHC, NSSFC, National Meteorological Center (NMC) and regional and national headquarters. On September 21, a late morning malfunction of the hotline resulted in NHC being unable to communicate with any office other than NMC. The malfunction came at a critical time; hurricane and tropical storm watches were being extended further up the East Coast. The NMC duty forecaster, however, managed to patch the NHC forecaster through another phone system allowing other offices to hear NHC's presentation. No two-way exchange was possible. By afternoon, the malfunction was corrected.

WSFOs Raleigh and Columbia are on the Hurricane Hotline, and they both coordinated with NHC on this system throughout the period of the storm. Coastal Weather Service Offices are not included on this circuit. Coordination information must be passed to these offices by their parent WSFO.

WSFO San Juan is not included on the Hurricane Hotline. Communications between it and NHC must be conducted over normal phone lines. The WSFO lost communication before noon Sunday, September 17. As a result, no San Juan information was available for formulating the official hurricane forecast track from that time on.

National Warning System (NAWAS)

NAWAS circuit is not available in Puerto Rico or the Virgin Islands. Accordingly, there is no dedicated hotline circuit connecting emergency management officials with the WSFO.

All NWS offices in the Carolinas are on the NAWAS system, but there are separate circuits for the two states. WSO Charlotte has recently acquired a drop on the South Carolina NAWAS circuit, but it is not possible for South Carolina NWS offices to contact any other North Carolina office on the NAWAS system. This forces these offices to rely on conventional telephone use for warning coordination. Emergency management and law enforcement officials near the North and South Carolina border cannot exchange severe weather reports directly to the neighboring state NWS or emergency management offices on the NAWAS system.

Other Communications Systems

Several other communications channels are available to WSFO San Juan for collecting and disseminating information. The Antilles Meteorological Circuit links all of the Caribbean islands for surface observations. The circuit went down at 10:15 PM Friday, September 15, and remained down throughout the storm.

Direct radio links are maintained to the Commonwealth CD in San Juan and to VITEMA headquarters in St. Thomas. Both organizations relay information to their local CD offices. A direct radio link also is in place to the Puerto Rican Water Authority (Acueductos).

Some communications systems in the Carolinas depended on microwave antennas. The force of the winds rotated these antennas, which are highly directional, thus knocking out microwave reception at many locations.

An amateur radio operator was brought on station at Columbia Thursday evening, September 21, and remained through the night to receive and relay storm reports and spotter information. The HAM weather network in the state had been activated on Thursday and was fully operational across the area by that afternoon.

At WSFO Raleigh and in North Carolina, the HAM radio net was functioning with an amateur radio operator at many NWS offices in the state and in the state Emergency Operations Center (EOC) from Thursday afternoon through Friday evening.

FINDING 3.4: Limited NOAA Weather Wire drops in Puerto Rico and the Virgin Islands resulted in few emergency managers having hard copies of Weather Service products. This increased the need for coordination efforts at the local WSFO.

FINDING 3.5: NWR reception is poor in the Virgin Islands.

FINDING 3.6: WSFO San Juan and most coastal WSOs are not on the Hurricane Hotline. Accordingly, they cannot participate in routine coordination calls with NHC, NMC and other coastal WSFOs.

FINDING 3.7: Puerto Rico and the Virgin Islands have no dedicated coordination line between emergency managers and the WSFO. In the Carolinas, lack of NAWAS drops from adjacent states hampered coordination efforts across state boundaries.

Commonwealth of Puerto Rico Emergency Operations Center.
Photo courtesy of Donald Wernly.

Chapter IV

AN EVALUATION OF THE PROCESSING, INTERPRETATION AND DISSEMINATION OF NWS INFORMATION

NATIONAL HURRICANE CENTER

Operations

NHC has access to nine numerical models for predicting hurricane tracks. Data from up to four models are available to the forecaster at any one time. Although each model has its own strengths and weaknesses, no one model consistently outperforms another over the life of a storm.

The numerical models may be broken into two categories -- statistical and dynamical. Statistical models, as their name implies, are based on statistical relationships and tend to perform best in the deep tropics where storms tend to maintain a persistent track. Dynamical models, which attempt to model physical atmospheric processes, tend to perform better at higher latitudes where storms recurve. This was born out in Hurricane Hugo when NHC83, a dynamical and statistical model, performed well overall while CLIPER, a climatological/persistence model, worked best in the tropics.

The predicted movement of Hugo was based on a combination of model output and forecaster experience. It takes an experienced forecaster to decide on the performance of each model before selecting a "future track" for each hurricane based on how the models are initialized and whether each run can handle the input data.

The statistical models can supply track positions to NHC within 10 minutes after initialization, yet, the Quasi-Lagrangian Model (QLM) takes approximately 6 hours to run. NHC83 and the statistical tracking models are run every 6 hours. The dynamical models are run every 12 hours at standard observation times.

Key ingredients needed by the models are initial storm position, motion and intensity. Current satellite capabilities for assessing storm motion and intensity do not equal the accuracy of aircraft reconnaissance measurements. These parameters can be measured by reconnaissance aircraft penetrating the storm and can be inferred from satellite imagery. The latter is used to track the centers of tropical cyclones over remote ocean areas. When storms approach islands or coastlines, aircraft reconnaissance planes are employed.

Satellite position estimates obtained from low resolution infrared are within an average of 25 miles of the reconnaissance position measurements for all tropical storm cloud pattern types improving to 16 miles for storms which have eyes. Differences between satellite estimates and reconnaissance measurements of 50 miles are not uncommon, however, with occasional differences exceeding 100 miles. Satellite intensity estimates are derived from the temperature difference between the eye and the surrounding eye wall combined with an empirical cloud pattern recognition technique. Another empirical relationship is used to estimate minimum sea level pressure and maximum wind speed from these temperature differences.

An example of the differing capabilities of the two methods; as Hugo approached the Leeward Islands, satellite-based estimates of surface winds were 115 MPH in contrast to the first aircraft penetration that measured flight level winds of 165 MPH and surface wind speeds of 135 MPH.

Aircraft reconnaissance is especially valuable in defining the wind fields of the storm -- a capability not yet present with satellites. Only aircraft can provide high density data on storm wind fields. Asymmetries in the wind fields detected by aircraft can be factored into the SLOSH model runs to assist in defining warning areas and the timing of evacuations. Figures 4-1 and 4-2 illustrate the wind field data provided to NHC by NOAA research aircraft in the Caribbean and off the Carolinas. During Hurricane Hugo, NOAA or Air Force aircraft were monitoring the storm on an average of every 2.1 hours.

Finally, SAB provides NHC forecasters with an analysis of the steering currents in which the storm is embedded. This product, the deep layer mean (DLM) steering wind, is derived primarily from satellite imagery. It is a composite of GOES cloud motion, water vapor motion, VISSR atmospheric sounder (VAS) soundings and radiosonde wind data.

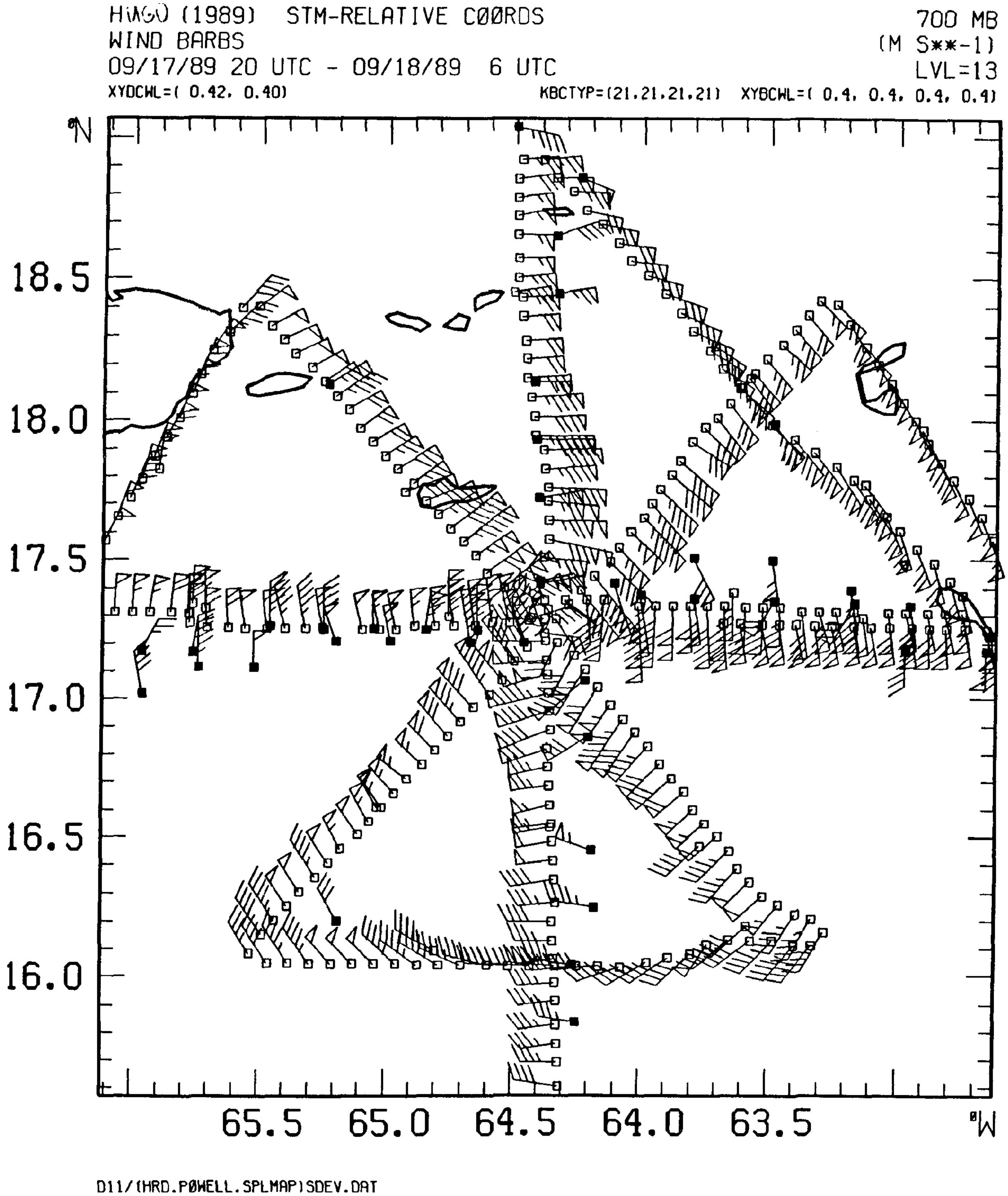


Figure 4-1. Two dimensional wind field at 700 mb of Hugo as it approached Puerto Rico and the Virgin Islands. Direction of wind indicated by direction of wind barb. Speeds given as follows: flag 50 meters/sec, large barb 10 meters/sec, small barb 5 meters/sec.

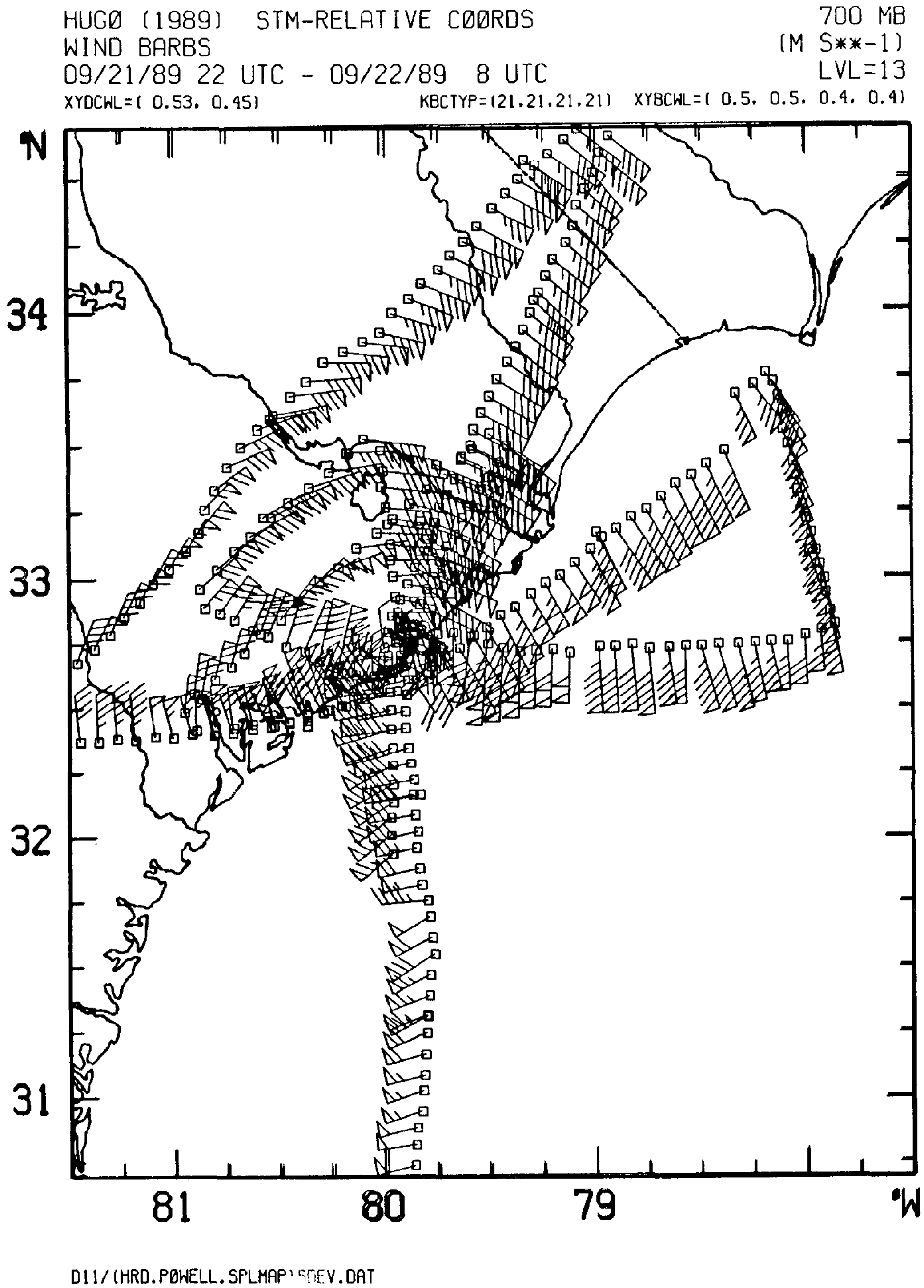


Figure 4-2. Two dimensional wind field at 700 mb of Hugo as it approached Charleston, South Carolina.

The DLM is fed through a data line to NHC's VAS Data Utilization Center (VDUC) computer. An example of the DLM for the evening of September 21, which graphically illustrates the probable track, is shown in Fig. 4-3.

FINDING 4.1: Aircraft reconnaissance is a necessary tool in hurricane forecasting.

NHC Forecasts

Table 4-1 lists the official track forecast errors along with the errors of several guidance models. The official errors were quite small for Hurricane Hugo. For example, the 24-hour average forecast error of 65 nautical miles during Hugo compares with the previous 10-year average official error of 109 nautical miles. The 72-hour Hugo error of 154 nautical miles compares with the previous 10-year average of 342 nautical miles. It should be noted that some of the guidance models also had small errors.

