Atlantic Hurricane Season of 1996

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ABSTRACT

A summary of the 1996 Atlantic hurricane season is given, and the individual tropical storms and hurricanes are described. This was the second active year in a row with a large number of intense hurricanes. Hurricane Fran, which hit the coast of North Carolina, was the strongest system to make landfall, and also the most destructive.

1. Introduction

For the second consecutive year, the Atlantic basin experienced above-normal hurricane activity. Of the 13 tropical storms that developed in 1996, 9 reached hurricane intensity. The two-year total of 20 Atlantic hurricanes in 1995 and 1996 is the highest ever recorded, going back to at least when accurate records began in the mid-1940s. Six of the hurricanes became ''major,'' that is, had maximum 1-min winds in excess of 49 m s^{-1} [category three or higher on the Saffir–Simpson Hurricane Scale (SSHS); Simpson (1974)] in 1996. This is three times the normal number and is the highest seasonal total of major hurricanes since 1961 (in which there were seven). Landsea (1993), however, has suggested that the major hurricanes in the 1940s through the 1960s were overestimated in wind speed intensity compared with those of the 1970s through the early 1990s. Landsea's bias-removed database suggests that 1996 was the busiest major hurricane season since the seven in 1950.

Every year, the National Hurricane Center (NHC, a component of the Tropical Prediction Center) produces a tropical cyclone ''best track'' database that consists of center positions and intensities every 6 h. These best track data are derived from position and intensity estimates using the following data: meteorological satellite imagery, reconnaissance aircraft reports, surface and upper-air observations (particularly surface ship reports), and (when the center of a tropical cyclone comes within a few hundred kilometers of the U.S. coastline) weather radar observations. The vast majority of satellite information during the 1996 season came from the geostationary satellite *GOES-8.* Position and intensity estimates using satellite data are obtained by using the Dvorak (1984) technique. Most of the aerial reconnaissance was accomplished by the ''Hurricane Hunters'' of the U.S. Air Force Reserve Unit. Reconnaissance aircraft are routinely deployed into Atlantic tropical cyclones that pose a potential threat to land areas. These aircraft observations are of vital importance to the tracking and forecasting of tropical cyclones and for the issuance of warnings, since aircraft provide more precise information on center location and intensity than satellites. It has been shown (Sheets et al. 1988) that Dvorak intensity and location estimates can differ significantly from aircraft estimates.

Table 1 lists the tropical storms and hurricanes of 1996, and Fig. 1 shows their tracks. As in the previous year, tropical cyclones tended to originate in the deep Tropics. All but two of the 1996 tropical cyclones developed south of latitude 20°N. Two hurricanes, Bertha and Fran, struck the United States near Wilmington, North Carolina. Two other systems, Tropical Storm Arthur and the extratropical Josephine, also passed close to Wilmington. Six hurricanes passed over the Caribbean or its adjacent land areas. This is the highest total of Caribbean hurricanes since 1916, even though each of the 1996 hurricanes was in that basin for a short period of time. Aside from Tropical Storm Gustav and Hurricane Isidore, all of the cyclones affected land.

Early in the season, it became clear that oceanic conditions over the tropical Atlantic basin were favorable for tropical cyclone formation. Figure 2 depicts the sea surface temperature anomalies for June and July of 1996. There was a broad area of warmer than normal surface waters over the eastern tropical Atlantic. This was likely a contributing factor for the development of tropical waves, emerging from western Africa near Cape

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TABLE 1. 1996 Atlantic hurricane season statistics.

Number	Name	Class*	Dates**	Maximum 1-min wind ($m\ s^{-1}$)	Minimum sea level pressure (mb)	U.S. damage ($ millions)	Direct deaths
1	Arthur	T	17–21 Jun	21	1004		
2	Bertha	H	5–14 Jul	51	960	270	8
3	Cesar	H	24–29 Jul	39	985		51
4	Dolly	H	19–25 Aug	36	989		14
5	Edouard	H	19 Aug–3 Sep	64	933		2
6	Fran	H	23 Aug–8 Sep	54	946	3200	26
7	Gustav	T	26 Aug–2 Sep	21	1005		
8	Hortense	H	3–16 Sep	62	935	127	21
9	Isidore	H	24 Sep–1 Oct	51	960		
10	Josephine	T	4–8 Oct	31	981	130	
11	Kyle	T	11–12 Oct	23	1001		
12	Lili	H	14–27 Oct	51	960		8
13	Marco	H	16–26 Nov	33	983		8

* T: tropical storm, wind speed 17–32 $m\ s^{-1}$ (34–63 kt). H: hurricane, wind speed 33 $m\ s^{-1}$ (64 kt) or higher.
** Dates begin at 0000 UTC and include tropical depression stage.

Verde, into tropical cyclones. Indeed, 1996 featured a large number of these so-called Cape Verde type hurricanes.

It has been known for several decades (e.g., Gray 1968) that the vertical shear of the horizontal wind is a major controlling factor in tropical cyclone genesis and intensity change. Figure 3 shows the anomalies of the vertical shear from the long-term mean for August,

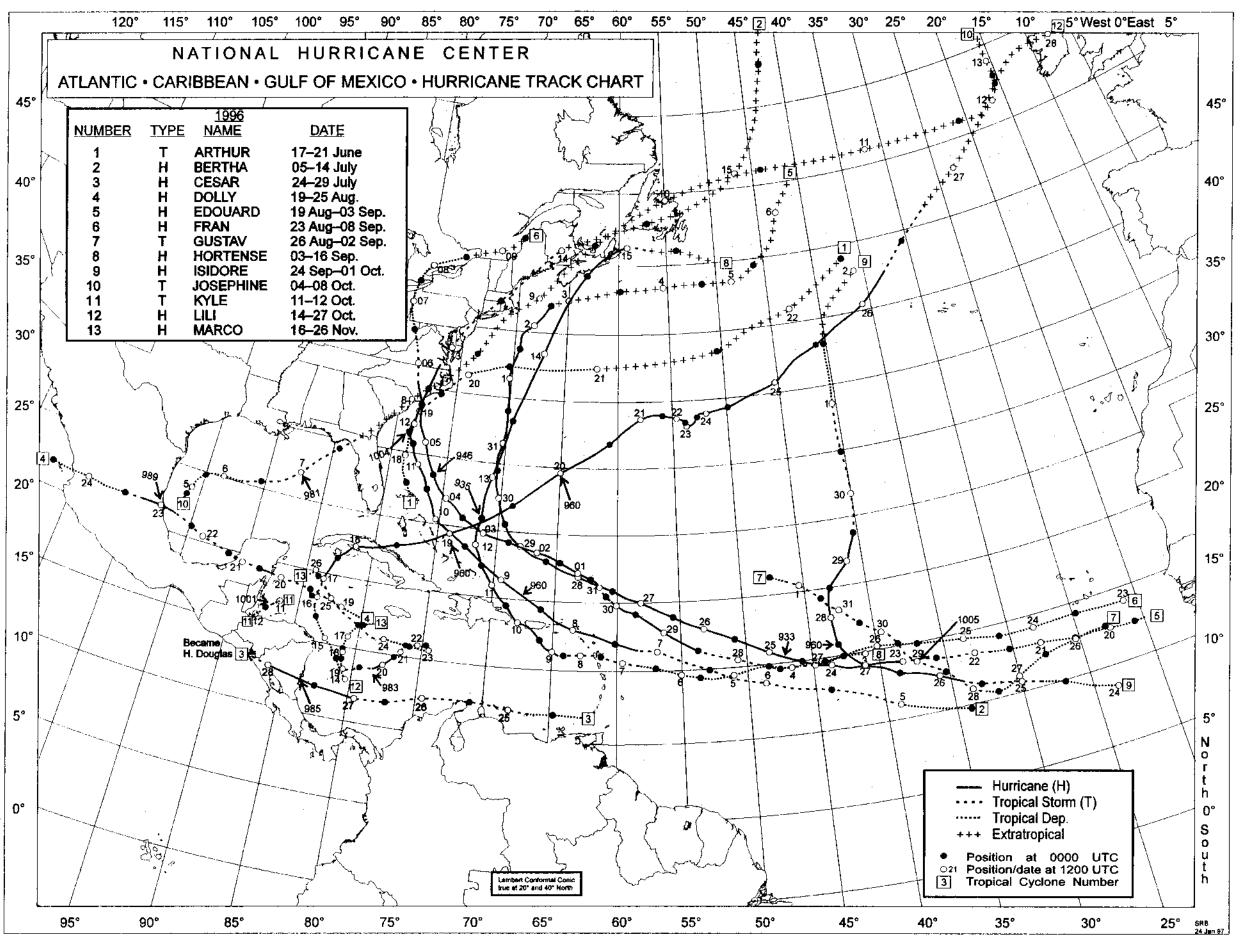

FIG. 1. Tracks of tropical storms and hurricanes in the Atlantic basin during 1996.

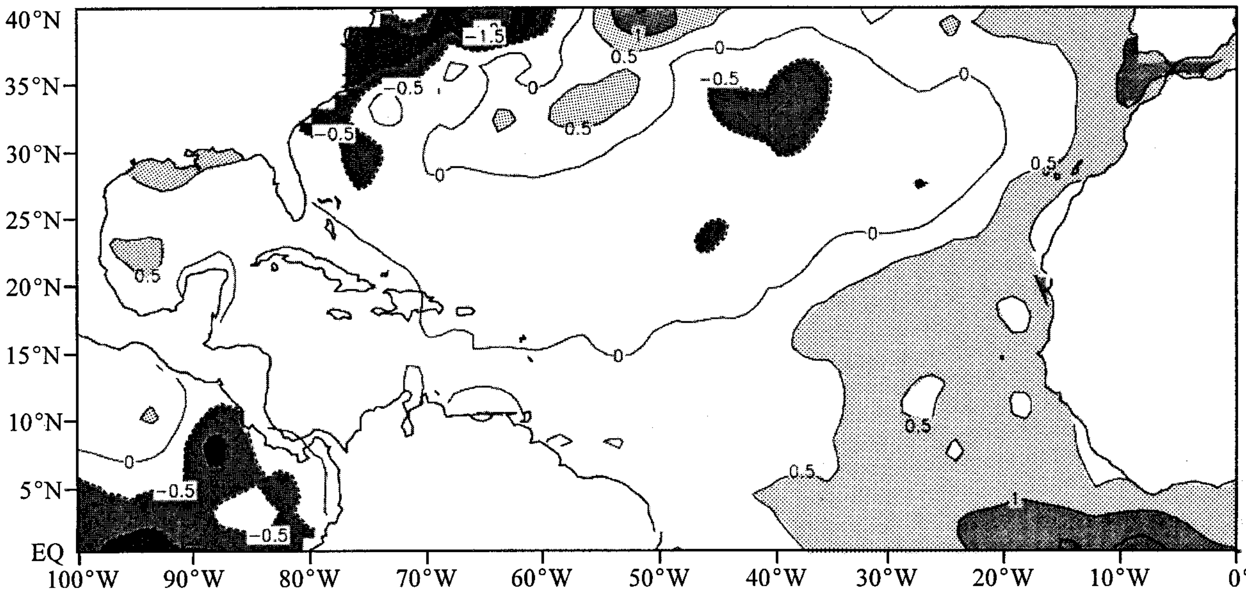

FIG. 2. SST departures from normal for the period 1 Jun–31 Jul 1996. Contour interval is 0.5°C. Shaded areas denote warm anomalies and stippled areas denote cold anomalies.

September, and October of 1996. Superimposed on this chart are dots showing the location where tropical cyclones reached tropical storm strength during these three months. No system developed into a tropical storm in an area where the long-term mean shear was above normal.

Figure 4 depicts the mean 500-mb wind field for August and September 1996. This shows the general steering pattern that prevailed during the two peak months of the season. Superimposed on this chart are the tracks of the tropical cyclones during this period. A northeast- to southwest-tilted trough was positioned over the eastern United States, and the subtropical ridge extended far enough west to steer several Atlantic hurricanes near or over the east coast of the United States in 1996. This is somewhat different than the situation that prevailed during much of the 1995 season, and the contrast in steering patterns between the two years can be seen in

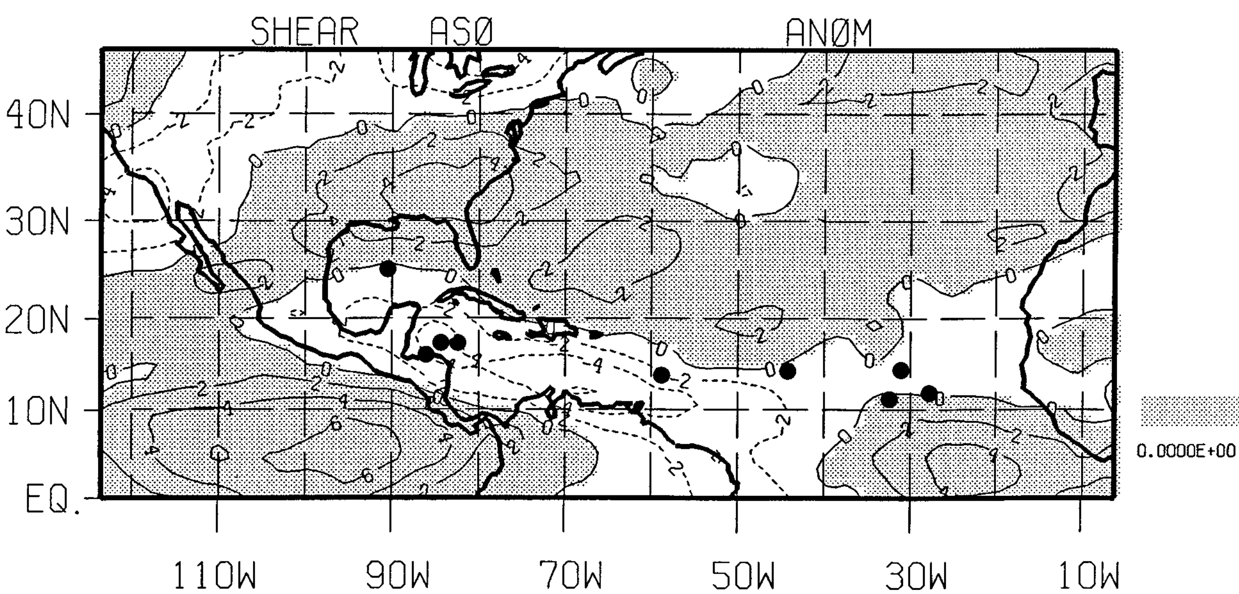

FIG. 3. Anomalies of the vertical shear (925 mb minus 200 mb) of the wind from normal for Aug–Oct 1996. Contour interval is 2 m s^{-1}. Dots show locations where tropical cyclones reached tropical storm strength during these three months.

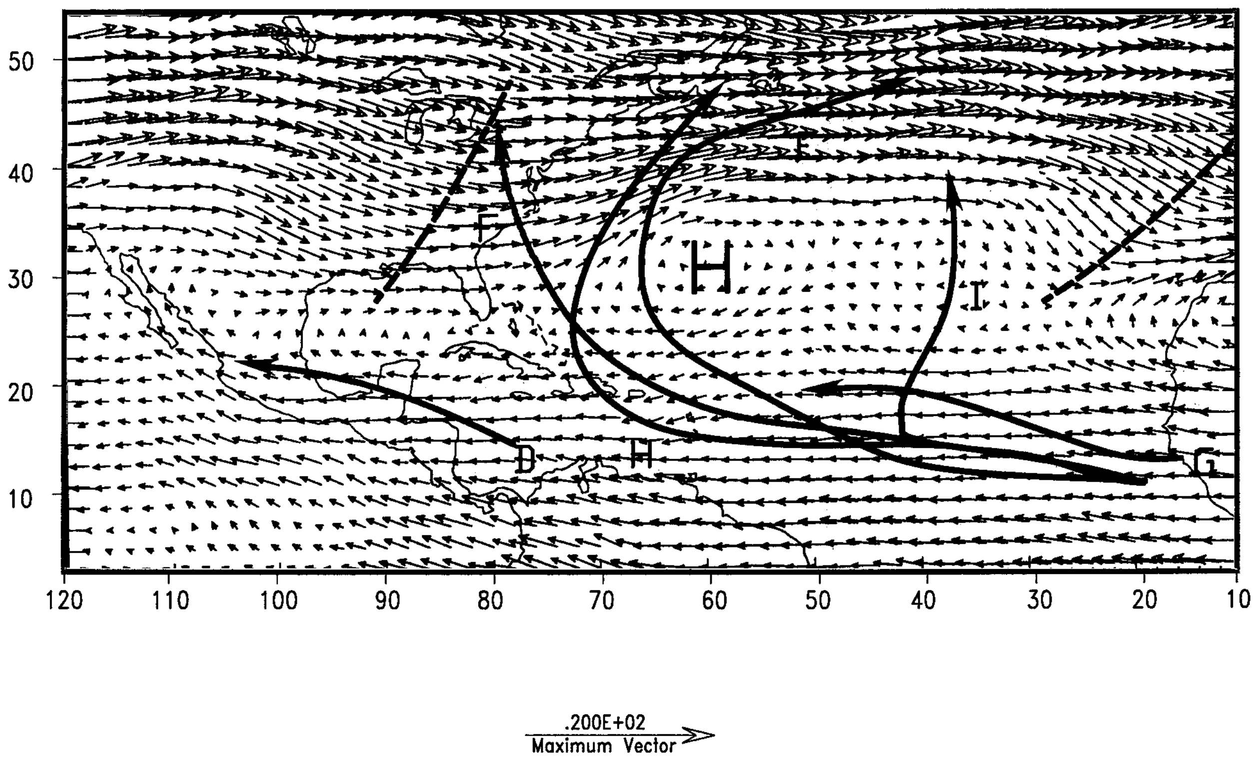

FIG. 4. Mean 500-mb winds for Aug–Sep 1996. Large-scale trough positions and tracks of Aug and Sep tropical storms and hurricanes are also shown.

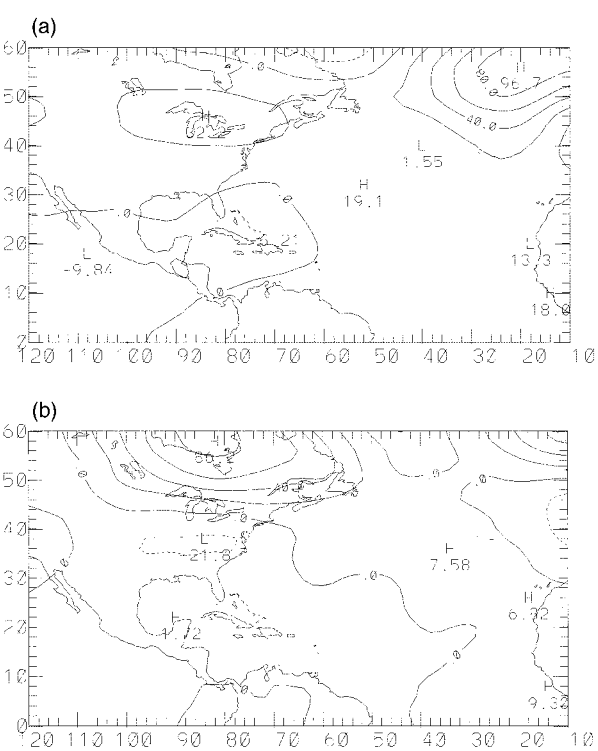

FIG. 5. 500-mb height departure from normal for (a) Aug–Sep 1995, and (b) Aug–Sep 1996. Contour interval is 20 m.

Figs. 5a and 5b. The former shows the 500-mb height anomalies for August and September of 1995 and the latter is the corresponding chart for 1996. One can see that, in 1995, there was a negative anomaly over the southwestern North Atlantic. In 1995, the ridge did not extend far enough west to allow any of the hurricanes that developed between Africa and the Caribbean to reach the east coast. This steering pattern during 1995 was also noted by Landsea et al. (1998). In 1996, however, there was a pronounced negative height anomaly over the east-central United States, which provided a kind of ''conduit'' that steered tropical storms and hurricanes northward in the vicinity of the U.S. east coast. Clearly, such shifts in the prevailing summer/fall mid-tropospheric height fields from year to year can have important, if not disastrous, consequences for residents near the coastline.

2. Tropical storm and hurricane summaries

a. Tropical Storm Arthur, 17–21 June

Arthur was a minimal tropical storm that brought locally heavy rains to coastal areas of the Carolinas. There was no significant damage.

1) SYNOPTIC HISTORY

Satellite imagery showed an increase in cloudiness and showers just east of the Bahamas on 16 June. This activity may have been associated with a tropical wave that brought pressure falls to Puerto Rico and the Dominican Republic on the previous day. On the 17th, increased organization of the system at low levels was observed in surface data, animation of satellite imagery, and the first aircraft reconnaissance reports. The Atlantic's first tropical depression of the year formed from this system at 1800 UTC, centered near the eastern end of Grand Bahama Island. The depression initially moved toward the north-northwest to north, steered by the low-level flow around the western periphery of the Atlantic subtropical ridge. The depression experienced considerable shear at this time due to strong upper-level winds associated with a cold low over the eastern Gulf of Mexico.

Deep convection increased in a small area mainly to the north of the center on 18 June. The depression became Tropical Storm Arthur at 0000 UTC on the 19th, based on analysis of reconnaissance aircraft data. Maximum winds of 21 m s^{-1} are based on a ship report received on this day. The storm began to turn more toward the northeast with time.

Arthur's center crossed over Cape Lookout, North Carolina, near 0000 UTC 20 June. As the storm continued moving toward the northeast, locally heavy rains occurred over portions of the Carolinas in advance of the cyclone's center. The center moved over the Pamlico Sound and the Cape Hatteras National Seashore and exited into the Atlantic. Satellite imagery indicated that the storm had a very well defined low-level circulation with minimal deep convection. It is likely that most of the tropical storm force winds associated with Arthur remained offshore over the Atlantic waters. The tropical storm weakened to a tropical depression about 185 km northeast of Cape Hatteras.

Arthur began moving toward the east-northeast and accelerated when westerly steering currents increased on the 20th. Deep convection developed on 21 June, but the cloud pattern was not very symmetrical in appearance, suggesting that the system was losing tropical characteristics. Forward motion increased to greater than 18 m s^{-1} and Arthur became an extratropical gale at 1200 UTC 21 June while centered about 650 km north-northeast of Bermuda. The remnant of Arthur was tracked for another 36 h and was last identified about midway between Newfoundland and the Azores, where it was absorbed by a much larger extratropical low over the North Atlantic.