TABLE 4-1

Hurricane Hugo Average Track Forecast Errors (Nautical Miles)

	Forecast Period Hours				
Model	12	24	36	48	72
Official	33	65	98	122	154
CLIPER	37	73	119	161	216
NHC83	38	61	88	106	178
QLM	81	90	119	172	268
SANBAR	28	55	92	141	302

Figure 4-4 is a graphical representation of the 24-hour forecast position errors. From the figure, one can discern the slowing of the storm as it approached the islands and its acceleration as it approached the mainland. Biases in the forecast, either to the left or right of the actual track, can be noted.

There was a left bias to the official forecasts for the period when Hugo was turning from west-northwestward to northwest. This occurred as Hugo reached Puerto Rico and continued for the following 2 days. This is a normal bias for NHC track forecasts in this area during recurvature situations. There was a slight right bias for two forecasts on Thursday, September 21, just before landfall. This caused the hurricane probabilities to peak at Myrtle Beach during that afternoon.

This was also a situation where a tropical cyclone went from a Category 2 to a Category 4 hurricane on the Saffir-Simpson Scale during the 30 hours prior to landfall. Forecasts of intensity changes proved particularly difficult while Hugo was approaching the Carolinas. For the 24 hours beginning 5 PM Wednesday, September 20, the highest sustained winds increased from 105 to 135 MPH. During this period, the wind forecast contained in all of the public advisories was "little significant change in strength is likely." The numerical model guidance contained no definitive information on potential strengthening. Satellite imagery suggested intensification which would indicate decreasing central pressure which is usually accompanied by increasing winds. Actual changes in storm intensity were gathered from aircraft reconnaissance data. It is important for users of NHC information to appreciate the limitations in tropical cyclone intensity forecasting.

During Hugo, storm surges of up to 8 feet were predicted for exposed coastal areas in the Virgin Islands and Eastern Puerto Rico. Storm surges of 6 feet were estimated on the south short of St. Croix and 4 feet on the north shore. Though no ground surveys were conducted on either St. Thomas or St. John, the bathymetry suggests surges should have averaged no more than 4 feet.

For Puerto Rico, estimates ranged from 4 to 8 feet on the northeast coast and 3 to 6 feet on the southeast coast with the maximum value of 8 feet occurring at Luquillo Beach on the northeast coast. Storm surge values of 7 to 8 feet probably occurred on the island communities of Vieques and Culebra especially at Ensenada Honda on the south side of

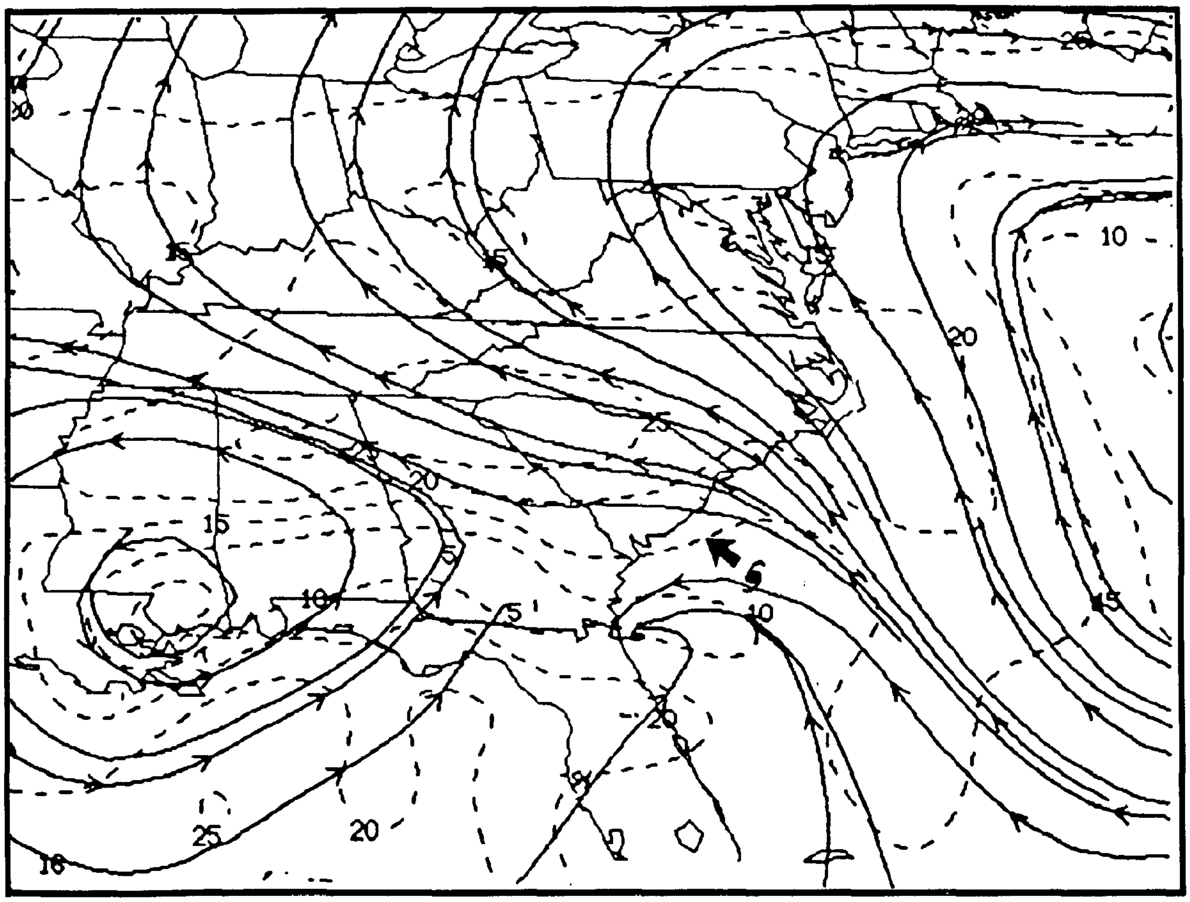


Figure 4-3. Deep Layer Mean flow streamlines (solid) and isotachs (dashed) in meters/sec. for 0000 UTC, September 22, as Hugo was approaching the South Carolina coast.

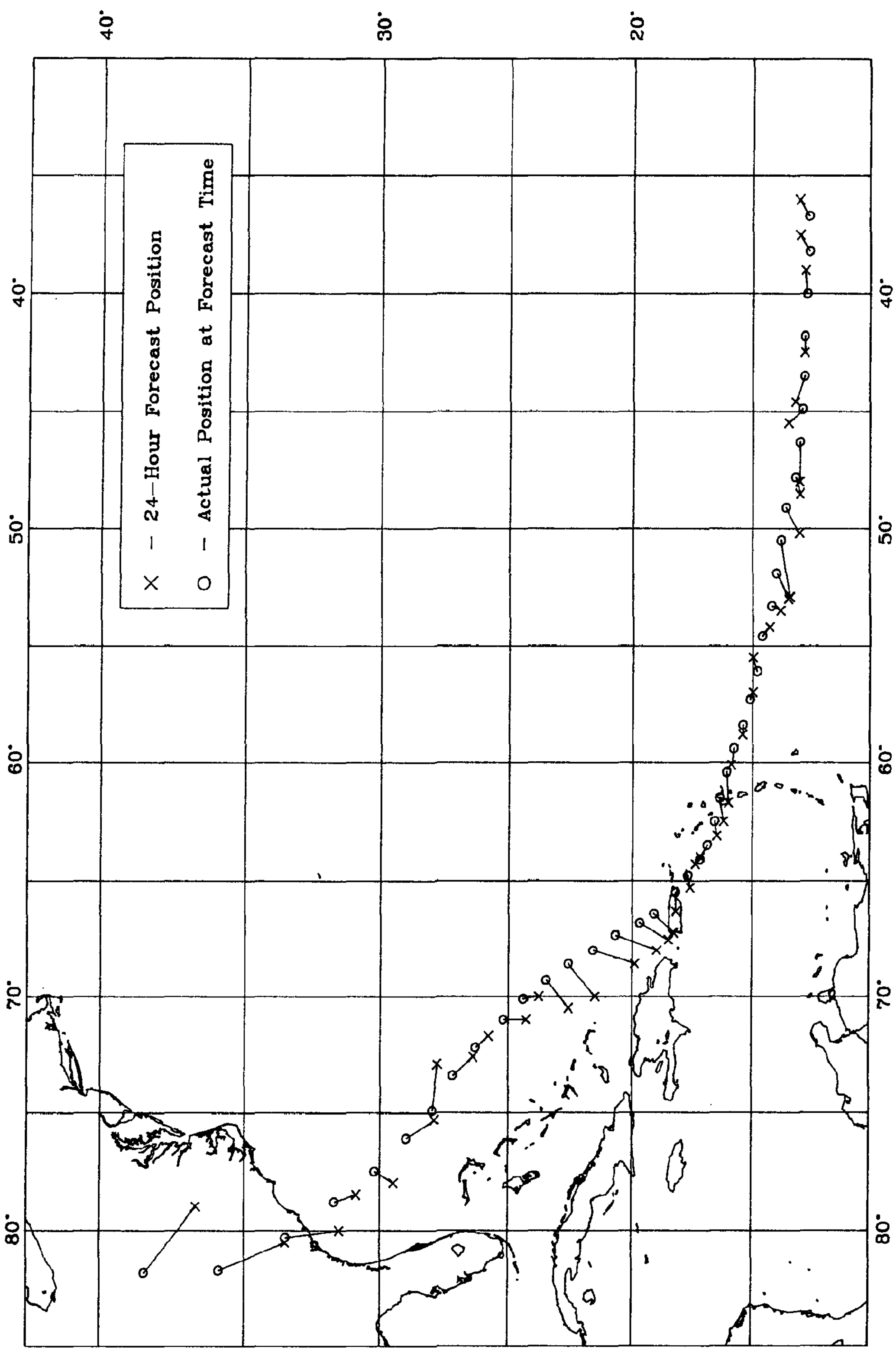


Figure 4-4. Track forecast errors for the 24-hour forecast position of Hurricane Hugo. The forecast location and the verifying actual position are connected by a line.

Culebra where the maximum wind on the east side of the eyewall rushed seawater inland.

The forecast for the Carolina coast was for surges from 14 to 17 feet. East of Charleston, surges of 16 to 18 feet were measured with a high storm tide (storm tide is the storm surge plus the astronomical tide) of 20.4 feet.

Measured High Water Levels

Astronomical tides for the periods around landfall in the Charleston area indicated that high tide would occur about 2 AM Friday, September 22. With landfall expected around midnight, the astronomical tide level at that time would be about a foot above mean sea level (ASL).

If Hugo made landfall over Sullivans Island, storm surges should have peaked to the right at approximately the storm's radius of maximum wind. Aircraft reconnaissance showed the radius of maximum wind to be about 30 miles during most of Thursday afternoon, September 21, but dropping to some 20 miles just before landfall.

With this radius of maximum wind, the highest surges should have occurred in Bulls Bay, a sparsely populated area between Charleston harbor and Cape Romain.

After most major hurricanes, the Corps of Engineers surveys high water marks caused by the hurricane and maps areas inundated by salt water. Both the U.S. Geological Survey and the Corps surveyed high water marks from Hugo's surge.

Some preliminary high-water marks were obtained. The tide gauge at Charleston measured 11.3 feet mean low water (MLW), approximately 9.5 feet NGVD. This observation is questionable, however, since there was roughly a foot of water inside the gauge-house. At the Custom House only a hundred yards or so away, a high-water mark of 11.5 feet was measured. At McClellanville, high-water marks of 16 to 18 feet were measured. The highest surge appeared to be at Awendaw, just a few miles southwest of McClellanville, where a value of 20.4 feet was measured. Figure 4-5 illustrates the spatial distribution of the storm tide while Figure 4-6 shows the storm tide as estimated along the immediate coast.

WEATHER SERVICE OFFICES -- LOCAL STATEMENTS AND WARNINGS

Puerto Rico/Virgin Islands

WSFO San Juan has no subordinate Weather Service offices. Therefore, the WSFO issues all HLSs for the Virgin Islands and Puerto Rico. HLSs usually are issued immediately after NHC advisories. When a storm nears the coast, NHC advisories normally are issued every 3 hours.

During Hugo, NHC began to issue 3-hour interval advisories at 9 PM Friday, September 15. WSFO San Juan followed suit by issuing 3-hour interval HLSs. To ensure that information was available as soon as possible, WSFO San Juan disseminated NHC advisories on NWR in English and Spanish immediately on receipt. Anticipating the first NHC advisory, a draft HLS already had been prepared in AFOS which then required only a limited editing before dissemination in English and Spanish over both NOAA Weather Wire and NWR.

The HLSs issued from San Juan contained numerous action-provoking statements. Starting at midnight Friday, September 15, residents of the Virgin Islands and Puerto Rico were advised to prepare to implement their action plans and to evacuate if advised by CD or other government agencies. Particular emphasis was placed on St. Croix.

Potential flooding, storm surge and beach erosion also were highlighted. At 3 PM Sunday, September 17, coastal flood warnings were issued for the Virgin Islands and eastern Puerto Rico along with a heavy surf advisory for the northern, southern and eastern portions of Puerto Rico. Later that evening, coastal flood warnings and heavy surf advisories were expanded even further.

The midnight Sunday morning HLS urged Virgin Islands residents to heed evacuation orders and to contact VITEMA for more information about evacuations. This statement was included as MIC Matos had just been in contact with VITEMA. He stressed the need to begin preparations immediately so that orderly evacuations could commence by

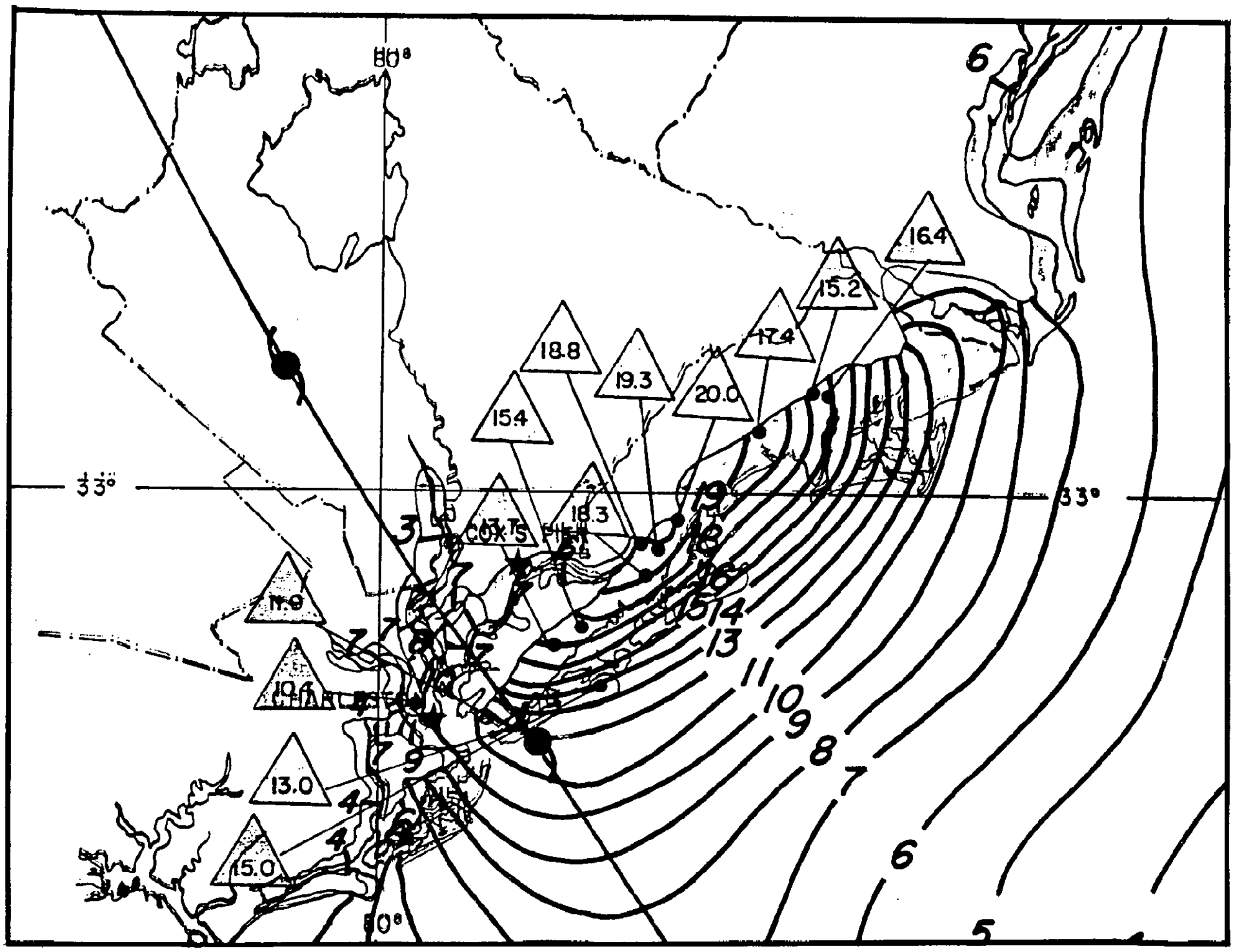


Figure 4-5. Spatial distribution of storm tides computed with the SLOSH model. The SLOSH model was run with preliminary "best fit" track and storm parameters several days after Hugo. Some preliminary high water marks are shown within triangles. All values of water level refer to National Geodetic Vertical Datum (NGVD).