2) METEOROLOGICAL STATISTICS

Intensity estimates derived from satellite data never exceeded 18 m s^{-1}. The maximum wind reported by U.S. Air Force reserve aircraft was 23 m s^{-1} at a flight level of 457 m at 0023 UTC 19 June. The ship *Atlantic Huron* reported a sustained wind of 22 m s^{-1} at 1500 UTC 19 June while located 65 km southeast of the cyclone's center. The C-MAN station at Frying Pan Shoals reported sustained winds of 18 m s^{-1} and a gust to 21 m s^{-1} at 1700 UTC on 19 June. This automated reporting station is located about 56 km southeast of Cape Fear, North Carolina, and the winds were measured at an elevation of approximately 24 m. A sustained wind of 17 m s^{-1} and a gust to 20 m s^{-1} were reported from Ocracoke Island on the North Carolina Outer Banks at 0512 UTC 20 June.

The largest rainfall total, 127 mm, occurred in Georgetown County, South Carolina. Several areas over the coastal plains of South Carolina and North Carolina reported between 50 and 100 mm of rain.

Surf as high as 1.5–2.1 m occurred off the North Carolina coast in the vicinity of Cape Lookout. No significant beach erosion was reported.

3) CASUALTY AND DAMAGE STATISTICS

No reports of casualties or significant damage associated with Arthur have been received at the NHC.

4) WARNINGS

A tropical storm warning was issued for the North Carolina Outer Banks at 0900 UTC 19 June, about 15 h prior to the landfall.

b. Hurricane Bertha, 5–14 July

Bertha was an early season Cape Verde Hurricane that moved across the islands of the northeastern Caribbean Sea as a category 1 hurricane on the SSHS and made landfall on the North Carolina coast near Wilmington as a category 2 hurricane. Bertha's 1-min winds reached their maximum value of 51 m s^{-1} on 9 July while located to the north of Puerto Rico. The last hurricane to reach this strength this early in the season was Alma in 1966 in the eastern Gulf of Mexico with 57 m s^{-1}.

1) SYNOPTIC HISTORY

Bertha originated from a tropical wave that moved from Africa to the Atlantic on 1 July. A weak circulation was first detected on satellite imagery on 3 July, centered about 925 km south of the Cape Verde Islands in the far eastern Atlantic Ocean. The track of the circulation center began on 5 July at 0000 UTC, when the circulation is believed to have reached the surface and become a tropical depression, in the central tropical Atlantic.

Bertha followed a fairly smooth curved path around the western periphery of the Atlantic subtropical high pressure ridge. This ridge changed little during Bertha's existence and a weak midlevel trough persisted in the western North Atlantic. For three days, the cyclone moved toward the west-northwest at the fast-forward speed of 10–13 m s^{-1} and strengthened to a hurricane with maximum sustained winds of 39 m s^{-1} on the 8th as the center moved across the Leeward and Virgin Islands of the northeastern Caribbean. The center moved between Antigua and Barbuda at 0600 UTC on the 8th, across St. Barthelemy, Anguilla, and St Martin, just north of St. Thomas, and over the British Virgin Islands by 1800 UTC.

The track gradually turned northwestward on the 9th and maximum sustained winds reached 51 m s^{-1} at 0600 UTC. Bertha was centered 220 km north of Puerto Rico at this time, but earlier passed within 55 km of this island. The strongest winds were located in the northeast quadrant of the hurricane and most of Puerto Rico experienced only tropical storm conditions, except for Culebra, over which hurricane-force winds might have occurred.

Moving northwestward at a slower forward speed of 8–10 m s^{-1}, the center of Bertha moved parallel to the Bahama islands, passing 75–110 km northeast of the Turks and Caicos Islands, San Salvador, Eleuthera, and the Abacos. Again, the strongest winds were located to the northeast of the center, but 33 m s^{-1} sustained winds might have reached some of the above-mentioned islands.

Continuing on its gradual turn, the track became north-northwestward on the 10th and 11th and the center moved parallel to the coast of Florida and Georgia at a distance of 280–325 km offshore. During this time, the forward speed slowed to about 4 m s^{-1}. Moving northward and re-accelerating to a forward speed of 8 m s^{-1}, Bertha made landfall at 2000 UTC on the 12th on the coast of North Carolina, with the center crossing the coast midway between Wrightsville and Topsail Beaches. The hurricane had been gradually weakening since its top speed of 51 m s^{-1} on the 9th to 36 m s^{-1} on the 11th. Then, in 12 h just before landfall, the winds abruptly increased to 46 m s^{-1}, which is the estimated maximum 1-min wind speed at landfall. Bertha quickly dropped below hurricane strength when it moved inland over eastern North Carolina.

The storm then moved northeastward along the U.S. east coast, producing 21–26 m s^{-1} sustained winds over land from northern North Carolina to New England and 31 m s^{-1} winds over nearby Atlantic waters. Bertha was declared extratropical on the 14th when the center moved from the Maine coast to New Brunswick, Canada. The extratropical storm brought 21–26 m s^{-1} winds to the Canadian maritime provinces and was tracked to just south of Greenland on the 17th.

2) Meteorological statistics

Table 2 lists selected surface observations of lowest pressure, peak wind, storm surge, and rainfall values. The minimum pressure of 960 mb occurred at 0600 UTC on the 9th and is based on a dropsonde measurement. The best track maximum sustained wind speed of 51 m s^{-1} at the same time is based on a 700-mb flight-level wind speed of 63 m s^{-1}, measured 35 km east-northeast of the center. Figure 6 shows a visible satellite image of Bertha near the time of peak intensity.

Observations are scarce from the Leeward and Virgin Islands, but because the circular eyewall was 35–55 km across, it is believed that hurricane conditions with sustained wind speeds to 39 m s^{-1} could have occurred on Antigua, Barbuda, Nevis, St. Eustatius, St. Bathelemy, Anguilla, St. Martin, and from St. Thomas northward through the U.S. and British Virgin Islands. Experience with Hurricane Marilyn in 1995 suggests that even higher sustained winds can occur over mountainous terrain as is found on many of these islands. Winds of 18–21 m s^{-1} were experienced over portions of Puerto Rico as indicated by the San Juan observations in Table 2.

A reconnaissance aircraft flight-level wind speed of 57 m s^{-1} in the northeast quadrant of the circulation several hours before landfall in North Carolina is the basis for estimating sustained surface winds of 46 m s^{-1} on that coast at landfall. The lowest sea level pressure observed at landfall was 977 mb at Surf City, North Carolina, and a value of 974 mb is assumed to be the minimum pressure at landfall.

Storm total rainfall amounts ranged from 125 to 200 mm along a coastal strip from South Carolina to Maine.

Coastal storm surge flood heights, from Florida through New England, ranged from 0.3 to 1.2 m, but values to 1.5 m were estimated on the North Carolina coast from Cape Fear to Cape Lookout. A storm surge of 1.8 m or a little higher is indicated near Swansboro, where 1.5–1.8 m of water was ''inside of businesses on the waterfront'' (from Newport, North Carolina, National Weather Service Forecast Office Preliminary Storm Report).

Seven tornadoes have been confirmed, and these occurred during the passage of an outer rainband. There were five tornadoes in Virginia, one in North Carolina, and one in Maryland.

3) Casualty and damage statistics

Twelve deaths have been related, in some way, to Hurricane Bertha. One, in Florida, was from an evacuating military jet crashing into a house and three others drowned in rip currents and high surf. One death from an auto accident occurred in North Carolina and another drowned in rip currents there. A surfer died in New Jersey. In Puerto Rico, two died in an automobile accident and another died while surfing. On the French part of St. Martin, one person was electrocuted and one fell off a boat and drowned. The fatalities caused by the jet crash and the auto accident were indirect, leaving a total of eight direct deaths due to Bertha.

The U.S. Virgin Islands and North Carolina were declared federal disaster areas. Surveys indicate that Bertha damaged almost 2500 homes on St. Thomas and St. John. For many, it was a second hit in the 10 months since Hurricane Marilyn devastated the same area.

It is likely that there was beach erosion on the north coast of the Dominican Republic when Bertha passed to the north. The Bahamas were also affected by the weak side of the hurricane, but there are no damage figures available from either of these locations.

The primary effects in North Carolina were to the coastal counties and included storm surge flooding and beach erosion, roof damage, piers washed away, fallen trees, and damage to crops. A survey indicated that over 5000 homes were damaged, mostly from storm surge. The Federal Emergency Management Agency (FEMA) estimated 750 000 people evacuated in South and North Carolina. Minor wind damage and flooding also spread along the path of the storm all the way to New England.

The American Insurance Services Group reports an estimate of $135 million in insured property damage, primarily along coastal North Carolina. A conservative ratio between total damage and insured property damage, based on past landfalling hurricanes, is two to one. Then the total U.S. damage estimate is $270 million. No damage totals are available from the Caribbean.

4) WARNINGS

Hurricane warnings were issued from Sebastian Inlet, Florida, to Chincoteague, Virginia, as well as for the Bahamas and for the islands of the northeastern Caribbean Sea from Antigua through Puerto Rico. Tropical storm warnings were issued from Sebastian Inlet to north of Deerfield Beach, Florida, and from north of Chincoteague to Watch Hill, Rhode Island. Almost all of the U.S. east coast was involved with some watch or warning and this is the result of the storm track's expected close passage to the southeast U.S. coast. The hurricane watch for the North Carolina landfall area was issued 65 h before landfall and the hurricane warning was issued 47 h before landfall. This is far more than the 36- and 24-h lead times that the National Hurricane Center strives for and is the result of the forward motion decreasing at a faster rate than expected.

c. Hurricane Cesar, 24–29 July

Hurricane Cesar caused at least 51 deaths and considerable destruction along its path through the southern Caribbean Sea and Central America.

1) SYNOPTIC HISTORY

The precursor of Hurricane Cesar was a tropical wave that passed Dakar, Africa, on 17 July and moved westward for a few days without development. The wave was accompanied by a large 200-mb anticyclone, which suggested a very favorable upper-level environment for development. Cloudiness and showers began to increase when the wave was about 1700 km east of the southern Windward Islands on 22 July. When the wave neared these islands, the 24-h surface pressure changes were near −3.0 mb (which is the threshold value that forecasters have typically found to be associated with a developing system), and a surface circulation center began to develop. The incipient center of circulation moved over Trinidad and Tobago early on 24 July. This system produced rains and gusty winds through a large portion of the Lesser Antilles. A post-analysis of the surface data and satellite images indicate that a tropical depression formed from the disturbed weather at 1800 UTC 24 July when the circulation center was moving just to the north of the island of Margarita along the north coast of Venezuela.

The depression moved westward through the southern Caribbean Sea and reached tropical storm status at 1200 UTC 25 July in the vicinity of Curacao. There was a well-defined upper-tropospheric anticyclone that accompanied the tropical cyclone at that time and also an area of above-normal surface pressure located to the north of the tropical cyclone from the Bahamas westward into the Gulf of Mexico. The latter probably reflects an anomalously strong and persistent high pressure system that forced Cesar to move westward and even south of due west for several days. In addition, this dipole in the pressure field is operationally recognized as a favorable pattern for the development and strengthening of tropical cyclones.

Cesar continued its general westward track very close to the coast of South America and gradually intensified. However, the development was inhibited by the close proximity to land and it was not until 1200 UTC 27 July that Cesar reached hurricane status over the open waters of the southwestern Caribbean Sea. Cesar began strengthening more rapidly prior to landfall just north of Bluefields, Nicaragua, and it reached its maximum intensity of 39 m s^{-1} and minimum pressure of 985 mb near landfall at 0400 UTC 28 July. Rapid intensification of hurricanes near landfall has been observed in the past—for example, Hurricanes Andrew and Cleo near south Florida in August 1992 and August 1964, respectively.

Cesar crossed Nicaragua and moved into the eastern North Pacific Ocean where it reintensified and became Hurricane Douglas. The most recent hurricane to hit Nicaragua before Cesar was Joan, a category 4 hurricane on the SSHS, in October 1988. Joan also redeveloped over the eastern Pacific and became Tropical Storm Miriam.

2) METEOROLOGICAL STATISTICS

Cesar was upgraded to tropical storm status based on a 21 m s^{-1} sustained wind and gusts to 26 m s^{-1} observed in Curacao at 1155 UTC 25 July. The central pressure in the best track associated with Cesar while moving near the coast of Colombia is estimated to be 1 or 2 mb lower than reported by the reconnaissance plane at that time because the storm's close proximity to land prevented the plane from reaching the pressure center. Ship

TABLE 2. Hurricane Bertha selected surface observations, July 1996.

Location	Press. (mb)	Date/time (UTC)	Sustained wind (m s^{-1})[a]	Peak gust	Date/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Florida								
Jacksonville	1011.9	11/2256	11 (2 min)	14	11/1721			Trace
Jacksonville Beach							0.6	
Georgia								
Sea Island							0.9	
St. Simon							0.9	
South Carolina								
Charleston international airport	1008.5	12/1155	15 (2 min)	20	12/0130			37.6
Charleston city office			19	26	12/1130			23.9
Charleston harbor						0.8		
Cheraw								9.7
Cherry Grove pier			29	35				55.1
Garden City pier			21	28				25.7
Loris								70.4
Myrtle Beach								61.0
Myrtle Beach, Sands Resort								120.1
Myrtle Beach Springmaid pier						1.0		
Myrtle Beach pavilion			22	27				41.7
Summerville								35.6
North Carolina								
Beaufort Duke marine lab						0.8		
Beaufort				29	12/2125			
Bath							1.8	
Bellhaven							2.3	
Brunswick							1.5	
Carolina Beach							1.8	
Cherry Point (NKT)				33	12/2242			
East Wilmington				36				
Elizabeth City (ECG)	998.9	13/1313	20	25	13/0055			
Greenville				39				104.4
Hatteras ferry office				32	13/0100			
Kure Beach			25	41	12/1835			
Lake Waccamaw								60.7
Newport	994.3			40				74.9
New Bern				32	12/2208			115.8[c]
New River (NCA)				48	12/2021			
Pongo River							1.4	
Seymour Johnson AFB	986.3	12/2355	17	27	12/2155			102.4
Snow Hill								138.2
S. Pamlico River							0.9	
Southport (Nixon)	978.3	12/1835	28	38	12/1703			
Surf City (Horodner)	977	12/2005						
Swansboro							2.4	
Williamston								104.1
Wilmington (ILM)	978.7	12/2028	24 (2 min)	31	12/1902	0.4		143.8
Wilmington, Fig. Eight Is.				43	12/1725			
Wilmington, NC, state port				40				
Wilmington port terminal	980.1	12/1850	NOAA ship *Whiting*, 34.2°N, 77.96°W					
CLKN7(C-MAN)	1002.0	12/2200	30 (2 min)	38	12/2300			
Diamond Shoals Buoy	1007.7	13/0300	30 (2 min)	37	12/2300			
FPSN7 (C-MAN)	977.5	12/1800	40 (10 min)	52	12/1610			
Wrightsville Bch. Banks ch.				41				
Virginia								
Cape Charles				31	13/0330			
Eastville, Northhampton Co.								177.8
Newport News (PHF)	993.1	13/0750						
Norfolk International airport	995.1	13/0756	16	22	13/0740			62.0
Norfold NAS (NGU)	994.4	13/0755	15	22	13/0155			
Norfolk, Sewells Point						0.8		
Oceana NAS (NTU)	997.2	13/0755						
Pasquotank River							1.5	
Plantation Creek								182.8
Potomac River at Wisc. Ave.							1.5	
Wallops Island			22	24	13/0605			
Washington Dulles airport				15	13/1218			28.4
Washington National airport	1001.7	13/1221		19	13/0639			31.5
Willis Wharf, Accomac Co.								147.3
CHLV2 (C-MAN)	998.9	13/0800	25 (2 min)	29	13/0700			
Fenwick Is. Buoy (44009)			21	25	13/1300			

TABLE 2. Continued.

Location	Press. (mb)	Date/time (UTC)	Sustained wind (m s^{-1})[a]	Peak gust	Date/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Maryland								
Andrews AFB (ADW)	1000.6	13/1155		18	13/0750			23.9
Baltimore Wash. airport	1000.3	13/1349		21	13/0704			57.9
Nanticoke, Wicomico Co.								127.8
Patuxent River NAS (NHK)	995.0	13/1100		22	13/0603			102.4
Salisbury								142.7
Delaware								
Dover	995.6	13/1155	15	26				
Lewes						0.5		
New Jersey								
Atlantic City						0.7		61.2
Estelle Manor								167.4
Harvey Cedars				28				
Newark airport			13 (2 min)	18	13/1521			
Teterboro airport			13 (2 min)	20	13/1547			
River Vale								
West Milford								55.1
								123.2
Pennsylvania								
Philadelphia		29	19					61.7
New York								
Ambrose Light Tower buoy				25				
Babylon Village, L.I.				33				
Buoy southwest of Fire Is.				19				
Brookhaven airport			13	19	13/1947			
East Quogue, Suffolk Co.								19.3
JFK airport			16 (2 min)	19	13/1458			
LaGuardia airport			15 (2 min)	20	13/1518			
Mt. Sinai (New York City)								63.2
Ossining, Westchester Co.								78.5
Pomona, Rockland Co.								118.1
Connecticut								
Bridgeport airport			14	18	13/1547			
Orange								
Preston				25				
Shelton								103.1
Vernon								139.3
Rhode Island								
Fox Point hurricane barrier						0.6		
Sachuest Point (Middletown)		13/2336	28	33	14/0010[f]			
Providence	995.9							137.4
Massachusetts								
Goshen								144.8
Billerica								182.9
Boston	996.3	14/0056						
New Bedford		14/0041	23	39	13/2030	0.5		
Taunton ASOS	995.6							
Puerto Rico								
Rio Icacos (Naguabo)								207.5
Roosevelt Roads	992.0	08/1930	20	27	08/1525			40.6
San Juan airport	996.8	08/2056	22 (2 min)	27	08/2110			39.6
U.S. Virgin Islands								
Mt. Zion (St. Thomas)								83.3
St. Croix Hess Oil			21		08/1918			

[a] Averaging period is 1 min unless otherwise indicated.
[b] Date/time is for sustained wind when both sustained and gust are given.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above national geodetic vertical datum.
[e] Top of rain gauge blew off and ''a lot of rain was sucked out.''
[f] Hand-held anemometer.

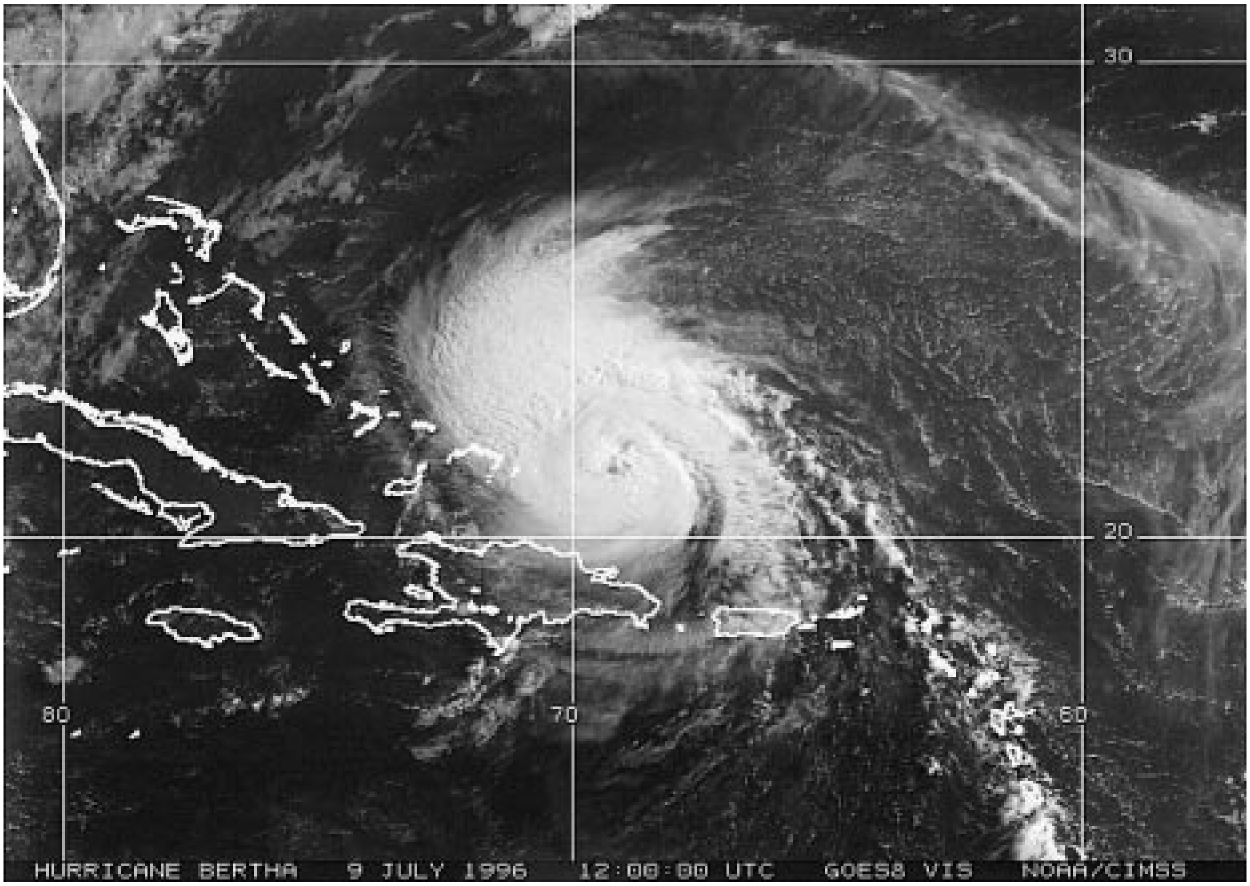

FIG. 6. Visible *GOES-8* satellite image of Hurricane Bertha at 1200 UTC 9 July 1996, just after it reached peak intensity.

observations and the Hurricane Research Division (HRD) surface wind analysis indicate that 18 m s^{-1} winds extended northward from the center for about 445 km. San Andres experienced calm winds at 2128 UTC followed by 33 m s^{-1} gusts marking the passage of a portion of Cesar's center. The strengthening just prior to landfall is supported by observations from the reconnaissance plane just before it departed the storm center. Data indicate the formation of an eye at 0050 UTC 28 July, a closed eyewall of 28-km diameter at 0256 UTC, and a drop in the surface pressure of 3 mb in 1 h. Satellite images confirmed the strengthening at landfall by showing an embedded center within cold tops between $-54°$ and $-63°C$ corresponding to a T number of 4.5 on the Dvorak scale. Table 3 contains selected surface observations associated with Cesar.

3) CASUALTY AND DAMAGE STATISTICS

Cesar was responsible for at least 51 deaths on its trek through the Caribbean Sea and Central America. Most of the deaths were attributed to heavy rainfall, which caused flash flooding and mudslides. The death total includes 26 people in Costa Rica, which was not in the direct path of the hurricane but was hit by floods and mudslides.