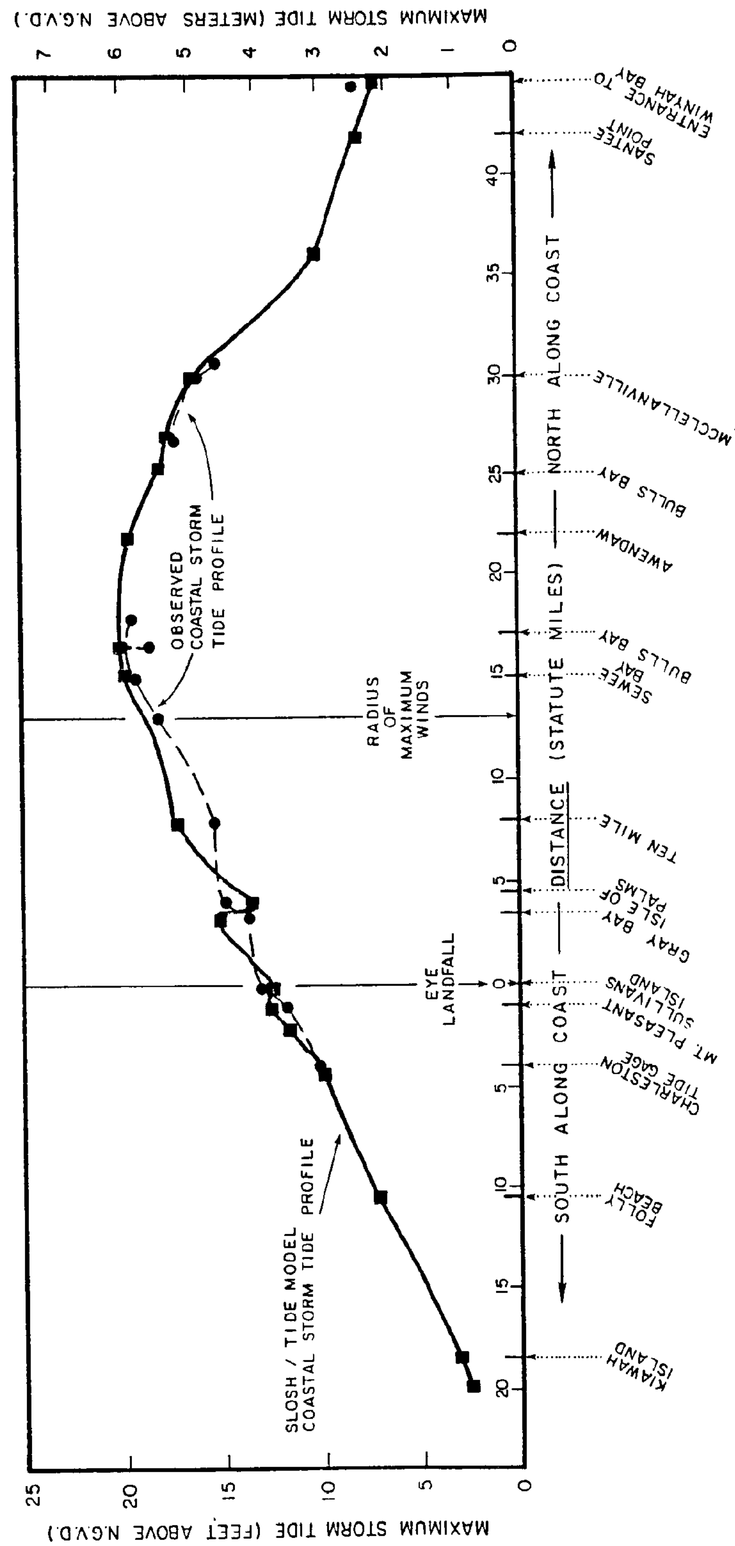


Figure 4-6. Distribution of storm tides along the South Carolina coast from Kiawah Island to Winyah Bay. The solid line represents the preliminary SLOSH run of Fig. 4-5. The dashed line connects values of observed high storm tide. Values are given in feet above NGVD.

sunrise. The 3 AM Sunday HLS urged Virgin Islanders to complete their emergency action plans by the afternoon and mentioned that shelters would open at 7 AM.

In the same advisory, Hugo's track was compared to Hurricanes San Felipe in 1928 and Betsy in 1956 both striking Puerto Rico. San Felipe severely affected the island. Both storms are well remembered and reinforced the urgency of taking appropriate action.

The 9 AM HLS also gave information on the opening of Puerto Rican shelters and contained vivid detail used to spur the public to action.

> **If the eye of Hugo moves across Puerto Rico as forecast, we can expect a 50-mile-wide path of extensive to extreme damage to occur. The storm surge will decimate the coastal section where it comes onshore. Then, hurricane-force winds will destroy wooden structures and uproot trees. Roofs could be removed and loose objects will become lethal airborne projectiles.**

Although NHC continued issuing advisories every 3 hours throughout the storm's passage over the islands, WSFO San Juan switched to issuing HLSs every 1 1/2 hours starting at midnight Monday, September 18. This effort, not trivial considering that separate versions had to be prepared in both English and Spanish, ensured that timely information on the storm and current evacuation information were available to citizens of the Virgin Islands and Puerto Rico.

When WSFO San Juan switched to 1 1/2 hour releases, information on the effects of the storm were included. Providing all this information resulted in long statements and a concern that the specific action statements might be lost due to their length. Accordingly, two public information statements (PNSs) were issued before the storm made landfall on Puerto Rico to ensure that critical information was readily available.

Finally, persons were urged to stay indoors following the wrath of the storm as downed power lines and mudslides would continue the threat. Individuals were also encouraged not to use their vehicles as roads would be impassable and their presence could impede disaster relief efforts.

WSFO San Juan's HLSs contained a high degree of specificity to give users as much information as possible. As mentioned in an earlier chapter, however, the inclusion of potential hurricane landfall areas for an island as small as Puerto Rico implied an accuracy greater than present forecast capabilities allow. This could have posed a problem with local decision-makers had not the WSFO coordinated so well with its users.

South Carolina -- WSFO Columbia

WSFO Columbia began highlighting the hurricane watch in the public and marine forecasts at 6 PM Wednesday, September 20, and to heighten awareness, a PNS was also issued. Shortly thereafter, the Governor's recommendation for a voluntary evacuation was aired on NWR.

A flash flood watch was posted for the coastal zones and the midlands of South Carolina at 4 AM Thursday. A hurricane warning for the entire coast was included in the 6 AM public and marine forecasts as well as in a 5 AM PNS while a high wind warning was issued for the midlands. At 8 AM, a flood potential outlook for most of the state was issued along with a PNS relaying the Governor's evacuation order for the South Carolina coast. Just before 2 PM, the flash flood watch was extended to include all of South Carolina.

The WSFO began issuing HLSs approximately every 4 hours beginning at 3 PM, Thursday, September 21, emphasizing high wind warnings and the flood potential. The HLSs specified watches in effect at the time including tornado watches that had been issued by the NSSFC.

At midnight, WSFO Columbia began issuing HLSs for WSO Charleston following a power failure there. The WSFO continued to issue separate HLSs for both its own county warning area and that of WSO Charleston throughout the night. Emphasized were high winds and the dangerous situation that existed with downed trees and power lines. Backup support to WSO Charleston also consisted of preparing Charleston's HLSs as well as relaying weather observations and providing supplementary radar surveillance.

WSFO Columbia provided quantitative precipitation forecast (QPF) support to the River Forecast Center (RFC) in Atlanta. In return, RFC Atlanta furnished contingency river forecasts to WSFO Columbia based upon its QPFs.

WSO Charleston

MIC Shenot began preparations for hurricane operations as early as Monday, September 18. Additional hydrogen for balloon runs and fuel oil for the generator were ordered. Supplies for the station, such as water, flashlights and batteries, were checked. New telephone handsets were placed on the NWR monitoring line and the upper air telephone line so they could be used as telephones when not needed for dedicated use.

On Wednesday, September 20, HAM operators were requested to set up operations while the office's Wide Area Telephone Service (WATS) telephone line was dedicated for incoming emergency calls. Finally, the airport was notified to secure windows in the Weather Service Office. All preparations were completed on Thursday as the station switched to emergency power.

WSO Charleston issued its first HLS at 6:30 PM Wednesday when the watch became effective. This was done primarily to provide information to residents of the area on actions needed to prepare for the storm later in the week. Additional statements followed at 9:30 and 11:10 PM.

The WSO began issuing HLSs every 3 hours at 5:50 AM Thursday when the warning went into effect for the South Carolina coast. Statements accentuated the need for action to prepare for hurricane landfall in the next 12 to 24 hours. As the day progressed, HLSs began to contain more of an urgent flavor and highlighted risks and types of hazards involved. The final two statements were issued at 9 and 11:10 PM as the storm neared and crossed the coast.

Shortly after midnight, the dedicated AFOS telephone line went down, but all other telephone lines remained in operation. The station had to implement backup operations with WSFO Columbia. All other equipment was still operating and the staff was able to phone observations to Columbia for entry into the AFOS system.

Shenot maintained contact with emergency management officials and the media as the storm approached the coast and continued so long as communications were available.

North Carolina -- WSFO Raleigh

Amateur radio operators were alerted to begin regular operations at the Weather Service offices around the state and to set up the HAM network on Thursday, September 21. The North Carolina Division of Emergency Management assigned a liaison to WSFO Raleigh for 48 hours before and after the storm.

WSFO Raleigh is responsible for providing QPF support to the RFCs at Slidell, Louisiana, and Atlanta. These QPF amounts were based on previous hurricane tracks across North Carolina but were overestimated in the east when the track bore further west than forecast by NHC. These QPFs were also factored into contingency river forecasts by the RFCs in WSFO Raleigh.

The Acting MIC and the Warning Preparedness Meteorologist each worked 12-hour shifts as the WSFO hurricane coordinator for the state since both are familiar with the state hurricane plan. This coordinator was also responsible for contacting the other two coastal offices and briefing them on the hurricane coordination calls with NHC. One additional forecaster was scheduled to work all shifts to assist in disseminating information and in preparing analyses and forecasts. Two meteorology student volunteers from North Carolina State University worked at night to assist with telephones and NWR.

A flash flood watch was issued at 6 AM Thursday covering the state for that night and Friday. This was followed by a flash flood statement at 1:30 PM that also dealt with the possibilities of tornadoes and high winds over the state's central and southeastern sections. Similar statements were issued at 5:30 and 9:15 PM. A high wind warning was issued at 10 PM for the east-central portion of the state again based on the forecast turn to the north. The high wind warning was extended at 3:15 AM into the western sections of the state as it became obvious that the storm center was tracking further west than expected.

Although the storm's center was tracked by radar at Columbia and Charleston, this equipment is a 5 cm surveillance (conventional) radar and is not capable of determining radial velocity. In addition, the storm's track traveled through a data-sparse area of South Carolina. The high winds thus were not anticipated as far inland as they occurred. Figure 4-7 shows the path of Hugo through the Carolinas and the resulting damage swath. Appendix E illustrates the direction of the damaging winds across the Carolinas from Hugo as determined from a post storm aerial survey by Dr. Ted Fujita of the University of Chicago.

Had the planned NEXRAD been available, it could have provided wind information on the storm as it moved through the Carolinas. ASOS planned for this area would have provided forecasters with continuous accurate rainfall, weather conditions and wind velocity observations on a real-time basis in data-sparse regions.

FINDING 4.2: NWS radars neither have the capability of measuring wind velocity nor can they integrate information horizontally and vertically in storms. This meant that much information had to be inferred or was not available for the warning process when Hugo moved over data-sparse areas.

WSO Charlotte

OIC Kuhn contacted emergency management coordinators in his 11-county area of responsibility on Thursday. He alerted them to the possibility of high winds, heavy rains and tornadoes if the storm tracked into North Carolina's southern Piedmont.

Further, Kuhn advised officials to use a winter storm plan or winter storm contingency if there were no specific plans for high wind warnings in their counties. Coordinators received additional briefings shortly after 2 AM Friday to alert them to high winds. Special weather statements were issued at 2 and 4 AM focusing on the high wind threat. A number of additional statements were issued to keep the public informed of the situation through the morning on a 1- to 3-hour basis.

The Mecklenburg County emergency management coordinator reported to the Emergency Operations Center at 3 AM, an hour after receiving the high wind threat alert. The hour's lead time enabled the city to mobilize road crews, cancel school, assign police to traffic control and dispatch power trucks to critical areas.

Wind gusts of more than 87 MPH and sustained winds of more than 65 MPH toppled trees over much of Charlotte. Damage was extreme as power outages became widespread and roads blocked. Emergency management estimated $750 million in damages in Mecklenburg County alone. The EBS failed shortly after 4 AM due to the high winds. Before this incident, warnings and statements were issued on EBS and NWR as well as NAWAS. NWR was used extensively in disseminating warnings in the county.

Other North Carolina WSOs

WSO Wilmington issued HLSs following the NHC bulletins. The staff briefed local coordinators and provided information to coastal decision-makers.

Coastal area coordinators used NWR extensively to monitor the storm's progress. Several commented that the amount of information broadcast on NWR compelled them to listen for long periods of time until they obtained the latest coordinates to be used in their "decision arc" techniques.

WSO Asheville issued five flash flood and special weather statements for high winds in its county warning area. The staff also issued two flash flood warnings for the several counties in the North Carolina mountains. Rains over 6 inches fell in some areas resulting in several streams exceeding bankful and washing out several bridges. The warnings and the watch proved accurate and helpful in the mountain counties. There were reports of several tornadoes in the mountains and widespread trees down due to high winds. WSO Greensboro issued two urban and small stream flood warnings for the northern mountains

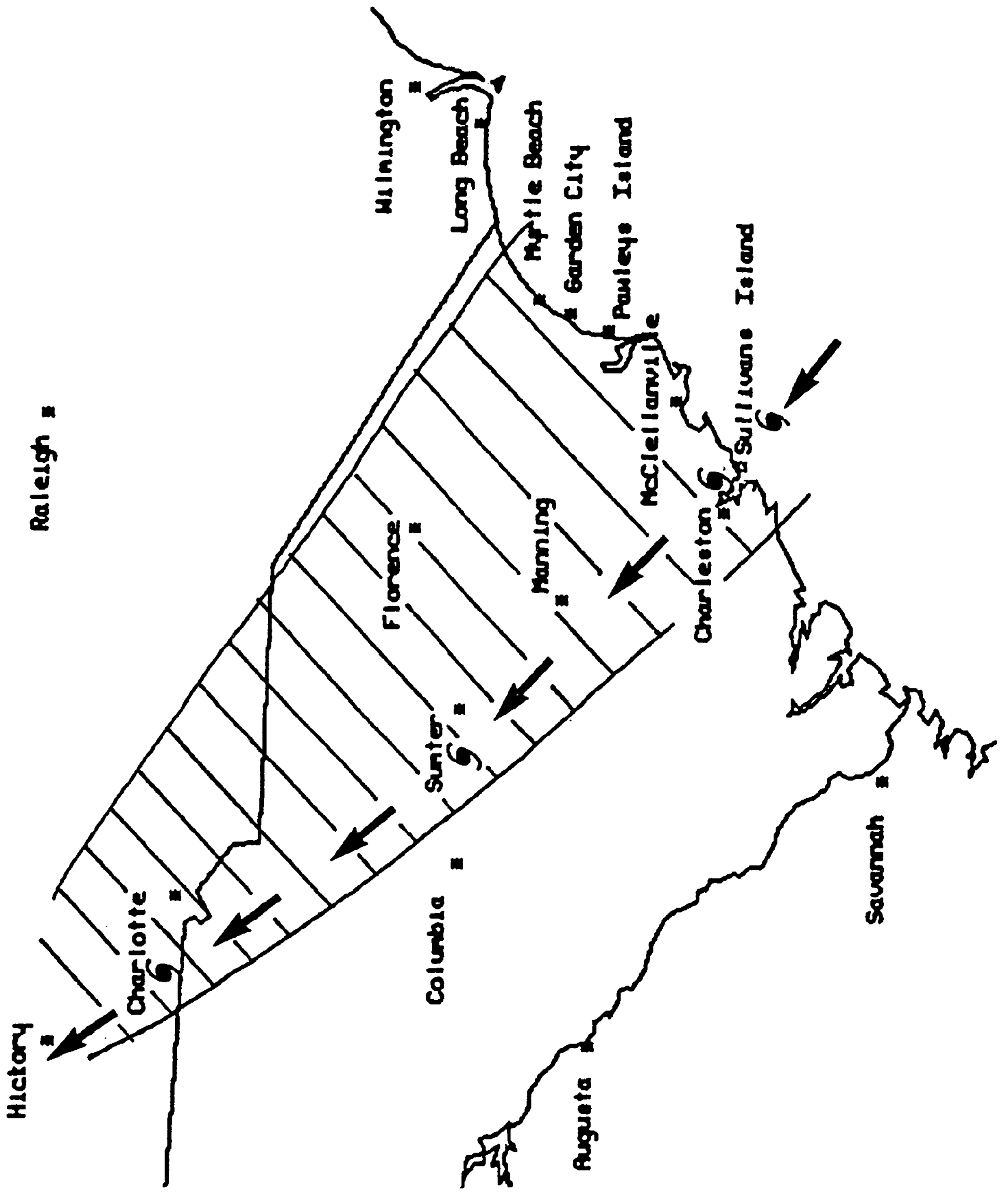


Figure 4-7. Track of storm center of Hurricane Hugo inland across South Carolina and western North Carolina. Hatch area is approximate area of significant damage resulting from storm.

in its county warning area. A number of statements were issued on the high wind warning that covered most of the area Thursday night and Friday.

Statements were issued by WSO Cape Hatteras frequently during the storm although there was no serious threat to this area from Hugo. A few decision-makers used voluntary evacuation in some counties when northeast winds brought high waters to several coastal communities Thursday afternoon.

Flooding

Despite Hugo's fury that made it the most damaging storm of this century, rainfall amounts were such that flooding was relatively minor. Rainfall totals averaged between 4 to 9 inches both in the Caribbean and over the U.S. mainland with isolated amounts in excess of 10 inches. Most major flood damage was inflicted on coastal areas as a consequence of storm surges and not rainfall.

Puerto Rico/Virgin Islands

Rainfall reports in Puerto Rico ranged from 5 inches in Arecibo on the north coast to 10.6 inches at Fajardo and to a maximum of 13.55 inches at the Lower Rio Blanco gauge in the northeastern mountains (Fig. 4-8). About 7 inches were measured at WSFO San Juan. The winds there, however, were strong enough that the gauge may not have collected all of the rainfall.

Rainfall across the Virgin Islands was difficult to assess as many of the rain gauges were damaged or missing. Available data from cooperative observers indicated rainfalls of 6 to 9 inches in the U.S. Virgin Islands with a maximum of 11.2 inches at Ham Bluff Lighthouse on the northwest coast of St. Croix. Other significant amounts were 9.08 inches at Caneel Bay Plantation in northwestern St. John and 5.2 inches at Water Isle off the south coast of St. Thomas. The Water Isle reading appears to be an underestimate when viewing the radar imagery for that area.

Concerning rivers in Puerto Rico, information from the U.S. Geological Survey showed that historical peak flows at a number of sites were exceeded. The Rio Fajardo (drainage area 15.9 square miles) probably peaked above the October 24, 1974, historical maximum of 19,600 cubic feet per second (cfs).

Another gauge, the Rio Mameyes near Sabana (drainage area 6.88 square miles), peaked at approximately 20,000 cfs exceeding the September 4, 1973, peak by about 200 cfs. Three other stream gauging stations in the nearby basins of Rio Espiritu Santo, Rio Sabana and Rio Icacos had peak discharges that ranged between 38 and 90 percent of former peaks of record. All of these rivers are located in northeast Puerto Rico just east of San Juan (Fig. 4-9).

Flash flooding was reported along the Rio Pita Haya and the Rio Espiritu Santo in northeastern Puerto Rico.

A major killer in Puerto Rico is the mudslides which can occur after heavy tropical rains. Although the potential for mudslides during Hurricane Hugo was great, none was reported.

Advisories from NHC began highlighting the threat of 5 to 10 inches of rain at 6 PM Friday, September 15. By 6 PM the next day, the potential for large amounts over higher terrain was mentioned. The threat of flash floods and mudslides was introduced in advisories at 6 AM Sunday, September 17, and were slowly escalated until, as the storm was making landfall, NHC advisories targeted Hugo as presaging upwards of 15 inches of rain and extensive flash floods and mudslides.

Rivers in Puerto Rico are short, steep and prone to flash floods. Little more than 6 hours is needed for a crest to develop in the mountains and reach the ocean. Accordingly, no specific stage forecast values are generated as the crest would most likely occur before a specific forecast could be produced.

WSFO San Juan is not directly supported by an RFC. Accordingly, the WSFO must generate its own flash flood guidance values. The numerical model used to generate its flash flood guidance is run on a weekly basis. The flash flood guidance

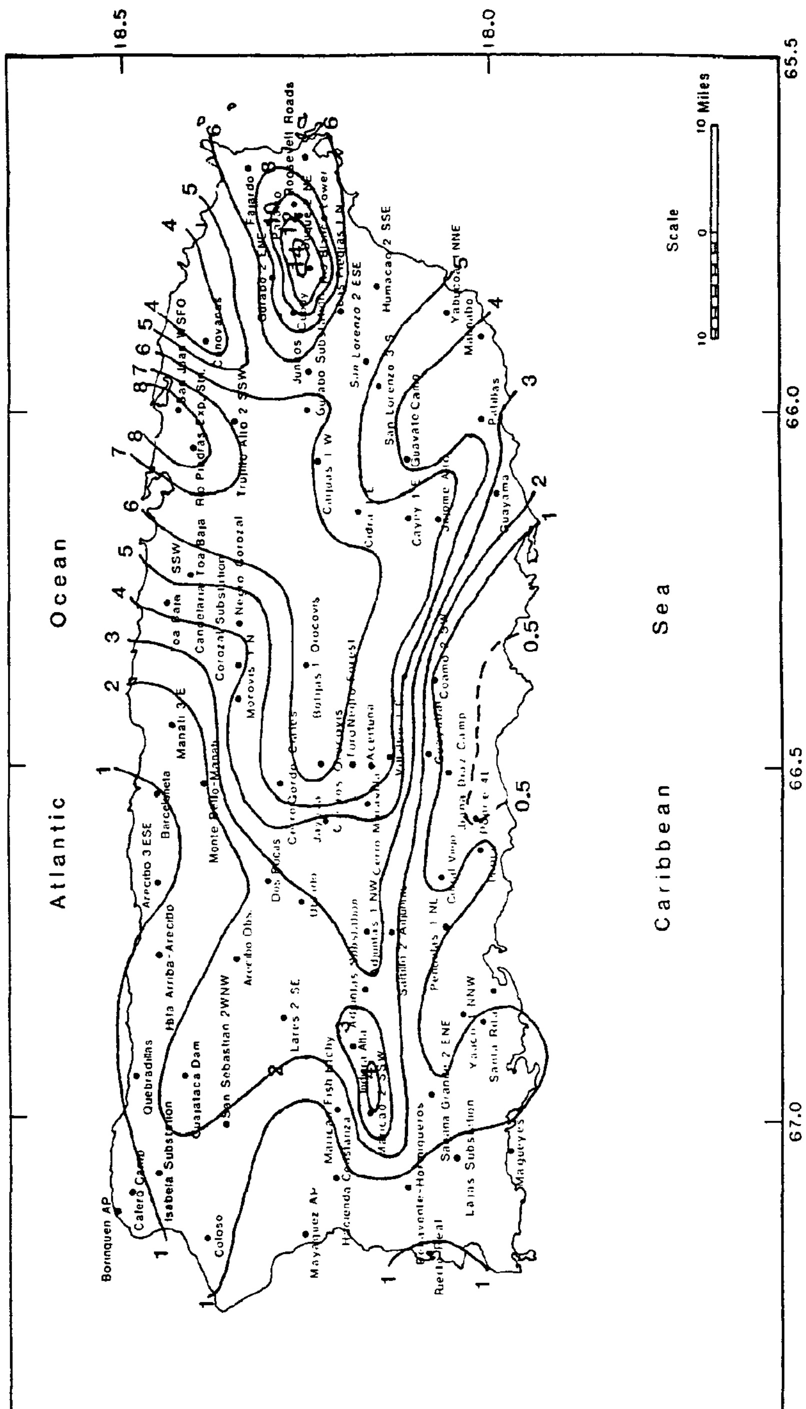


Figure 4-8. Hurricane Hugo rainfall (inches) for Puerto Rico.

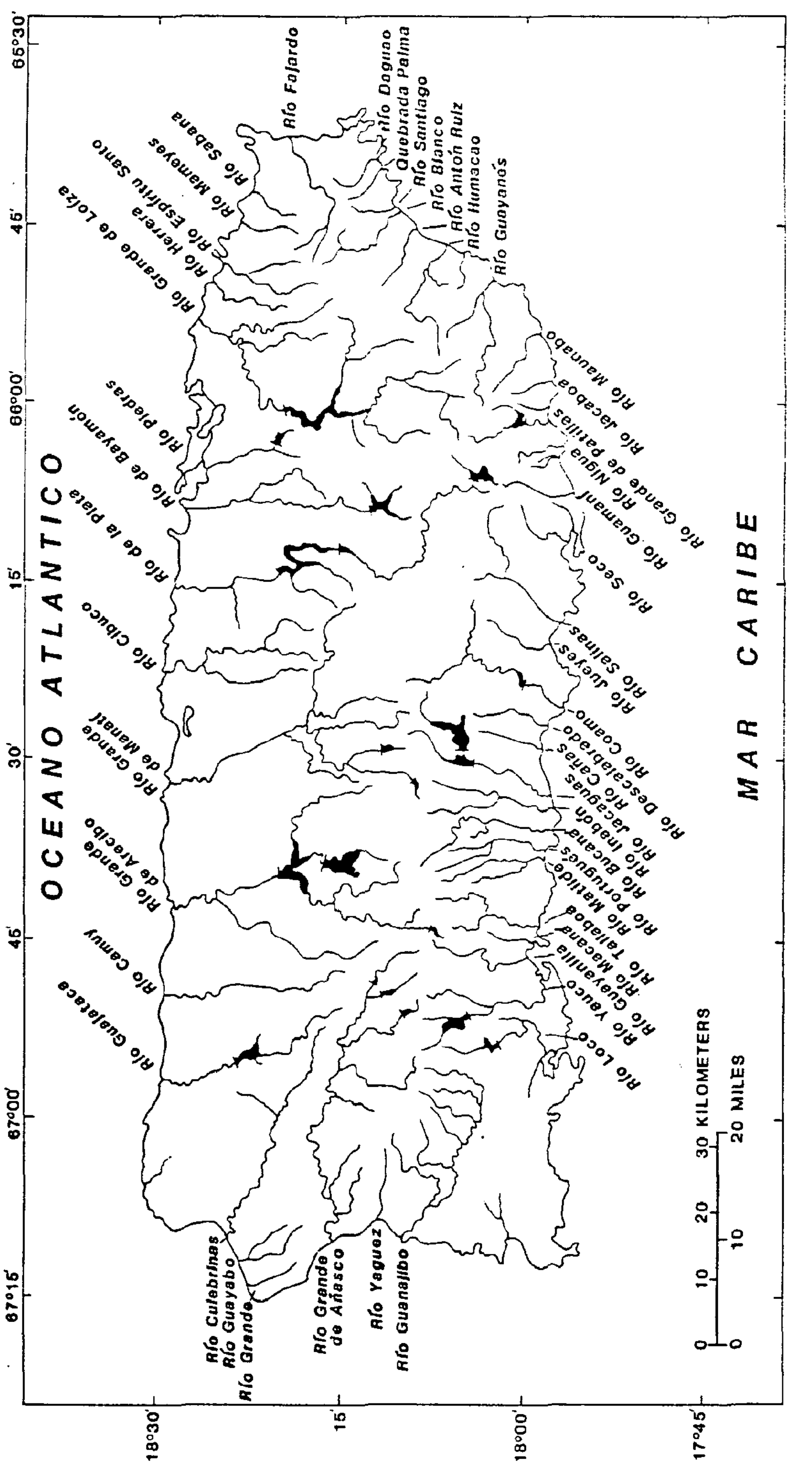


Figure 4-9. Major river systems of Puerto Rico.

available to the office was run September 8. It indicated that most areas were saturated and that 3 inches of rain in a 3-hour period would be sufficient to cause flash flooding.