4) WARNINGS

Hurricane warnings for Nicaragua were issued about 30 h before landfall.

d. Hurricane Dolly, 19–25 August

1) SYNOPTIC HISTORY

Hurricane Dolly formed from a tropical wave of large lateral extent that moved from the west coast of Africa to the central Caribbean Sea during 9–18 August 1996. Although the wave generated deep convection when it emerged from Africa, there was little accompanying thunderstorm activity for much of its passage across the tropical North Atlantic Ocean. Deep convection redeveloped when the wave reached the eastern Caribbean but did not persist in a concentrated pattern until the system was south to southwest of Jamaica on the 18th–19th. A low- to midlevel cyclonic circulation was then detected in data obtained during a National Oceanic and

TABLE 3. Hurricane Cesar selected surface observations, July 1996.

Location	Press. (mb)	Date/time (UTC)	Sustained wind (m s^{-1})*	Peak gust	Date/time (UTC)**	Total rain (mm)
Netherlands Antilles						
Aruba	1002.2	25/2100				
Curacao	1004.9	25/1155	21	26		
Colombia						
San Andres				33	27/2220	
Nicaragua						
Bluefields	999.0	28/0600				271.8
Corinto						208.3
Masatepe						238.8

* Averaging period is 10 min.
** Date/time is for sustained wind when both sustained and gust are given.

Atmospheric Administration (NOAA) research flight to study the development of tropical cyclones. Satellite analysts indicated that the system was too weak to classify using the Dvorak technique late on the 18th, but they calculated Dvorak T numbers of 1.5 and 2.0 on the afternoon of the 19th. By midafternoon on the 19th, the first center fix by reconnaissance aircraft was made and data from the plane, satellite, and a ship that reported 23 m s^{-1} at 1800 UTC were used to estimate that the tropical depression stage began with a poorly defined circulation center near 0600 UTC on the 19th. The data also indicate that the depression became Tropical Storm Dolly a little more than 6 h later.

The tropical cyclone developed near or just south of a mid- to upper-level anticyclone. In that environment, Dolly strengthened on the 19th and 20th and moved toward the west-northwest at a speed that decreased from 8 m s^{-1} to about 4 m s^{-1}. Convection became better organized near the circulation center on the 20th and, just before making landfall on the Yucatan peninsula to the northeast of Chetumal, Dolly became a hurricane. It weakened back to a tropical depression and its forward speed slowed to about 3 m s^{-1} during its 24-h passage over the peninsula, and satellite pictures showed the center of cloud rotation displaced to the south of the estimated surface circulation center.

Gradual restrengthening began a few hours after the surface center arrived over the Bay of Campeche. Dolly regained hurricane status and was at its strongest, with 36 m s^{-1} winds and a central pressure of 989 mb, when it accelerated to 8 m s^{-1} and made its final landfall about midway between Tuxpan and Tampico near 1800 UTC on the 23d.

Dolly then weakened and, as a tropical depression, crossed central Mexico. It continued to generate areas of deep convection and, likely, heavy precipitation even while its surface center dissipated over the eastern North Pacific Ocean on the 25th.

2) METEOROLOGICAL STATISTICS

The only available official observations of at least tropical storm force winds from a surface land site came from Tampico, Mexico. There, 10-min winds of 21 m s^{-1} with gusts to 31 m s^{-1} occurred at 1045 UTC and 1145 UTC on the 23d. An amateur radio report of a gust to 30 m s^{-1} was received from Tampico.

The three largest 24-h rainfall totals reported to the meteorological service of Mexico came from Micos (329 mm), Santa Rosa (269 mm), and Puerto de Valles (254 mm). The rains, which in some cases were heavier on Mexico's west coast that its east coast, also occurred in the more widely known cities of Acapulco (125 mm), Los Mochis (179 mm), Tuxpan (149 mm), Chetumal(146 mm), Monterrey (125 mm), and Cancun (34 mm).

3) CASUALTY AND DAMAGE STATISTICS

According to newspaper reports, Hurricane Dolly was responsible for 14 deaths in Mexico—including six in Veracruz (all drowned), three in Nuevo Leon, and one each in Pueblo Viejo and Monterrey. Two people were missing in Nuevo Leon.

Those reports also indicated hundreds of residences destroyed and 35 000 people displaced. Severe damage occurred in Tuxpan, Tamiahua, Pueblo Viejo, Platon, Panuco, Tampico Alto, and elsewhere along the coast of northeast Mexico. A river overflowed its banks causing damage in Pueblo Viejo. A large area of farm land was lost to flooding in Quintana Roo on the Yucatan peninsula.

Rain prompted evacuations in the southern part of the state of San Luis Potosi. About 6500 people were evacuated from low-lying zones of Tampico.

Widespread communication and power outages were noted as far west as Mazatlan.

4) WARNINGS

A tropical storm warning was issued for the Yucatan peninsula from Chetumal northward and westward to Progreso at 1800 UTC 19 August. This was replaced by a hurricane warning from Chetumal northward to Cozumel at 1600 UTC 20 August, as Dolly reached marginal hurricane strength shortly before landfall on the peninsula. A hurricane warning was issued for the coast of Mexico from Veracruz northward to La Pesca at 1500 UTC 22 August, 21 h before landfall in that area.

e. Hurricane Edouard, 19 August–3 September

Edouard, the strongest tropical cyclone of the 1996 Atlantic season, was a prototypical Cape Verde hurricane. It had a very long track, and maintained category three or greater intensity on the SSHS for nearly eight days. Edouard's fringes lashed southeastern New England as its center recurved out to sea.

1) SYNOPTIC HISTORY

Edouard originated from a tropical wave that was already well marked by a large spiral-shaped mass of convective clouds while moving across western Africa on 17–18 August. The wave crossed the west coast of Africa early on the 19th, accompanied by a 23 m s^{-1} midtropospheric jet seen in rawinsonde data. Observations from Dakar and nearby stations showed thunderstorms and squalls, along with 24-h surface pressure falls on the order of 3–4 mb as the wave passed. Soon after entering the eastern tropical Atlantic, ship reports showed the presence of a large surface circulation. It is estimated that a tropical depression formed around 1800 UTC on 19 August, centered about 550 km southeast of the Cape Verde Islands. This was the first in a series of four tropical cyclones that would form over the eastern Atlantic from waves that moved off the west coast of Africa during a two-week span in late August and early September of 1996. Three of these systems (Edouard, Fran, and Hortense) eventually became category three (or stronger) hurricanes.

Initially, it appeared that the westward-moving tropical cyclone would soon take a northwestward turn in response to a weakness in the subtropical ridge over the eastern Atlantic. However, the subtropical ridge remained strong enough to the north of the system to keep it on a generally westward track into the central tropical Atlantic. Higher-level winds favored intensification of the cyclone, as an upper-tropospheric anticyclone became well established over the area. The system became Tropical Storm Edouard early on 22 August and strengthened into a hurricane around 1200 UTC the following day, when a banding-type eye was noted in satellite pictures.

When the hurricane neared 45°W long on the 24th, a deep-layer cyclone to the east of Bermuda began to create a weakness in the subtropical ridge. In response to this, Edouard's direction of motion changed from westward to west-northwestward. Meanwhile, intensification continued, and Edouard's winds strengthened to 51 m s^{-1} on the 24th and to 64 m s^{-1} on the 25th, making it a category four hurricane (Fig. 7). The latter wind speed was the maximum intensity, and a similar wind speed is estimated on the 26th and also around 0000 UTC on the 28th. From the 26th to the 28th, some fluctuations in intensity were noted, apparently as the result of eyewall replacement cycles and occasional doses of stronger vertical shear over the area. Nonetheless, Edouard maintained 51 m s^{-1} or greater winds throughout the above period. The final deepening episode in Edouard was observed late on 29–30 August. During that event, *three* concentric eyewalls were indicated by aerial reconnaissance observations. Overall, Edouard remained a powerful, 51 m s^{-1} or stronger hurricane for a very long time—from 24 August until early on 1 September.

Edouard moved relentlessly toward the west-northwest, at around 6 m s^{-1}, until 29 August. This track kept the hurricane well to the northeast and north of the islands of the northeastern Caribbean Sea. On the 29th, a midtropospheric trough became established near the U.S. east coast, creating a more northward steering component for Edouard. Slowing its forward speed slightly, the hurricane turned northwestward, and then northward, while gradually weakening. The cyclone passed about midway between Cape Hatteras and Bermuda on 1 September, and then started moving slightly east of north. Late on the 1st, the hurricane wobbled toward the north, in the general direction of southeastern New England. However, early on the 2d, Edouard veered sharply toward the northeast, and the center of the hurricane passed about 140 km southeast of Nantucket Island around 0900 UTC, the closest point of approach to the United States. Maximum winds had diminished to near 36 m s^{-1} by that time.

Edouard weakened to a tropical storm near 0000 UTC on the 3d, and became extratropical shortly thereafter. The storm's motion became east-northeastward, keeping the center south of Nova Scotia and well offshore of Newfoundland. Edouard's remnant low was drawn around and into the circulation of a larger extratropical cyclone on the 6th, and was absorbed by this bigger system by 0000 UTC 7 September.

2) METEOROLOGICAL STATISTICS

Most of the aircraft reconnaissance flights into Edouard were accomplished by the Hurricane Hunters, who flew 15 missions and made 66 center fixes. NOAA aircraft provided four additional fixes. The highest wind speed reported was 72 m s^{-1} (at 700 mb) at 0003 UTC 28 August. Lowest central pressure reported was 934 mb at 1727 UTC 30 August. However, the highest wind