Flash flood watches were posted about 7 hours before heavy rains began in the Virgin Islands and about 15 hours before heavy rains began in Puerto Rico. Flash flood warnings were timed to begin shortly before the heavy rains moved over the watch areas. After heavy rains persisted for 4 hours or more, flash flood warnings were converted to flood warnings. Mudslides were highlighted in the statements although not to the extent NHC advisories did.

The Loiza River, one of the larger rivers in Puerto Rico, drains the northeastern sections of the island and feeds the Carraizo Dam whose reservoir is San Juan's water supply. After the ALERT systems' repeater failed, the WSFO staff maintained contact with the Carraizo Dam personnel to keep them apprised of Loiza Basin rainfall from the gauges that remained available. As it was, water flooded pumps that resulted in a loss of water to San Juan and the airport, including WSFO San Juan, for more than a week.

South Carolina

Hugo came ashore at Charleston minutes before midnight Friday, September 22. The storm moved quickly to the northwest, passing to the east of Columbia about 3 AM Friday and then just west of Charlotte 3 hours later.

Rainfall amounts ranged from 6-plus inches near the south coastline to 2 to 4 inches over most of the rest of the state (Fig. 4-10). A maximum of 10.28 inches was recorded along the coast at Edisto Island. Charleston recorded 5.84 inches of precipitation and Columbia recorded 2.98 inches.

Flash flood watches were issued some 16 hours prior to landfall. Numerous HLSs, flood potential outlooks, river statements and flood forecasts were issued from early on September 21 through September 26 alerting the public to the dangers of flooding and issuing forecasts for specific locations.

North Carolina

Hugo entered North Carolina west of Charlotte around daybreak on September 22. It moved quickly northwest across the state, exiting over the northern mountains by noon. Rainfall totals generally ranged from 1 to 2 inches in eastern and western North Carolina to 3 to 5 inches in west-central North Carolina. Fig. 4-11 shows 48-hour rainfall totals for Hugo for the state.

Some individual rainfall totals, as measured by the IFLOWS gauges, approached 7 inches. Boone, North Carolina (Watauga County), measured 6.91 inches while Cone Ridge, North Carolina (Yancey County), measured 6.23 inches.

There was no major river flooding in North Carolina from Hugo -- rainfall totals simply were too small. There was, however, some minor flooding in the northern mountains of North Carolina, east and north of Asheville. Minor highway flooding occurred in Allegheny, Wilkes, McDowell, Mitchell, Surry, Stokes and Watauga Counties. Rises to near bankful occurred on the Roanoke River at Williamston.

Twenty-four hours before the storm's advent, a flash flood watch covered all of North Carolina. WSOs Asheville and Greensboro issued flash flood warnings that emphasized the possibility of heavy rainfall from Hugo and the flood dangers expected.

Virginia

In southwestern Virginia, small stream flood warnings were issued for 12 counties in the WSO Roanoke service area. Although the flooding was minor, the Virginia IFLOWS backbone communications network for southwestern Virginia failed. The IFLOWS communications network piggybacks on the Virginia State Police intrastate communications system. During the storm, one line-of-site repeater tower was toppled eliminating communications both for IFLOWS and the State Police. The Virginia State Police are investigating this incident to develop a fail-safe system.

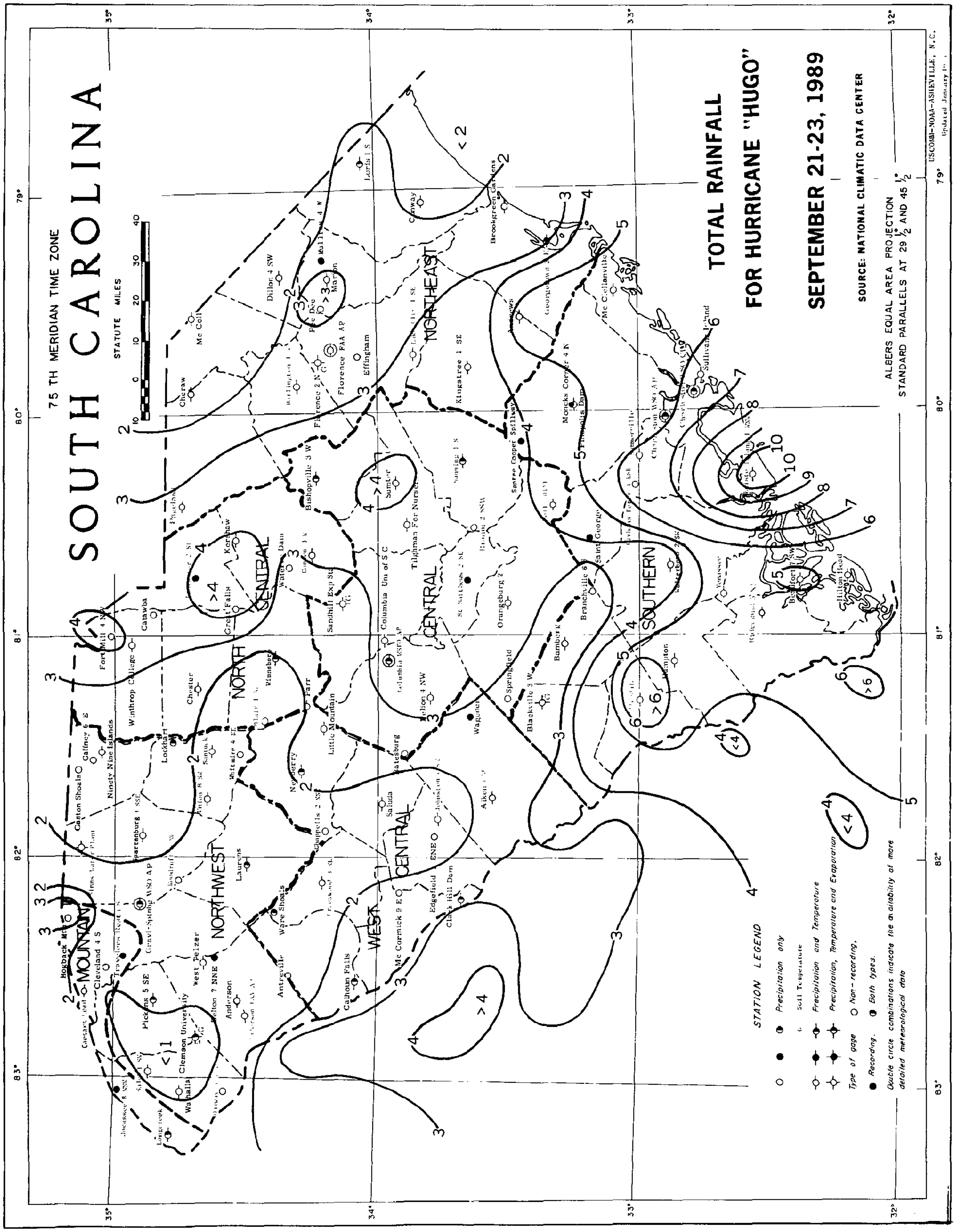


Figure 4-10. Hugo Precipitation Totals for South Carolina.

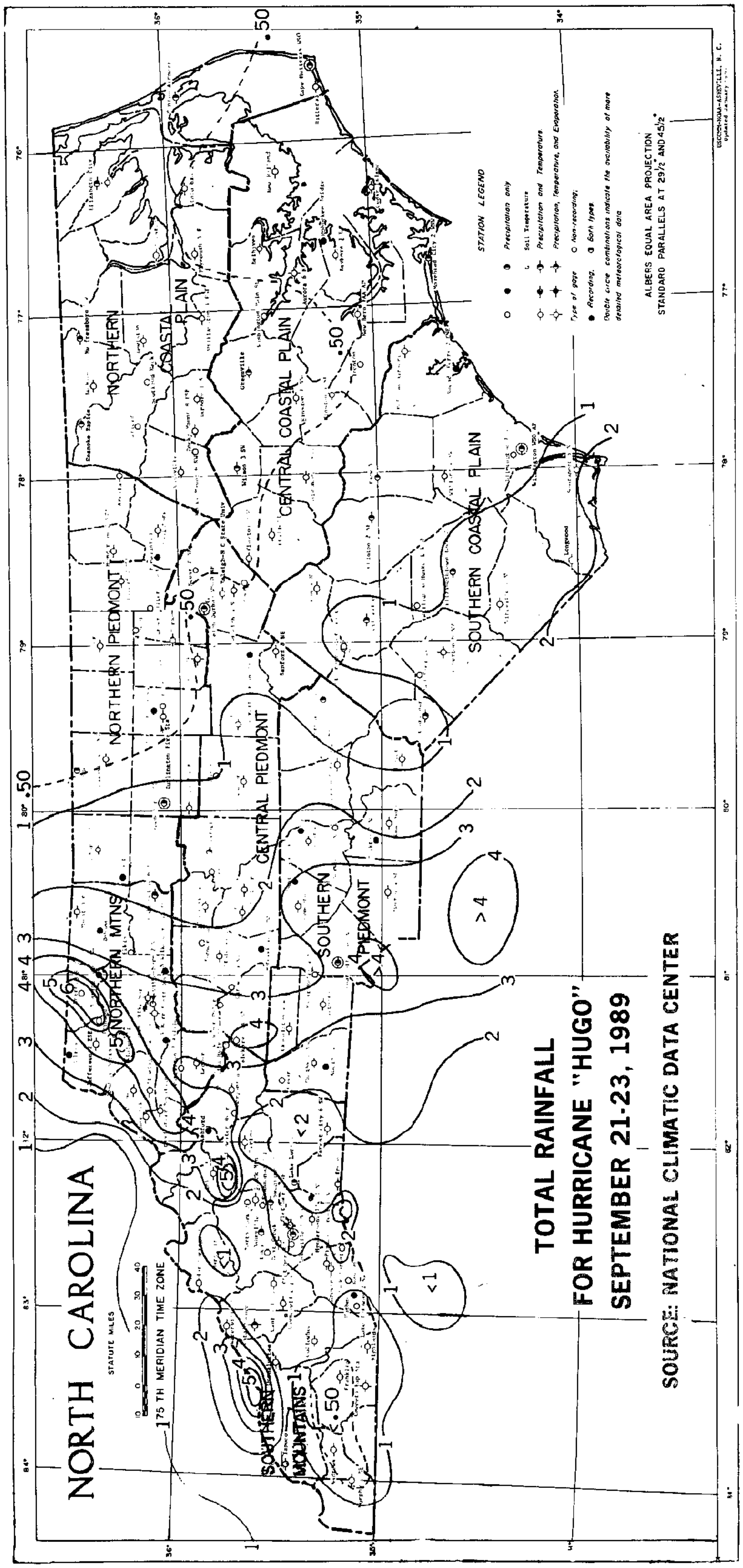


Figure 4-11. North Carolina Precipitation.

Local Office Working Conditions

Before, during and after the storm, NOAA personnel set aside their personal concerns to ensure that critical warning information was available to local officials and the general public and that local offices and equipment remained operational. This meant that they were away from their loved ones and property for an extended time without information about their safety. This was especially so in the cases of WSFO San Juan and WSOs Charleston and Charlotte where personnel were subject to considerable danger when high winds and rain struck their respective areas.

As the storm battered San Juan, rain was driven through the hurricane shutters posing an electrical shock hazard from the equipment. Windows began to bow from the winds and file cabinets were pushed up against them to keep them in place. The water supply failed shortly after the eye brushed the coast causing a loss of air conditioning and rest room facilities. This situation lasted for more than a week and caused extremely difficult working conditions.

At WSO Charleston, the station experienced damage to the roof when the main fasteners gave way as the winds increased to hurricane force. The roof began to buckle and MIC Shenot asked employees and visitors in the office to remain in the interior hallways away from the upwind side of the building. Glass on the doors at the northeast corner of the building were bowing inward from the wind pressure. It was feared that the glass would shatter and spray shards into the operations area.

When the eye passed over the station, it was possible to observe the damage to the building. The roof had buckled at many points. The inflation building was severely damaged and the door had been blown in. Winds shifted after the passage of the eye driving rain into the building through the weakened roof and into the operations area of the office. The staff used plastic sheeting to cover the radar and the AFOS equipment as well as the forms and logs that were being maintained on station.

Safe fresh water was not available and the lack of water pressure disabled pressure-valve flush toilets in the office for several days after the storm.

In both WSFO San Juan and in the Carolinas, hurricane duty meant working long hours without a break. All available personnel reported for duty and stayed on station for the duration of the storm. Weather offices do not contain facilities or sufficient area for sleeping so individuals rested or napped anywhere convenient. WSFO San Juan is located within the airport hotel building. Rooms were provided for the staff during Hugo although no water, rest rooms or air conditioning were available. Shifts were frequently 12 hours or more in length with no days off for up to 10 days. When individuals returned to their homes, some found them in considerable disarray. Fortunately, no employees or members of their families suffered serious injury.

FINDING 4.3: In all offices affected by the storm, employees remained on duty with only a minimum of food storage facilities, cooking and refrigeration capabilities and virtually no personal hygiene facilities or temporary sleeping area. Most offices did not contain a safe and secure area for the protection of employees from high winds.

RESPONSE OF THE MEDIA

Coverage of NHC

NHC responded to a multitude of requests for storm information from local, national and foreign electronic and print media. The initial wave of six television cameras and crews from the Miami area grew to a flood of news interests that descended on NHC on Sunday, September 17, when Hurricane Hugo smashed Guadeloupe and the British and U.S. Virgin Islands. All TV networks, along with major news providers, were represented. Interviews were conducted at 5-minute intervals through a busy 18-hour period.

Dr. Sheets and key NOAA personnel called for a local, regional and network pool that became effective by 5 AM Monday, September 18. Working smoothly and cooperatively, the pool ended when Hugo dissipated inland late Friday night, September 22.

During 8 days of coverage, a total of at least 700 spots originated from NHC. Dr. Sheets handled 70 percent of them while the rest were handled by hurricane forecasters. Interviews were restricted to 5-minute segments with exceptions only for special network hurricane programs.

Meriting special mention was coverage by Spanish-language stations, WLTV-23 and WSCT-TV, serving Greater Miami and through their networks, Univision and Telemundo, serving Spanish-language stations throughout the country. Their effective coverage was aided by the NHC in providing Spanish-speaking meteorologists whenever possible.

LOCAL MEDIA COVERAGE

Puerto Rico/Virgin Islands

While not equipped with as much sophisticated equipment and weather information sources available on the U.S. mainland, electronic and print media organizations on Puerto Rico and the U.S. Virgin Islands provided extensive coverage of Hugo. Media concentrated all-out coverage 2 days before the hurricane made landfall at St. Croix and Puerto Rico.

Television coverage was provided by the four stations on Puerto Rico and the four in the Virgin Islands. None has a professional meteorologist. Most stations do not use NOAA Weather Wire relying mainly on the Associated Press (AP) and the United Press International (UPI) wires.

With nearly 100 stations operating on Puerto Rico, radio played a key role in keeping citizens advised on hurricane developments. WKAQ, which has access to the NOAA Weather Wire, is designated as the EBS station for the island and also covers the Virgin Islands. WSTX, St. Croix, and WVWI, St. Thomas, also serve as EBS stations.

WKAQ, which must request EBS activation through the Commonwealth CD, did so eight times before Hugo made landfall. Once activated, WKAQ's EBS broadcasts were broadcast by other radio stations. WKAQ provided timely and credible information to Puerto Rico and the Virgin Islands.