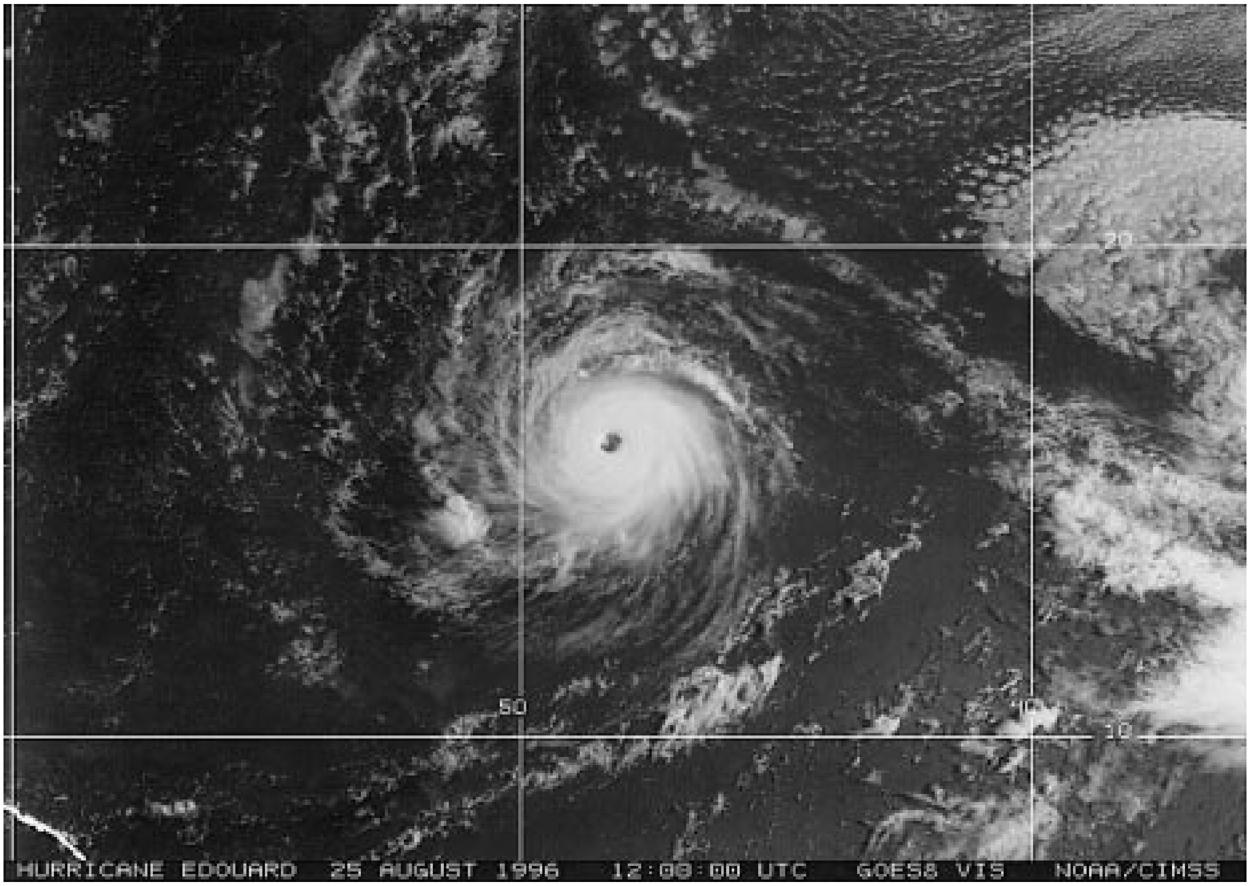

FIG. 7. Visible *GOES-8* satellite image of Hurricane Edouard at 1200 UTC 25 August 1996, showing a well-defined eye. The hurricane is near its maximum intensity of 64 m s^{-1}.

reported by aircraft around that time was 69 m s^{-1}. Subjective and objective Dvorak intensity estimates indicate that Edouard was stronger on 25–26 August, and also at 0000 UTC 28 August, than it was at the time of the minimum aircraft-reported pressure. At the latter time, the hurricane appeared considerably less organized on satellite images than on the earlier days.

The hurricane came close enough to New England to produce sustained winds of tropical storm force at Nantucket Island and the Cape Cod area. Wind gusts to hurricane force were reported at Nantucket. Table 4 lists selected surface observations from Massachusetts, New Hampshire, and Maine. In addition, there were unofficial reports of wind gusts to 40 m s^{-1} at Nantucket, 36 m s^{-1} at Martha's Vineyard, and 34 m s^{-1} on Cape Cod.

Large swells, minor beach erosion, and some coastal flooding, presumably minor as well, occurred along the coast from North Carolina northward through Maine.

3) CASUALTY AND DAMAGE STATISTICS

Two deaths have been directly attributed to Edouard. A 71-year-old man died when his boat capsized in heavy surf in Great Egg Harbor Inlet, south of Atlantic City, New Jersey. A 28-year-old man drowned while surfing at Lavallette, northeast of Tom's River, New Jersey. Additionally, a 44-year-old man suffered a broken neck (but survived) while surfing near Atlantic City. Overall, the effects of Edouard on land were apparently minor. Most of the damage was to boats at Martha's Vineyard and Nantucket.

4) WARNINGS

Since the official forecast tracks were bringing Edouard close to the U.S. east coast, and there was the usual uncertainty in these forecasts, watches and warnings were required from the mid-Atlantic states northward. A hurricane warning was posted for portions of Rhode Island and Massachusetts at 0900 UTC 1 September. Although sustained hurricane force winds did not occur in these areas, sustained tropical storm force winds, with gusts to hurricane force, were observed in the eastern end of the hurricane warning area 18–24 h after the issuance of the warning. At 0900 UTC on the 2d, the hurricane warning was changed to a tropical

TABLE 4. Hurricane Edouard selected surface observations, September 1996.

Location	Press. (mb)	Date/time (UTC)	Sustained wind (m s^{-1})[a]	Peak gust (m s^{-1})	Date/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Massachusetts								
Brant Point Coast Guard			26	35	02/1900			
Buzzards Bay buoy (44028)			20	28	02/1500			
Chatham upper-air site				32	02/1117			
Falmouth	1001.7	02/1021						126.2
Georges Bank buoy (44011)	986.8	02/1700	20	26	02/1700			
Hyannis	1001.0	02/1039						132.1
Martha's Vineyard	1000.0	02/0945		24				
Menemsha Coast Guard			28		02/1500			
Nantucket buoy (44008)	979.9	02/0500	20	26	02/0500			
Nantucket Island						0.6	1.7	
Nantucket tower (ACK)	995.9	02/0945	23	33	02/0945			
New Bedford ASOS			18	24	02/1029			
Pocasset								119.4
West Dennis								161.8
West Yarmouth								120.7
New Hampshire								
Portsmouth								25.40
Maine								
Eastport								31.2
Eliot								29.7
Matinicus Rock C-MAN			18	21	02/1900			
Mt. Desert Rock C-MAN			21	24	02/2000			
Westbrook								29.5

[a] NWS standard averaging period is 1 min; ASOS and C-MAN are 2 min; buoys are 8 min.
[b] Date/time is for sustained wind when both sustained and gust are listed.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above national geodetic vertical datum.

storm warning over southeastern New England, even though it was clear that Edouard was bypassing the area. The reason for downgrading the warning (as opposed to lowering all warnings) was that Edouard was slow to exit, and strong winds were likely to continue lashing the coast in the vicinity of Cape Cod during the day. All U.S. warnings were dropped at 0000 UTC 3 September, by which time Edouard was nearing Nova Scotia.

f. Hurricane Fran, 23 August–8 September

Fran was a Cape Verde hurricane that moved across the Atlantic during the peak of the hurricane season. It made landfall on the North Carolina coast as a category three hurricane on the SSHS, resulting in significant storm surge flooding on the North Carolina coast, widespread wind damage over North Carolina and Virginia, and extensive flooding from the Carolinas to Pennsylvania. Fran was, by far, the most destructive tropical cyclone of the 1996 season.

1) SYNOPTIC HISTORY

Hurricane Fran formed from a tropical wave that emerged from the west coast of Africa on 22 August. Deep convection associated with the wave was organized in a banding-type pattern and animation of satellite images suggested a cyclonic circulation. Ship reports soon confirmed that the circulation was on the surface, and the system became a tropical depression just southeast of the Cape Verde Islands at 1200 UTC 23 August.

The tropical depression moved westward near 8 m s^{-1} for the next few days without significant development. This lack of development may be attributed, in part, to disrupted low-level inflow due to the large and powerful Hurricane Edouard, which was centered about 1400 km to the west-northwest. Satellite intensity estimates suggest that the depression became Tropical Storm Fran at 1200 UTC 27 August while located about 1650 km east of the Lesser Antilles.

Fran began to track toward the west-northwest in the wake of Hurricane Edouard. Deep convection became more concentrated and Fran is estimated to have reached hurricane status at 0000 UTC 29 August while centered about 835 km east of the Leeward Islands. The hurricane passed a little less than 300 km to the northeast of those islands on the following day.

The tropical cyclone weakened to just below hurricane strength later on the 30th, possibly due to the low-level inflow being disrupted again by Edouard. About

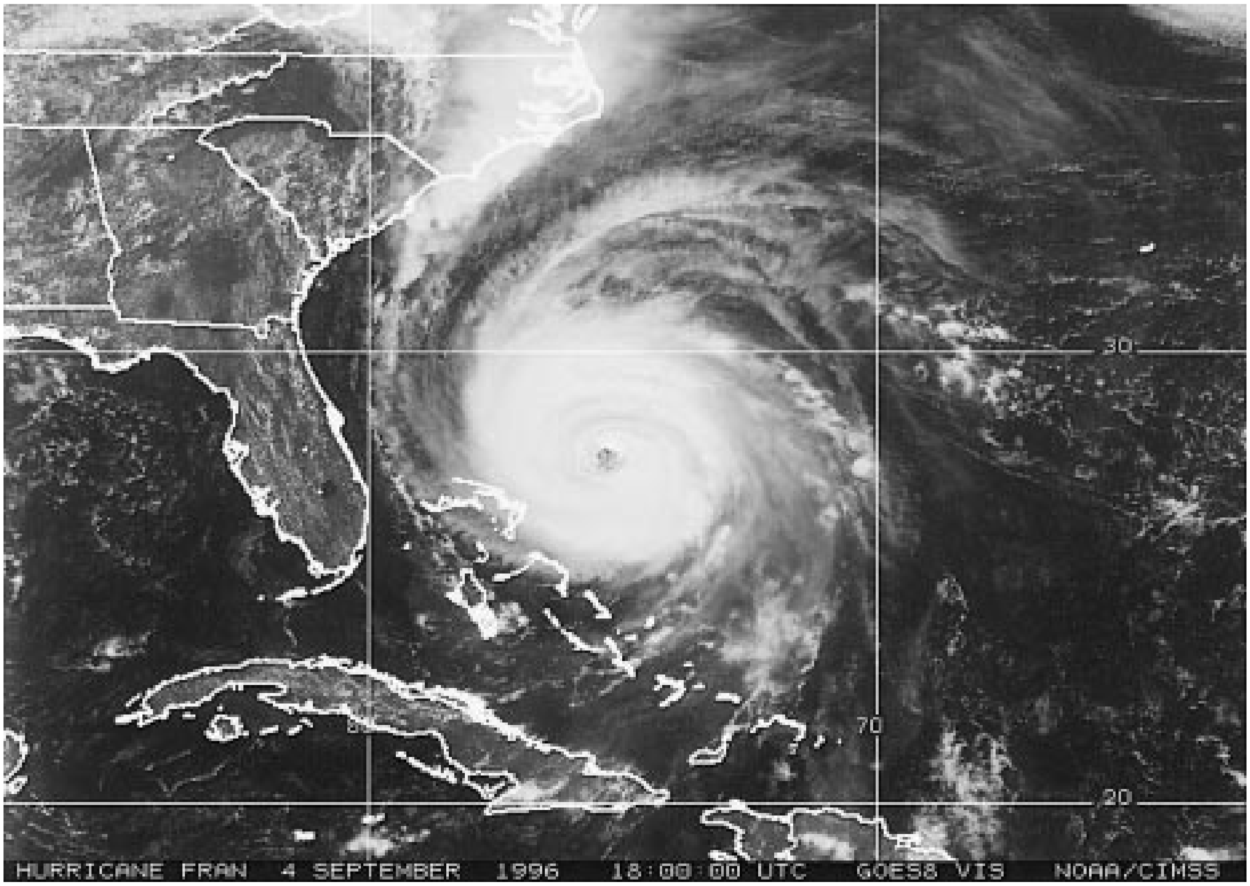

FIG. 8. Visible *GOES-8* satellite image of Hurricane Fran at 1800 UTC 4 September 1996, as it neared peak intensity.

this time, changing steering currents caused Fran to turn toward the northwest and slow to about 3 m s^{-1}.

By 1200 UTC 31 August, as Edouard moved farther away, Fran had regained hurricane strength. As Hurricane Edouard moved northward off the U.S. mid-Atlantic coast, the subtropical ridge became better established to the north of Fran, causing Fran to resume a west-northwestward motion with an increased forward speed of about 5 m s^{-1}. Fran moved on a track roughly parallel to the Bahama Islands with the eye remaining a little more than 185 km to the northeast of the islands.