In preparing for Hugo's arrival, the hub of activity was WSFO San Juan. Three TV channels dispatched camera crews to WSFO San Juan while one channel elected instead to send a crew to the Commonwealth CD office. In addition, several radio stations broadcast from the WSFO. No camera or equipment pooling arrangements were made and interviews with the WSFO staff were conducted on an as-needed basis. The office is short on space and lacks a good location to accommodate the cameras and equipment for the media. The spirit of cooperation between the two groups ensured amicable and effective operations.

About 150 interviews were conducted by the WSFO San Juan staff with media representatives throughout the islands and on the U.S. mainland. MIC Matos and John Toohey-Morales, who were interviewed the most, stressed that errors up to 60 miles were possible in the forecast track for Hugo. Their statements helped keep Puerto Rico and the Virgin Islands at their highest readiness.

A significant EBS broadcast took place Sunday around 11 PM. That broadcast included Rafael Hernandez Colon, Governor of Puerto Rico; Heriberto Acevedo, Commonwealth CD Director; and MIC Matos. Matos presented the meteorological situation and introduced the Governor who urged all individuals to take the warning information seriously. The Governor then introduced his CD Director who outlined the appropriate response actions.

The Governor's timely action reflected his faith in the forecasts and information provided by the NWS. Coordination among the Governor, local emergency management officials and the NWS resulted in one of the most successful evacuations ever conducted in Puerto Rico. Public response was also heightened in the Virgin Islands due to EBS activation and live broadcasts by Alexander Farrelly, Governor of the Virgin Islands and William Harvey, Civil Defense Director.

Most TV stations signed off around midnight Monday morning, but Channel 24 remained on the air with 15-minute updates until it went off the air at 7 AM Monday. WKAQ and two radio stations broadcasting from WSFO San Juan stayed on the air throughout the hurricane. In the Virgin Islands, 24 hour coverage throughout the storm was provided by radio station WSTA St. Thomas which can be received in St. Croix.

Media representatives did not attempt to second guess the NWS. NHC advisories and HLSs were available to them, and they reported developments without putting "a twist" or "a spin" on them. Media personnel relied heavily on telephone contact with the NWS staff. They regarded NWS at WSFO San Juan and the NHC as authoritative and reliable.

The Carolinas

As South Carolina braced for Hugo's landfall, the broadcast media continued to air the NHC bulletins but local stations began to shift emphasis more to local NWS sources. HLSs, bolstered by NHC advisories, were monitored carefully.

There are four Charleston area commercial television channels. One employs its own meteorologist. Most media representatives were assigned on the day of Hugo's landfall to Emergency Preparedness Headquarters which was in constant communication with WSO Charleston. One TV channel camera crew aired storm coverage from WSO Charleston until less than 90 minutes before Hugo's arrival.

Media representatives were satisfied with the quality of NWS weather information especially noting NOAA Weather Wire and NHC's use of hurricane probabilities. They reserved their most eloquent praise for local Weather Service staff. This emphasis underscored their confidence in NWS employees (who lived and worked in communities under Hugo's threat) as intrinsic to full and accurate coverage of the storm.

For example, News Director Jack Jones said the South Carolina Radio Network relied heavily on NWS information. He said the NWS and NHC reports especially were important in covering Hugo since the network provides 5-minute broadcasts updated on the hour. Jones lauded NWS and NHC performances. His network services 57 stations or more than half of those in the state.

Educational Television (ETV) stationed camera and crew at the Emergency Operations Center and used NWS and NHC weather information extensively in their broadcasts and updates. It provided pool coverage for the Governor's office and broadcast the Governor's evacuation orders. Besides feeding commercial TV, ETV operates eleven TV and seven radio transmitters. News and Public Affairs Director Tom Fowler praised the quality of NWS weather information and noted that an ETV artist used graphics prepared from NWS data for TV charting of Hugo's track.

In South Carolina, the NWS is authorized to activate the EBS during weather emergencies. WSO Charleston activated the system at 5:52 AM Thursday, September 21. WXTC in Charleston is the primary station and rebroadcasts to other commercial outlets.

MIC Shenot said normally there is only one activation. After that, stations receive weather information through their usual channels and broadcast at their discretion. Shenot said a major development in the weather situation could lead to NWS activating this system again. This was unnecessary during Hugo.

Two events -- one national and the other local -- departed from the otherwise excellent media coverage. An incident concerning Hilton Head Island drew the most criticism. A network evening newscast portrayed island residents as dismayed and frightened by lack of evacuation planning. A local Hilton Head Island reporter dismissed the account and noted that the evacuation was successful and without incident.

The other event involved a TV channel in eastern North Carolina where its meteorologist emphasized the prediction of a more northward course for Hugo. Lower coast residents, responding to the TV presentation, pressured officials into opening public shelters. Local officials described the unnecessary opening of the shelters as a good test of their sheltering capabilities.

RESPONSE OF THE EMERGENCY MANAGEMENT COMMUNITY

Puerto Rico and Virgin Islands

All elected officials and emergency managers interviewed, including the Governor of Puerto Rico, the Mayor of San Juan and CD Directors of the Commonwealth, San Juan and St. Croix, categorically stated that the coordination between them and the WSFO San Juan was outstanding. This coordination ensured that local officials had the information needed to make prompt, effective decisions. Properly informed leaders meant that the public was provided authoritative information on appropriate procedures to safeguard their lives and property.

Both the Commonwealth CD and San Juan Municipio CD offices have NOAA Weather Wire and NWR. They also receive NWS broadcasts on their portable radios they carry with them in the field. Commonwealth CD Director Acevedo Ruiz also has NWR in his car.

Most other municipio CDs do not have a drop on the weather wire or on NWR. The city of Ponce on the south coast, however, is one of the few other municipios that does have NWR. The Commonwealth CD office fans out weather information to the municipio CDs by a radio link.

VITEMA headquarters are located in Charlotte Amalie, St. Thomas, the capital. On St. Croix, the Vice Governor and VITEMA offices are located in Christiansted. Information from NWR is relayed by radio to St. Croix from VITEMA headquarters in St. Thomas. NOAA Weather Wire is also available.

During the storm, WSFO maintained frequent telephone contact with the Commonwealth and San Juan CD offices and VITEMA headquarters. All CD officials interviewed by the survey team mentioned that direct contact with WSFO staff was most important in helping them to assess the impact of the storm on the area.

For the highly successful EBS broadcasts in Puerto Rico, the WSFO had to request activation through the Commonwealth CD office. The working relationship with CD in Puerto Rico allowed the dramatic inclusion of the Governor into the broadcast.

Active discussions with CD also ensured that timely evacuation orders were formulated. Shortly after midnight Sunday, September 17, Matos advised Commonwealth CD that planning should begin then to ensure an effective evacuation order by 6 AM.

Similarly, government officials on St. Thomas, St. Croix and St. John were advised at 9:15 PM Saturday that evacuation needs should be addressed and evacuations be completed by 10 AM Sunday. CD Director Harvey stated that an evacuation order was issued and that the people took it seriously.

Communications were maintained to all CD offices throughout the storm. Those to St. Croix, however, were lost during the height of the storm shortly after midnight Monday, September 18.

The Carolinas

Key officials and emergency managers in the path of Hurricane Hugo received much of their weather information through the NOAA Weather Wire, NWR and by monitoring broadcast news media. Direct personal contact coupled with the confidence and trust that these local officials place in the NWS cannot be overstated. Emergency management coordinators and most decision-makers lauded actions of NWS offices and the Weather Service in general. Among comments was that Hugo was the best-handled hurricane they experienced. South Carolina's Adjutant General offered glowing praise as did the North Carolina State Emergency Operations Officer.

Starting Tuesday, September 19, WSFO Columbia maintained regular contact with the State Emergency Preparedness Division and briefed the county EPD directors on Hugo's expected path. Thus, state and county officials could begin their own alert and planning processes. Further, WSFO Columbia notified the American Red Cross' Hurricane Watch District in Columbia.

In North Carolina after initial briefings with the Governor's staff on September 20, WSFO Raleigh's acting MIC met separately with the Secretary of

Crime Control and Public Safety and Director of Emergency Management. Ultimately, the state emergency agency put a full-time liaison into WSFO Raleigh.

Emergency management agencies, in turn, used NWS information to guide preparations tying them to evacuation planning, public information and decisions on when and where to open shelters, to position police and National Guard troops on evacuation routes and to make other assignments.

One dramatic example of how the NWS worked with elected officials and emergency managers was when MIC Palmer in Columbia talked with Governor Carroll A. Campbell, Jr., of South Carolina on Wednesday evening, September 20. During that discussion, he suggested that the Governor call for a voluntary evacuation before the hurricane warning was posted. Palmer advised him that the warning would be issued the next morning, that landfall would take place Thursday night and that the hurricane probably would be higher than Category 2.

Acting on Palmer's advice, the Governor issued a voluntary evacuation recommendation for all South Carolina beach communities. He urged local officials to help arrange voluntary evacuation and provided National Guard assistance. The Governor also asked that persons in shelters closer to the coast be moved further inland since a high storm surge was expected. These actions eased traffic problems when the mandatory evacuation order was issued the following morning.

Emergency managers also attested to the value of how well the "decision arc" program worked in their planning efforts. However, most of them commented that though objective methods such as these were valuable, they still contacted their local NWS meteorologists to confirm their conclusions. When confronted by conflicting information, whether from the objective schemes or from outside sources, they turned to their local NWS office for guidance.

A coastal community police chief in northern South Carolina told survey team members, "Thursday afternoon, I heard on a North Carolina TV station that the storm was coming ashore between Myrtle Beach and Murrells Inlet. I called Dick Shenot (Charleston MIC) and he told me that the storm was still coming at Charleston. I put my faith in Dick Shenot's advice."

In Charlotte, the County Emergency Management Coordinator pointed out the value of the Thursday phone call by Charlotte's OIC. His call on the high winds provided an hour's lead time so Charlotte officials could mobilize. Further, the official said the forecast of heavy rains was used by the power company to release water from the hydroelectric dam reducing flood risk in the area. Sue Myrick, the Mayor of Charlotte, also commented on the importance of NWS weather information to her city.

The only known criticism from government officials or emergency coordinators came from the Mayor of McClellanville (the town which was swamped by a huge storm surge). Although many of the residents evacuated before Hugo hit, the Mayor wanted to know why NWS did not warn of the hurricane's danger. The Mayor is a member of the Local Area Emergency Council but did not attend the meeting the night before the storm arrived.

The Mayor was among several hundred who took shelter at the high school that was inundated by storm surge waters. Unfortunately, this shelter -- as described previously -- was the one listed with the erroneous elevation. Residents managed to remain above the waters until they subsided. Several other shelters suffered roof and wall damage.

<u>FINDING 4.4</u>: The public receives most of its warning information from the media. During Hugo, both NHC and the local offices worked exceptionally well with the media. This ensured that timely, consistent and credible information was issued.

<u>FINDING 4.5</u>: In both the Caribbean and the Carolinas, emergency managers coordinated frequently with their local NWS offices. They initiated calls to gather additional information, to corroborate their own decisions and to receive guidance.

<u>FINDING 4.6</u>: NWS offices in the affected areas served a most important role in saving lives. The personnel of these offices knew local conditions and

local emergency managers. They interpreted for these emergency managers the implications of NHC advisories and the appropriate local response. The best public response occurred where there was the strongest working relationship between the NWS and the local emergency management community. Participation by the Governors of Puerto Rico and South Carolina in the evacuation decisions and in broadcasts resulted from the close working relationship between the NWS office and the Governors' offices.

FINDING 4.7: The EBS in Puerto Rico can only be activated through the Commonwealth CD. In many other EBS areas, the local NWS office may directly request activation of the EBS system for weather emergencies.

Delivery of drinking water, Puerto Rico. Photo courtesy of Joseph Golden.

Chapter V

PUBLIC RESPONSE AND USER BENEFITS

OVERVIEW

The successful public response during Hurricane Hugo is a result of efforts begun in 1974 when NWS created its disaster preparedness program throughout the Nation. Together with the NOAA Public Affairs Office, awareness materials in the form of brochures, films, slides and public service announcements were created and distributed widely. Annual preparedness meetings were conducted in coastal communities with local emergency managers, the media and citizens' groups. These activities, sponsored regularly over the past 15 years, were greatly responsible for public response in evacuations as Hugo neared and, hence, for the low loss of life. Previous Category 4 hurricanes, striking the Virgin Islands, Puerto Rico and the U.S. mainland, have resulted in loss of life by the hundreds.

The successful evacuations and low casualty rates reflect the growing sophistication and team efforts of the NWS and the emergency management community. Years of coastal planning and development of SLOSH models and the building of evacuation plans around them have created a mutual trust and credibility. These cooperative efforts of NWS, the Corps of Engineers, FEMA and regional and local groups have been buttressed by awareness campaigns and exercise drills, which have resulted in the high degree of public responsiveness.

A critical factor in the success of warning and evacuation efforts in both the Caribbean and the Carolinas was the fact that Matos, MIC at San Juan, and Palmer, MIC at Columbia, were able to talk directly to the respective Governors and key aides as well as to state and county emergency managers. As a result, they were able to provide the timely guidance needed for evacuation-related decision making.

Guided by timely, understandable NWS information, news media that did not second guess official information, and knowledgeable and credible local officials and emergency management agencies, people moved when told to do so. By and large, they found evacuation routes cleared and shelter facilities ready and available if they sought them. In a life-saving sense, the NWS/emergency management relationship had come of age.

PUBLIC RESPONSE

Puerto Rico/Virgin Islands

Governor Colon of Puerto Rico, along with Hector Luis Acevedo, the Mayor of San Juan, and Luis Island, the San Juan Civil Defense Director, proclaimed the public's response to warnings for Hugo as a success story. The NWS shared the evacuation burden with local emergency managers both in Puerto Rico and the Virgin Islands. At 9:15 PM Sunday, September 17, WSFO San Juan asked VITEMA to begin planning so evacuations could start at sunrise. Similar scenarios took place in Puerto Rico with the Commonwealth CD and San Juan CD Directors.

The close association between WSFO San Juan and local government was mirrored by the WSFO and media relationship. A constant stream of weather information was provided to the public and decision-makers in both Spanish and English. Weather and official evacuation instructions and other pertinent information were issued by the NWS, the Commonwealth CD and VITEMA to the media for public dissemination.

Government and media representatives said the Hugo evacuation was the best coordinated weather event they could recall. The fact that at least 30,000 people evacuated in Puerto Rico, including areas such as San Juan's La Perla, is a credit to everyone involved. Citizens obviously had been convinced of the danger. A total of 217 shelters were opened in Puerto Rico and the Virgin Islands. An official Red Cross tally put shelter population at more than 161,000.

The Carolinas

As was so in Puerto Rico and the Virgin Islands, the combination of a timely and credible forecast-warning system, coupled with close NWS cooperation with emergency managers, was cited as the key to successful evacuations in advance of a powerful storm. The voluntary evacuation begun on Wednesday evening, September 20, was credited to Dr. Wayne Beam of the South Carolina Coastal Council as saving lives on the vulnerable barrier islands.

The result: thousands of people began moving inland that evening more than 24 hours before Hugo's landfall. Charleston County EPD Director, Dennis Clark, recalled that by midnight Wednesday, a full day before the storm crossed the coast, an endless stream of headlights could be seen crossing the Cooper River Bridge into Charleston as people left coastal towns and barrier islands. They were responding both to the Governor's widely broadcast statement and corollary official public information.