Fran strengthened to a category three hurricane by the time it was northeast of the central Bahamas on 4 September. Figure 8 is a satellite image of the hurricane at that time. The powerful tropical cyclone began to be influenced by a cyclonic circulation centered over Tennessee that was most pronounced in mid- to upper levels of the atmosphere. Fran was steered by the resulting flow around the low over Tennessee and the western extension of the subtropical ridge over the northwest Atlantic. The hurricane gradually turned toward the northwest to north-northwest and increased in forward speed.

The minimum central pressure dropped to 946 mb and maximum sustained surface winds reached 54 m s^{-1}, Fran's peak intensity, near 0000 UTC 5 September when the hurricane was centered about 465 km east of the Florida east coast.

Fran was moving northward near 8 m s^{-1} when it made landfall on the North Carolina coast. The center moved over the Cape Fear area around 0030 UTC 6 September, but the circulation and radius of maximum winds were large and hurricane force winds likely extended over much of the North Carolina coastal areas of Brunswick, New Hanover, Pender, Onslow, and Carteret counties. At landfall, the minimum central pressure is estimated at 954 mb and the maximum sustained surface winds are estimated at 51 m s^{-1}. The strongest winds likely occurred in streaks within the deep convective areas north and northeast of the center.

Fran weakened to a tropical storm while centered over central North Carolina and subsequently to a tropical depression while moving through Virginia. The tropical cyclone gradually lost its warm core as it moved over the eastern Great Lakes and became extratropical near 0000 UTC 9 September while centered over southern Ontario. The remnants of Fran were absorbed into a frontal system near 0600 UTC 10 September.

2) Meteorological statistics

All operational aircraft reconnaissance flights into Fran were provided by the U.S. Air Force Reserves. These Hurricane Hunters made 71 center fixes during 17 flights. The minimum central pressure reported by aircraft was 946 mb at 2306 UTC 4 September. A circular eye with a diameter of 46 km was observed on aircraft radar at this time. The 946-mb minimum pressure was measured by dropsonde and was the lowest pressure reported during Fran's existence. The maximum winds of 59 m s^{-1} from a flight level of 700 mb (near 3 km) were measured about 6 h prior to the 946-mb pressure report. Flight-level winds in excess of 50 m s^{-1} were reported several times during the two days prior to landfall. Winds of 58 m s^{-1} were reported from aircraft 96 km east of the hurricane center at 2314 UTC 5 September, and 55 m s^{-1} winds were reported 76 km northeast of the center at the time of landfall. However, the core of the hurricane weakened somewhat on radar presentations, and a closed eyewall was not reported by aircraft during the two hours prior to the center moving onshore.

Objective intensity estimates from digital infrared satellite imagery peaked near the time that the minimum central pressure was reported by reconnaissance aircraft.

The Weather Surveillance Radar—1988 Doppler (WSR-88D) at Wilmington, North Carolina, measured winds in excess of 60 m s^{-1} at about 1.5-km elevation as the inner convective bands approached the Cape Fear area at 2130 UTC 5 September.

A ship with call sign LAVX4 reported 44 m s^{-1} winds and a pressure of 984 mb at 1800 UTC 5 September while located about 110 km northeast of the hurricane center. Several other ship reports were helpful in defining the extent of tropical storm force winds, as were reports from a network of NOAA drifting buoys deployed offshore of the Carolinas in advance of Fran.

Several wind gusts to hurricane force were measured from coastal areas in North Carolina. As usual for landfalling hurricanes, however, reports of sustained hurricane force winds are difficult to find. Table 5 lists selected U.S. surface observations. The NOAA C-MAN station at Frying Pan Shoals (about 95 km south-southeast of Wilmington, North Carolina) reported sustained winds of 41 m s^{-1} and gusts to 56 m s^{-1} from a tower about 24 m above sea level.

Numerous pressure and wind reports from North Carolina were relayed to the NHC through amateur radio volunteers. The lowest pressure was 954 mb from Southport. The highest measured wind gust was 61 m s^{-1} at an elevation of 9 m (mounted on a house approximately 1 m above the chimney) from a Davis Instruments anemometer located at Hewletts Creek in Wilmington, North Carolina. Gusts to 57 m s^{-1} were measured at Long Beach, 56 m s^{-1} at Wrightsville Beach, and 55 m s^{-1} on Figure Eight Island. Although these measurements are very much desired to supplement the more official observations, they are not listed in Table 5 because their accuracy has not been determined.

Several tornadoes were indicated by WSR-88D radar in North Carolina and Virginia. Confirmation, however, was not made due to the extensive nature of straight line wind damage across the region.

Survey results showed an extensive storm tide along the North Carolina coast primarily southwest of Cape Lookout. Still water mark elevations on the inside of buildings, indicative of the storm tide, ranged from 2.7 to 3.7 m. Outside water marks on buildings or debris lines were higher, due to the effect of breaking waves.

Rainfall totals exceeding 150 mm were common near the path of Fran. WSR-88D radar precipitation estimates were as high as 300 mm over portions of Brunswick and Pender counties in North Carolina. Extensive flooding spread well inland from the Carolinas into Virginia, West Virginia, and Pennsylvania. Some of this flooding was considered the most severe in years. Near Washington, D.C., for example, the Old Town district of historic Alexandria was partially evacuated as the Potomac River rose, flooding streets with more than 1 m of water.

3) Casualty and damage statistics

Hurricane Fran was directly responsible for 26 deaths. Most of the deaths were caused by wind in the Carolinas, and by flash flooding in Maryland, Pennsylvania, Virginia, and West Virginia. The death toll by state is as follows: North Carolina, 14; Virginia, 4; Maryland, 2; South Carolina, 2; West Virginia, 2; and Pennsylvania, 2.

Storm surge on the North Carolina coast destroyed or seriously damaged numerous beachfront houses. Widespread wind damage to trees and roofs, as well as downed power lines, occurred as Fran moved inland over North Carolina and Virginia. Extensive flooding was responsible for additional damage in the Carolinas, Virginia, West Virginia, Maryland, Ohio, and Pennsylvania.

Nearly a half-million tourists and residents were ordered to evacuate the coast in North and South Carolina. Press reports from Reuters News Service stated that 4.5 million people in the Carolinas and Virginia were left without power.

The American Insurance Services Group reports that Fran caused an estimated $1.6 billion dollars in insured property damage to the United States. This estimate includes $1.275 billion in North Carolina, $20 million in South Carolina, $175 million in Virginia, $50 million in Maryland, $20 million in West Virginia, $40 million in Pennsylvania, and $20 million in Ohio. Using the previously mentioned ratio of two to one between total damage and insured property damage, the total U.S. damage estimate for Fran is $3.2 billion.

4) WARNINGS

Hurricane warnings were posted for the hardest hit portions of the North Carolina coast about 27 h prior to landfall.

g. Tropical Storm Gustav, 26 August–2 September

The origin of Gustav is tracked back to an area of disturbed weather that moved from Africa to the Atlantic Ocean on 24 August accompanied by a low-level cloud circulation. This was the third of three closely spaced tropical cyclones that included Hurricanes Edouard and Fran. The disturbed weather gradually became better organized and a tropical depression formed from this weather at 0000 UTC on the 26th, just south of the Cape Verde Islands.

The depression moved west-southwestward at about 6 m s^{-1} for two days, under the steering of a ridge of high pressure to its north. The track turned toward the northwest on the 28th in response to a mid-Atlantic trough. The trough became a cutoff low that continued to steer the storm northwestward for about five days, after which dissipation occurred. The maximum intensity of Gustav is estimated at 21 m s^{-1} on the 29th. A limiting factor in the storm's development was originally the outflow from Hurricane Fran, which interfered with the organization of convection during the 26th and 27th. Then the cutoff low mentioned above produced a shearing environment that eventually led to Gustav's dissipation on 2 September.

h. Hurricane Hortense, 3–16 September

Hortense became the season's second category four hurricane and fourth category three hurricane on the SSHS. Hortense was a wet hurricane and most of the damage was caused by its accompanying torrential rains. The center of Hortense crossed the southwestern part of Puerto Rico and the eastern tip of the Dominican Republic as a category one hurricane on the SSHS and the associated floods killed at least 21 people. Hortense moved northward over the western Atlantic and crossed Nova Scotia as a weakening hurricane.

1) SYNOPTIC HISTORY

A broad area of low pressure associated with a tropical wave crossed Dakar, Africa, on 30 August. The Dakar vertical-time section during that period showed a well-marked cyclonic wind shift below 700 mb and a 28 m s^{-1} easterly jet at 550 mb. Surface observations indicated that a 1005-mb low associated with the wave moved just south of the Cape Verde Islands on the 31st. Although the system had a well-defined low- to midlevel circulation, satellite images indicated that the deep convection was minimal. The low-pressure area continued moving westward and during 3 September it crossed an array of NOAA drifting buoys. Data from these buoys helped to determine that the system had become a tropical depression at 1200 UTC 3 September.

The depression continued almost due westward around the periphery of a strong high pressure ridge with no significant change in strength. Satellite images suggest that for the next couple of days, deep convection was rather intermittent and not well organized. In fact, on 6 September, the first reconnaissance flight into the system found a broad circulation and only a few squalls. As the depression approached the Lesser Antilles, upper-level winds became more favorable for strengthening and satellite images showed an increase in deep, organized convection. It is estimated that the depression reached tropical storm status at 0600 UTC 7 September. An early reconnaissance flight on that day encountered peak winds of 32 m s^{-1} at flight level and a minimum pressure of 1001 mb, confirming the strengthening of the system.

Hortense moved over Guadeloupe, where the pressure dropped to 998 mb and sustained winds of 24 m s^{-1} with gusts to 36 m s^{-1} were observed. It also produced torrential rains. The tropical cyclone moved westward into the eastern Caribbean and encountered a fast eastward-moving, upper-level short-wave trough. This increased the vertical wind shear, which temporarily inhibited strengthening. In fact, high-resolution visible satellite images clearly showed that the low-level center of the tropical cyclone became exposed during the morning of the 8th. A new burst of deep convection developed over the center later that afternoon and a gradual intensification began. By then, the short wave had moved out of the area and the shear had relaxed. Hortense became a hurricane near 0600 UTC 9 September.

After slowing down just to the south-southeast of Puerto Rico, Hortense took a jog toward the northwest and the center moved over southwestern Puerto Rico. Fixes from the San Juan WSR-88D radar indicate that the eyewall of Hortense reached the coast near Guanica about 0600 UTC on the 10th and moved over the extreme southwestern part of the island for about 2 h.

Hortense moved through the Mona Passage and weakened slightly while the circulation was interacting with land. The center passed very close to Punta Cana, on the eastern tip of Dominican Republic, where a calm was felt and the pressure dropped to 988 mb. The hurricane continued on a northwesterly track and the center moved just east of the Turks and Caicos Islands. Hurricane conditions were observed in some of these islands. Thereafter, Hortense briefly reached category four status with a peak intensity of 62 m s^{-1} and 935-mb minimum pressure at 0000 UTC 13 September. Figure 9 is a satellite image of Hortense as it neared peak intensity.

A developing trough along the eastern United States forced the hurricane to turn northward and increase its

TABLE 5. Hurricane Fran selected surface observations, September 1996.