At 6 AM Thursday when a hurricane warning was posted for the South Carolina coast, the Governor's evacuation order for the barrier islands and the coast became mandatory. Charleston County was excepted. The Governor specified that evacuation be completed by 3 PM.

More than 186,000 persons left their homes. Only a few diehards stayed behind. Evacuations took place from Hilton Head Island to Myrtle Beach. Only two persons were believed drowned in their homes, a remarkable fact considering the depth of the storm surge.

Charleston residents actually responded to the voluntary evacuation of the Governor. A subsequent mandatory evacuation was issued by Charleston Mayor Joseph P. Riley, Jr. Fearing a tremendous storm surge, Riley ordered evacuation of all one-story buildings.

Survey team members visiting Sullivans Island and the Isle of Palms a week after Hugo's landfall found extensive damage. The surge had destroyed many houses and poured over the pews in the Stella Maris Roman Catholic Church. A woman who evacuated came back to see what was left of her home. Looking at neighbors trying to salvage remains, she said of the NWS, "These people are alive because of you." Similar sentiments were expressed by many other residents of storm-battered areas.

Although Charleston coastal areas had not experienced a major hurricane in at least a decade, public reaction in evacuating so expeditiously was a tribute to the continuing awareness efforts of WSFO Columbia's Preparedness Meteorologist and the MICs of Columbia and Charleston. It served also as a tribute to the continuing awareness and preparedness efforts at the county EPD and local Red Cross chapters.

Supporting public reaction to Hugo warnings was a media-driven awareness of what the storm had done in the Caribbean and saturation warnings through the media. An indicator of public acceptance of NWS and emergency management information supplied by the media is illustrated by the Public Hurricane Hotline (1-900-410-NOAA). In 1985, Hurricane Gloria resulted in 587,000 calls. In 1988, Hurricane Gilbert produced 140,000 calls. In contrast, Hurricane Hugo drew only 94,000 calls.

Generally, county emergency managers planned for the worst. Typically, they laid plans on the basis of a storm a category higher than the one predicted officially.

At Myrtle Beach, people moved from one shelter to another on higher ground long before the tidal surge arrived. If there was any criticism of the warning information by emergency managers and public officials, it was that, at one point, the probabilities for Myrtle Beach were higher than for Charleston and that the storm never did move north along the coast.

In both Carolinas, the response of emergency managers and public officials was overwhelmingly positive to NWS forecast information. Again, the emphasis on hurricane probabilities of Hugo's landfall was cited frequently as helpful. Working relationships between state and local officials, and the NWS were perceived as excellent. This perception included many rural counties that obtained weather information through NOAA Weather Radio, CD or the media rather than from personal contact with NWS staff.

The most vocal example of this working relationship came from Charleston County EPD Director Clark. He told the survey team that he accepted his job because of his belief in the support he would receive from Shenot, MIC at Charleston. The Red Cross, for example, credited timely weather information with impelling its opening of hurricane watch offices that coordinate responses of local chapters. Ultimately, the organization opened 397 shelters in the Carolinas accommodating some 80,000 evacuees for at least a night.

The Charleston Port Authority, whose operations were severely affected by the storm, was joined by other organizations in praising the NWS weather information. Included in issuing the plaudits were the South Carolina Climatology Office which assigned two staff members to act as weather liaison at EOC and the Governor's command post, the South Carolina Coastal Council and the military.

Perhaps, the most telling comments came from two South Carolina officials. Warren Tompkins, the Governor's Chief of Staff, said, "The information we received was key to helping the Governor decide to urge early evacuation." Governor Campbell's official evacuation statement was included in all subsequent NWS issuances. The State Adjutant General, T. Eston Marchant, who commands the National Guard and Emergency Preparedness Department, said, "On a scale of 1 to 10, you are a 10. If the Governor hadn't made that decision, we could have lost 3 to 5 thousand people.... The warnings and evacuation couldn't have been done any better."

Several emergency managers and public officials remarked that, even with the successful evacuation, there were problems in getting escape routes adequately policed and shelters supplied and staffed in time for the first evacuees. They suggested that announcing a hurricane warning usually is the action that triggers state and local evacuation decision making (a voluntary evacuation in South Carolina preceded the mandatory order) and urged that NWS warnings be issued with longer lead times. These officials said this would permit more timely preparations for the evacuation.

Unfortunately, the present state of the science is such that hurricane forecast errors preclude the issuances of warning with longer lead times. Local decision-makers must use hurricane probabilities in connection with their evacuation plans to determine when actions need to be taken. If their areas require a long evacuation time, preparations for evacuations may have to be taken before a warning is issued. Local emergency managers rely heavily on weather information from local NWS offices. Modernization of NWS will ensure that areas served by future NWS offices will have the technology and meteorological capabilities to provide even more site specific information directly to emergency managers. This should enhance the decision-making capabilities of public officials.

Finally, although watches and warnings were timely and information on the storm was readily available, some persons still could not fathom the magnitude of the danger. Even though storm surges of 12 to 17 feet were forecast along the South Carolina coast, frequent responses from local residents were, "We didn't think it (Hugo) would be this bad!" Regardless, most people understood that Hugo was going to hit their communities even if they did not anticipate its magnitude.

<u>FINDING 5.1</u>: Even though much information is made available to the public, people still cannot adequately appreciate what the forecast conditions mean until they have lived through a storm.

User Benefits

As in other hurricane episodes, the greatest user benefit from NWS was public safety. The storm was a potential killer of thousands. Early, informative advisories and serious public response nullified much of the storm's dangers to lives.

In analyzing further the response to Hugo, it was evident that the continued fine-tuning of the NWS hurricane forecast process and the Weather Service's working relationship with emergency managers, the media and the public produced the eventual payoff when the hurricane came ashore. The storm was in and the people were out -- out of danger.

What began as a cloudy image on a satellite photo had become a stream of headlights crossing Charleston's Cooper River Bridge or leaving low-lying areas of San Juan well before wind and heavy rain signaled it was too late.

For the emergency management community, the success of Hugo evacuations set a new standard for further planning and awareness efforts. Some day, with improved building standards, land-use laws and regulations and continuing evacuation planning, even fewer will perish when other hurricanes cross our coasts.

McClellanville fishing fleet, McClellanville, South Carolina.

Chapter VI

FINDINGS AND RECOMMENDATIONS BY CHAPTER

CHAPTER II: SUMMARY OF PREPAREDNESS ACTIONS, INFORMATION AND WARNING SERVICES

FINDING 2.1: Errors in base elevation information on shelters or evacuation routes could result in loss of life as evacuees move to unsafe shelters or through unsafe evacuation routes.

RECOMMENDATION 2.1: Coastal offices should encourage local emergency management officials to verify periodically the elevation and structural soundness of shelters prior to the onset of the hurricane season.

FINDING 2.2: A comprehensive evacuation study has not undertaken for Puerto Rico and the Virgin Islands.

RECOMMENDATION 2.2: A comprehensive evacuation study should be conducted for Puerto Rico and the Virgin Islands in concert with FEMA and the Corps of Engineers. Because of bathymetry of the area, a wave study should be part of this project.

FINDING 2.3: In its HLSs, WSFO San Juan referenced potential landfall sites with a degree of specificity that was greater than current forecast capabilities allow. Frequent coordination calls with users kept decision-makers from overly focusing on the forecast track.

RECOMMENDATION 2.3: In preparing HLSs, WSFOs should ensure that references to potential landfall areas realistically reflect the uncertainties involved.

FINDING 2.4: In both the Caribbean and the Carolinas, hurricane probabilities were used in varying degrees by decision-makers to incorporate forecast uncertainties in their planning efforts.

RECOMMENDATION 2.4: At annual workshops NHC should continue to emphasize to emergency managers current forecasting capabilities and limitations.

FINDING 2.5: In two hurricane advisories, the addition of two significant changes without reasons for these changes created some problems for emergency managers and the media.

RECOMMENDATION 2.5: NHC should include in its advisories underlying reasons for significant forecast changes. Understanding what the forecast means and reasons underlying forecast changes would increase the confidence of emergency managers and the media in the advisories used by NHC, thereby, enhancing vital cooperation between local NWS offices, local officials and the media. It also would heighten public awareness to changes which require additional public response.

FINDING 2.6: The lack of emphasis in NHC public advisories for the Carolinas on inland high winds left the media and local officials with little guidance on how to respond.

RECOMMENDATION 2.6: NHC should include in its public advisories sufficient plain language information on significant potential inland impacts contemplated to ensure a properly coordinated response by emergency managers and the media. Bearing in mind that local coordination is the key to effective local response, the NWS should develop policy and provide guidance to NHC, other national centers and field offices on how to provide timely, adequate information on the inland affects of hurricanes to WSFOs and to emergency managers.

CHAPTER III: DATA COLLECTION AND COMMUNICATIONS

FINDING 3.1: The density of surface observations in the Caribbean and the Carolinas is extremely low. This posed a significant problem to forecasters trying to obtain information during the storm.

RECOMMENDATION 3.1: ASOS should be implemented as a part of the modernization and restructuring program to provide cost-effective, reliable observations in data-sparse areas.

FINDING 3.2: A dedicated connection to the Roosevelt Roads radar would ensure full radar coverage for WSFO San Juan.

RECOMMENDATION 3.2: The NWS should investigate acquiring a dedicated drop on the Roosevelt Roads military radar for WSFO San Juan.

FINDING 3.3: A fully operational ALERT system for the Virgin Islands would assist the WSFO staff in preparing flood-related warnings and assist VITEMA in responding to flood situations.

RECOMMENDATION 3.3: The NWS, in concert with FEMA and VITEMA, should again explore the establishment of an ALERT system in the Virgin Islands.

FINDING 3.4: Limited NOAA Weather Wire drops in Puerto Rico and the Virgin Islands resulted in few emergency managers having hard copies of Weather Service products. This increased the need for coordination efforts at the local WSFO.

RECOMMENDATION 3.4: The NWS should work with FEMA to explore funding of additional critical outlets on the upgraded NOAA Weather Wire in Puerto Rico and the Virgin Islands.

FINDING 3.5: NWR reception is poor in the Virgin Islands.

RECOMMENDATION 3.5: The NWS should work with other interests in the Virgin Islands to establish an English-language NWR transmitter to provide broadcasts for the Virgin Islands.

FINDING 3.6: WSFO San Juan and most coastal WSOs are not on the Hurricane Hotline. Accordingly, they cannot participate in routine coordination calls with NHC, NMC and other coastal WSFOs.

RECOMMENDATION 3.6: The NWS should explore replacing the current land line Hurricane Hotline with a satellite coordination system that could link WSFOs, WSOs within 300 miles of the coast and national centers.

FINDING 3.7: Puerto Rico and the Virgin Islands have no dedicated coordination line between emergency managers and the WSFO. In the Carolinas, lack of NAWAS drops from adjacent states hampered coordination efforts across state boundaries.

RECOMMENDATION 3.7: The NWS should request FEMA to investigate the possibility of a communications system that would allow interstate as well as intrastate coordination between and among NWS offices and emergency management agencies.

CHAPTER IV: AN EVALUATION OF THE PROCESSING, INTERPRETATION AND DISSEMINATION OF NWS INFORMATION

FINDING 4.1: Aircraft reconnaissance is a necessary tool in hurricane forecasting.

RECOMMENDATION 4.1: Aircraft reconnaissance should be continued until other sensing platforms can provide data fields of equal accuracy and density.

FINDING 4.2: NWS radars neither have the capability of measuring wind velocity nor can they integrate information horizontally and vertically in storms. This meant that much information had to be inferred or was not available for the warning process when Hugo moved over data-sparse areas.

RECOMMENDATION 4.2: The NWS should continue to develop and deploy the NEXRAD Doppler Radar.

FINDING 4.3: In all offices affected by the storm, employees remained on duty with only a minimum of food storage facilities, cooking and refrigeration capabilities and virtually no personnel hygiene facilities or temporary sleeping area. Most offices did not contain a safe and secure area for the protection of employees from high winds.

RECOMMENDATION 4.3: Construction of future NWS offices in hurricane-prone areas should have hardened hurricane-proofed areas for personal safety. Reasonable amenities should also be provided including cots, limited shower facilities, kitchen facilities, refrigerators, emergency food supplies and backup toilet facilities.

FINDING 4.4: The public receives most of its warning information from the media. During Hugo, both NHC and the local offices worked exceptionally well with the media. This ensured that timely, consistent and credible information was issued.

RECOMMENDATION 4.4: NWS offices should continue to work with the media to ensure that each has an understanding of the other's responsibilities and requirements in the warning process.

FINDING 4.5: In both the Caribbean and the Carolinas, emergency managers coordinated frequently with their local NWS offices. They initiated calls to gather additional information, to corroborate their own decisions and to receive guidance.

RECOMMENDATION 4.5: Direct two-way links, that are not susceptible to outage during critical weather situations, should be provided between NWS and emergency management communications systems.

FINDING 4.6: NWS offices in the affected areas served a most important role in saving lives. The personnel of these offices knew local conditions and local emergency managers. They interpreted for these emergency managers the implications of NHC advisories and the appropriate local response. The best public response occurred where there was the strongest working relationship between the NWS and the local emergency management community. Participation by the Governors of Puerto Rico and South Carolina in the evacuation decisions and in broadcasts resulted from a close working relationship between the NWS office and the Governors' offices.

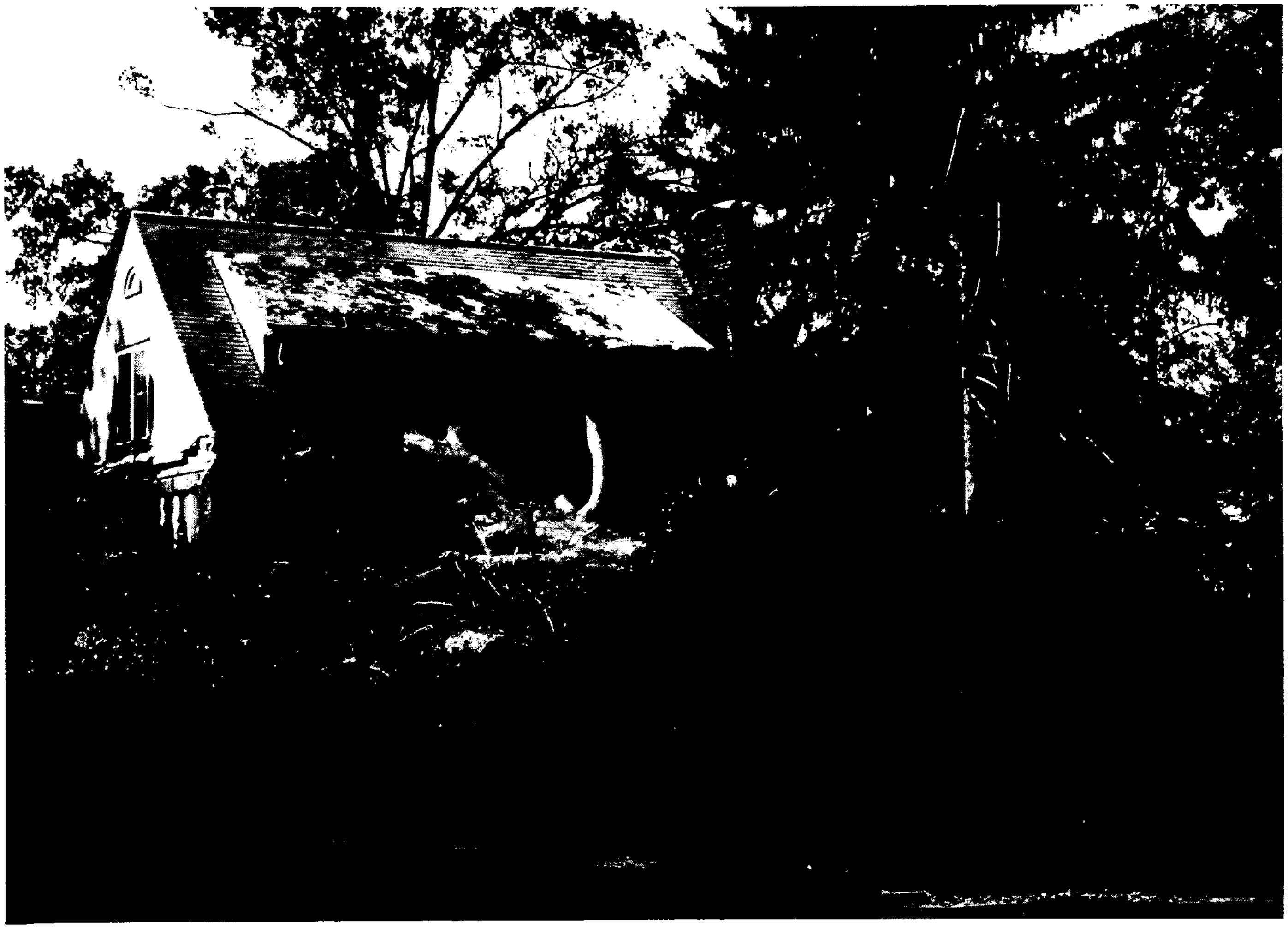
RECOMMENDATION 4.6: The NWS should encourage local offices to maintain the close relationship with state and local emergency managers including the Governor and state staff, the Mayors and the local and area emergency management coordinators. NHC advisories and Hurricane Hotline discussions should encourage that mutual respect and trust which proved so valuable during Hurricane Hugo.

FINDING 4.7: The EBS in Puerto Rico can only be activated through the Commonwealth CD. In many other EBS areas, the local NWS office may directly request activation of the EBS system for weather emergencies.

RECOMMENDATION 4.7: WSFO San Juan should investigate the possibility of acquiring authority to request EBS activation directly.

FINDING 5.1: Even though much information is made available to the public, people still cannot adequately appreciate what the forecast conditions mean until they have lived through a storm.

RECOMMENDATION 5.1: The NWS should continue to work with other agencies, the media and the private sector to increase the impact of hurricane awareness program by vividly portraying the devastating power of hurricanes and how to survive a hurricane.



Trees falling on homes were the major cause of damage in Charlotte, North Carolina.

Appendix A

SUMMARY OF RECORDED AND ESTIMATED SURFACE WIND SPEEDS IN HURRICANE HUGO

Recorded Surface Wind Speeds

Roosevelt Roads Naval Station, PR
Date = Sept. 18
Anemometer Ht. = 23 ft.
Peak Gust = 120 mph @ 7:58 AM
Max. Sustained Speed = 98 mph
Max. 10-Min Mean Speed = 76 mph @ 9:20 AM

WSFO San Juan, PR
Date = Sept. 18
Anemometer Ht. = 20 ft.
Peak Gust = 92 mph @ 7:52 AM
Max. Sustained Speed = 77 mph @ 7:50 AM
Max. 10-Min Mean Speed = 61 mph @ 7:50 AM

Charleston Naval Station, SC
Date = Sept. 21-22
Anemometer Ht. = 118 ft.
Peak Gust = 137 mph @ 11:30-11:45 PM, Sept. 21
Max. Sustained Speed = N/A
Max. 15-Min Mean Speed = 74 mph @ 1 AM, Sept. 22

Charleston (City Site), SC
Date = Sept. 21
Anemometer Ht. = 25 ft.
Peak Gust = 108 mph @ 11:40 PM
Max. Sustained Speed = 87 mph @ 11:30 PM

WSO Charleston Airport, SC
Date = Sept. 22
Anemometer Ht. = 20 ft.
Peak Gust = 98 mph @ 12:59 AM
Max. Sustained Speed = 78 mph @ 1:03 AM
Max. 10-Min Mean Speed = 59 mph @ 1:10 AM

Myrtle Beach AFB, SC
Date = Sept. 22
Anemometer Ht. = 15 ft.
Peak Gust = 76 mph @ 1:55 AM
Max. Sustained Speed = 52 mph @ 1:55 AM

Shaw AFB, SC
Date = Sept. 22
Anemometer Ht. = 15 ft.
Peak Gust = 109 mph @ 2:46 AM
Max. Sustained Speed = 67 mph @ 2:55 AM

WSFO Columbia, SC
Date = Sept. 22
Anemometer Ht. = 20 ft.
Peak Gust = 70 mph @ 3:27 AM
Max. Sustained Speed = 48 mph @ 3:50 AM
Max. 10-Min Mean Speed = 46 mph @ 3:20 AM

WSO Charlotte, NC
Date = Sept. 22
Anemometer Ht. = 20 ft.
Peak Gust = 87 mph @ 5:20 AM
Max. Sustained Speed = 46 mph @ 5:51 AM
Max. 10-Min Mean Speed = 38 mph @ 6:20 AM

Courtesy of
R. D. Marshall
Research Structural Engineer
National Institute of
Standards and Technology

ESTIMATED SURFACE WIND SPEEDS

Estimated as a reduction of aircraft observations and
700 mb analyses to surface values and
inferred speeds due to damage patterns

Location	Sustained (MPH)	Gusts (MPH)
St. Croix	132	161
Sts. Thomas/John	98	121
Vieques	109	132
Culebra	121	150

Courtesy of
Joseph Golden
Senior Meteorologist
Office of the Chief Scientist
NOAA

ESTIMATED SURFACE WIND SPEEDS

Location	Sustained (MPH)	Gusts
14°31'N,54°35'W (East of Guadeloupe)	160[1]	N/A
Bulls Bay South Carolina	135[2]	N/A

Courtesy of
Robert Sheets
Director, National Hurricane Center
NOAA

1 Estimated using step frequency micro wave radiometer aboard NOAA Research Aircraft.

2 Estimated from a reduction of observed flight level winds and the empirical pressure wind relationship.

Appendix B

SAFFIR-SIMPSON HURRICANE SCALE

This can be used to give an estimate of the potential property damage and flooding expected along the coast with a hurricane.

Category	Definition -- Effects
ONE	Winds 74-95 MPH or storm surge 4-5 feet above normal. No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery and trees. Also, some coastal road flooding and minor pier damage.
TWO	Winds 96-110 MPH or storm surge 6-8 feet above normal. Some roofing material, door and window damage to buildings. Considerable damage to vegetation, mobile homes and piers. Coastal and low-lying escape routes flood 2-4 hours before arrival of center. Small craft in unprotected anchorages break moorings.
THREE	Winds 111-130 MPH or storm surge 9-12 feet above normal. Some structural damage to small residences and utility buildings with a minor amount of curtainwall failures. Mobile homes are destroyed. Flooding near the coast destroys smaller structures with larger structures damaged by floating debris. Terrain continuously lower than 5 feet ASL may be flooded inland 8 miles or more.
FOUR	Winds 131-155 MPH or storm surge 13-18 feet above normal. More extensive curtainwall failures with some complete roof structure failure on small residences. Major erosion of beach areas. Major damage to lower floors of structures near the shore. Terrain continuously lower than 10 feet ASL may be flooded requiring massive evacuation of residential areas inland as far as 6 miles.
FIVE	Winds greater than 155 MPH or storm surge greater than 18 feet above normal. Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. Major damage to lower floors of all structures located less than 15 feet ASL and within 500 yards of the shoreline. Massive evacuation of residential areas on low ground with 5-10 miles of the shoreline may be required.

Appendix C

FUJITA TORNADO INTENSITY SCALE

Category	Definition -- Effects
(F0)	Gale tornado (40-72 MPH): Light damage. Some damage to chimneys; break branches off trees; push over shallow-rooted trees; damage sign boards.
(F1)	Moderate tornado (73-112 MPH): Moderate damage. The lower limit is the beginning of hurricane wind speed; peel surface off roofs; mobile homes pushed off foundations or overturned; moving autos pushed off the roads.
(F2)	Significant tornado (113-157 MPH): Considerable damage. Roofs torn off frame houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light-object missiles generated.
(F3)	Severe Tornado (158-206 MPH): Severe damage. Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off ground and thrown.
(F4)	Devastating tornado (207-260 MPH): Devastating damage. Well-constructed houses leveled; structure with weak foundation blown off some distance; cars thrown and large missiles generated.
(F5)	Incredible tornado (261-318 MPH): Incredible damage. Strong frame houses lifted off foundations and carried considerable distance to disintegrate; automobile sized missiles fly through the air in excess of 100 yards; trees debarked; incredible phenomena will occur.

Appendix D

SLOSH MODELING

Most segments of coastline have experienced few, if any, landfalling hurricanes. Intense hurricanes are rare. During this century, only two Category 5 hurricanes made landfall in this country -- the 1935 Labor Day Hurricane in the Florida Keys and 1969 Hurricane Camille which made landfall at Pass Christian, Mississippi. Massive devastation occurred in each area. What could happen in an area like Charleston from a major hurricane? How much flooding could be experienced? How far inland would flooding extend? These are some of the questions that can be asked of a numerical model.

The first step of a SLOSH simulation study is to choose representative hurricanes. The climatology of hurricanes that came within 50 nautical miles of Charleston was examined to choose representative hurricane characteristics, directions and forward speeds. Hurricane track directions were chosen as west, north, northwest and northeast. For each track direction, a series of parallel tracks were determined making landfall approximately 15 to 20 miles apart along the entire coast. One forward speed was selected for each of the track directions. For example, a 12 MPH forward speed was chosen for hurricanes moving in a northeasterly direction. Hurricanes of Saffir-Simpson Scale Categories 1 to 5 were simulated in the study. A total of 214 hurricanes were simulated in the Charleston simulation study.

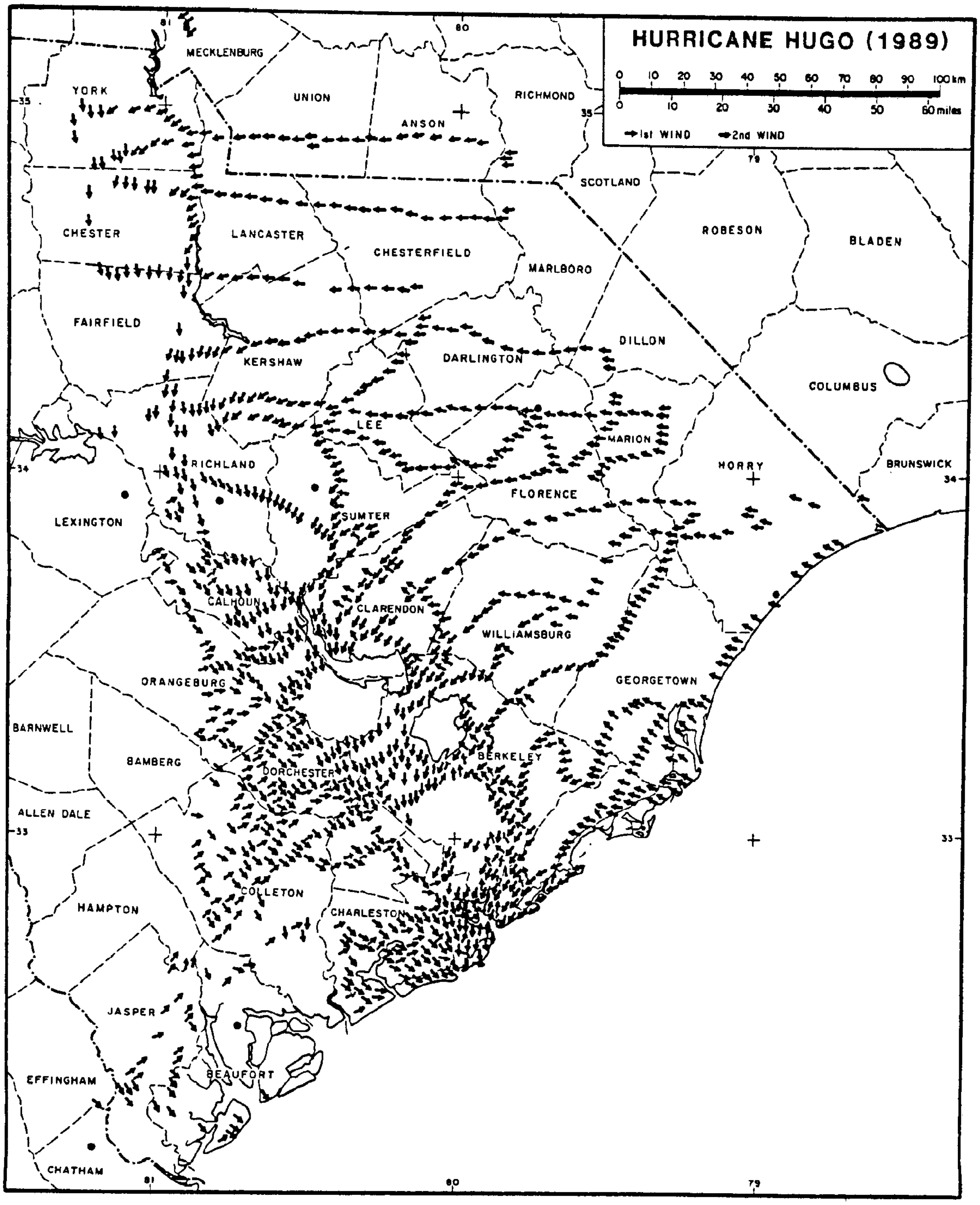
The SLOSH model creates a large volume of data from each "forecast" of a hurricane. In order for the model's results to be useful and practical, the massive amounts of data generated by a simulation run needed to be condensed. One such way is to composite the output from several similar SLOSH runs forming one "output" or map from many individual runs. This was done by producing MEOW maps. This composite is formed as the highest surge height at each SLOSH grid-square generated by any of the composited runs. Typically, a MEOW is created for all runs of a given category and track direction. For example, a MEOW is created from all northerly tracks of Category 2 moving at 20 MPH. The result is an overestimate for the flooding of any single hurricane of these characteristics but represents the potential flooding from this type of hurricane.

The MEOW concept has proven extremely useful in evacuation planning. When evacuation decisions need to be made -- roughly 18 to 24 hours in advance of the storm's landfall -- the NWS's forecast position has an average error of roughly 100 miles. NWS cannot say with precision that, in the next 24 hours, a hurricane will strike Charleston, Savannah or Myrtle Beach. The MEOW concept now takes on great significance. By evacuating for the MEOW, or potential flooding, the emergency manager is relatively certain that the proper segment of coastline is evacuated.

In reality, either of two conditions is examined to determine when an evacuation should be completed: when winds get to tropical storm force (40 mph) or when roadways become flooded. Tropical storm force winds are typically the cutoff for moving vehicles (especially those with large cross-sections) over bridges. The second condition -- flooding -- poses an obvious threat to vehicles moving through water. In most instances, tropical storm force winds are encountered first.

Appendix E

Direction of Damaging (All) Winds



Based on aerial mapping and photography on Sep.27 - Oct.2, 1989