Location	Press. (mb)	Date/time (UTC)	Sustained wind (m s^{-1})[a]	Peak gust (m s^{-1})	Date/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
South Carolina								
Charleston (CHS)	998.0	05/2234	14	19	05/2330			27.90
Charleston City Office			15	21	05/1850	0.3		22.10
Cheraw	992.2			29	06/0315			33.50
Cherry Grove Pier				35	05/2215			212.3
Conway				25				127.5
Dillon								117.3
Florence			15[g]	29[g]	06/0250			56.10
Garden City Pier				33	05/2215			175.5
Loris				24				130.6
Marion								76.50
Mullins								101.1
Myrtle Beach Pavilion				34	05/2215			178.5
MB Springmaid Pier				34	05/2215	1.1		
North Carolina								
Apex (South RDU)								153.9
Atlantic Beach				45				
Butner								157.7
Cherry Point MCA (NKT)[g]	993.9	06/0255	26	34	06/0244			
Duck Pier	1006.9	06/0800	21	26	06/0900	0.5		
Duke Marine Lab				41		1.7		
Elizabeth City CG (ECG)	1005.1	06/1147	19	25	06/1255			
Fayetteville (FAY)	971.6	06/0430	28	36	06/0430			
Figure Eight Island							3.0–3.7[e]	
Fort Bragg (FBG)	972.3	06/0246	20	33	06/0431			119.4
Graham								168.9
Greensboro (GSO)	984.4	06/0900	15	22	06/0537			99.30
Greenville				45				
Hatteras Pier (NOS)	1004.4	06/0600	19	26	06/0600			
Hatteras ASOS (HSE)			20	25	06/0300			
Holden Beach				31	05/2300			
New River	982.0	05/0230	30	42	06/0156			179.1
Newport								82.30
North Topsail Beach			33		05/0045		2.4–2.7[e]	
Oregon Inlet							0.7	
Pope AFB (POB)	977.6	06/0455	22	30	06/0418			170.7
Raleigh–Durham (RDU)	977.6	06/0653	20	36	06/0453			223.5
Rocky Mount (RWI)[h]	980.7	06/0200	9	20	06/0445			93.5
Rougemount (Durham Co)								152.9
Seymour Johnson (GSB)	981.0	06/0555	28	36	06/0555			162.1
Southport State Pilot Office				47				
Wilmington (ILM)	961.4	06/0036	30	39	05/2349			
Wilmington Tide Gauge						1.7		
Wrightsville Beach							3.0–3.4[e]	
NOAA Ship Whiting[f]	959.9	05/2135						
Virginia								
Charlottesville (CHO)[g]	998.6	06/1645	11	20	06/1045			
Danville (DAN)[g]	987.5	06/1151	17	24	06/0449			
Hot Springs (HSP)[g]	1002.4	06/1400	15	25	06/1540			
Lynchburg (LYH)[g]	990.6	06/1454	9	20	06/1243			
Norfolk NAS (NGU)	1004.6	06/0855	19	28	06/0805	0.8		
Richmond (RIC)	1000.8	06/1141	17	24	06/1141			
Roanoke (ROA)[g]	994.7	06/1254	17	23	06/0954			
Staunton (SHD)[g]	997.6	06/1840	13	22	06/1120			
Washington, D.C.						1.7/2.2[i]		
CMAN Stations								
Frying Pan Shoals (FPSN7)	960.6	05/2300	41	56	05/2100			
Diamond Shoals (DSLN7)	1006.6	06/0500	30	34	06/0400			
Cape Lookout (CLKN7)	996.9	06/0100	29	37	06/0300			
Folly Island (FBIS1)	997.6	05/2200	12	21	05/1900			
Cheasepeake Light	1007.1	06/0900	21	24	06/1000			
Savannah Light (SVLS1)	1002.8	05/2000	15	19	05/1900			

TABLE 5. Continued.

Location	Press. (mb)	Date/time (UTC)	Sustained wind (m s^{-1})[a]	Peak gust (m s^{-1})	Date/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Buoys								
41004	988.7	05/1900	25	33	05/1900			

[a] NWS standard averaging period is 1 min; ASOS and C-MAN are 2 min; buoys are 8 min.
[b] Date/time is for sustained wind when both sustained and gust are listed.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above national geodetic vertical datum.
[e] Estimated.
[f] Docked at Wilmington State Pier.
[g] Taken directly from METAR reports.
[h] Station not reporting from 0200 to 1000 UTC 6 September.
[i] The 1.7-m value occurred on 6 September at 1700 UTC and was the actual storm surge; the 2.2-m value occurred as a much broader peak on 9 Sept at 0418 UTC from freshwater runoff.

forward speed. A weakened Hurricane Hortense rapidly crossed eastern Nova Scotia on 15 September and became extratropical while moving just south of Newfoundland later on that day.

2) METEOROLOGICAL STATISTICS

Hortense was a wet hurricane. It produced about 500 mm of rain in Guadeloupe and dumped between 375

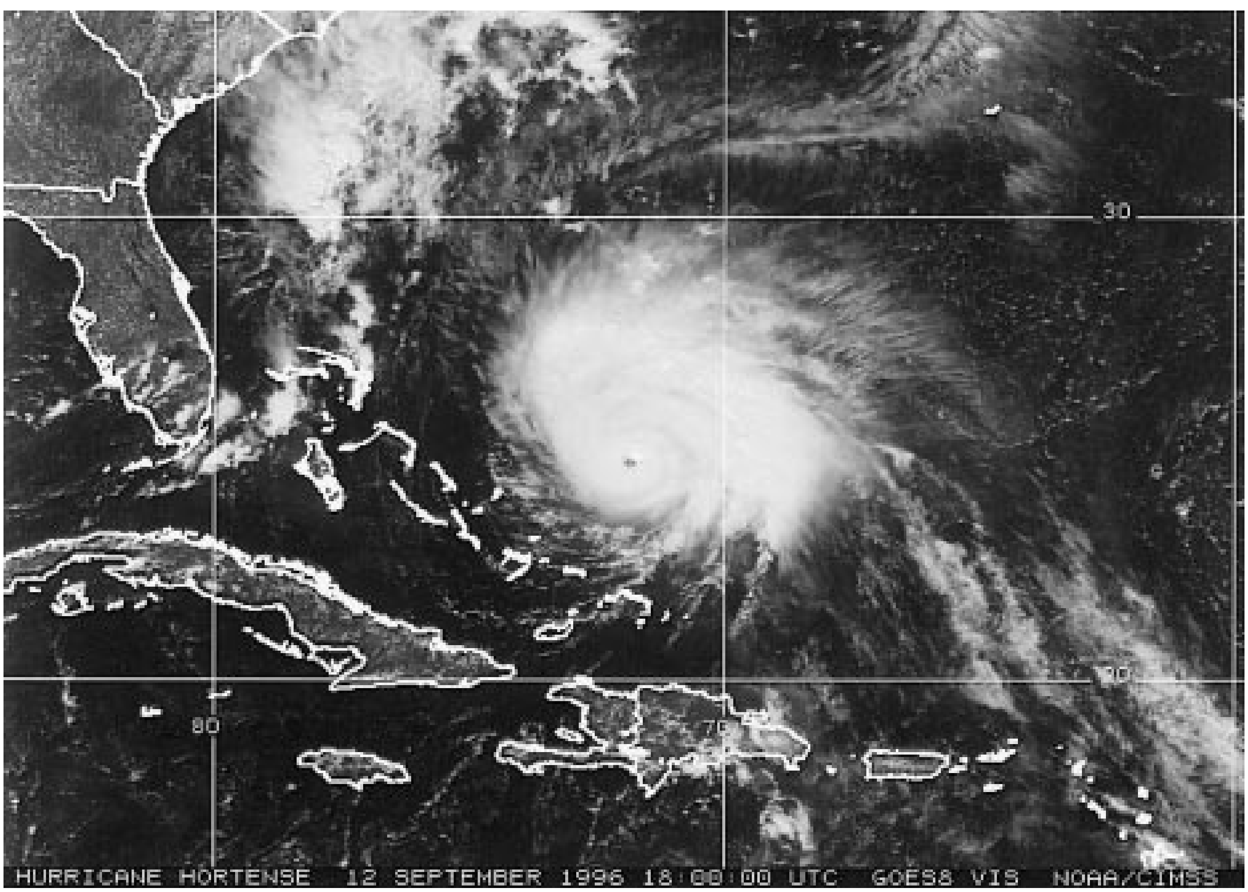

FIG. 9. Visible *GOES-8* satellite image of Hurricane Hortense at 1800 UTC 12 September 1996, just before peak intensity. Note the well-defined eye.

TABLE 6. Hurricane Hortense selected surface observations, September 1996.

Location	Press. (mb)	Date/time (UTC)	Sustained wind (m s^{-1})*	Peak gust	Date/time (UTC)**	Total rain (mm)
Guadeloupe						
Desirade			24	36	8/0000	
Maison du Volcan						317.5
Saint-Claude Bourg						269.2
Le Raizet	998.7	7/2100	24	36		
U.S. Virgin Islands						
Hamilton Arp.			17	23	9/1556	
USDA						305.8
St. Thomas Scott Free						157.5
St. Thomas Univ.						123.2
Hess Oil		9/2130		28	9/2130	
Puerto Rico						
Carolina Arp.	1005.1	10/0615	22	28	10/0555	240.0
Cupey, Rio Piedras				33	10/0735	
Ceiba, Naval Base			21	24	10/2155	
Dominican Rep.						
Punta Cana			41		11/1616	
Punta Cana	987.3	10/1737	Calm			
El Macao	990	10/unknown	31	38		
Puerto Plata	989	10/2025	33	38		
San Rafael de Yuma		10/2030	31	40	10/2030	
Samana	1007	11/0047	18	26		
Turks and Caicos						
Grand Turks			27	40	11/1620	
Bahamas						
Mayaguana	973	11/2245	33	40	11/2245	
Canada						
St. Paul Island	994.4	15/0742	34	42	15/0742	
Sidney	984.8	15/0900	15	26	15/0448	102.1
Forchu Head			22	27	15/0348	65.4
Hart Island	978.4	15/0545	16	25	15/0145	
Beaver Island	982.8	15/0144	22	28	15/0144	136.6
Halifax Intl.	989.8	15/0200	10	20	15/0200	
Shearwater	985.0	15/0200	15	22	15/0200	99.6
Cape Sable				32	Unknown	
Cape Race, NF	994.0	15/2043	21	25	15/2043	
Canadian buoys						
44144	997.6	15/0000	25			
44144	997.6	15/0300	31			
44144	995.1	15/0600	27			
44144	999.1	15/0900	21			

* Averaging period is 1 min for U.S. stations and 10 min otherwise.
** Date/time is for sustained wind when both sustained and gust are given.

and 500 mm of rain over Puerto Rico and the U.S. Virgin Islands with possibly higher amounts in the mountains. The Dominican Republic also experienced torrential rains with a maximum of 489 mm in the town of San Rafael de Yuma.

There are unconfirmed reports of gusts to 49 m s^{-1} over the southwestern tip of Puerto Rico about 0800 UTC 10 September. These strong winds may have been a local effect caused by the Venturi effect (acceleration between walls of structures). Residents of the southwestern portion of Puerto Rico reported calm winds and that the ''stars were out'' as the eye crossed the area. Peak winds of hurricane force were reported in the Dominican Republic, Grand Turk Island, and (several days later) in Nova Scotia. Table 6 contains selected surface observations associated with Hortense.

Hortense was upgraded to a category four hurricane of 62 m s^{-1} based on a report from a Hurricane Hunter plane of 63 m s^{-1} at 700 mb in the northeast quadrant at 2130 UTC followed by 66 m s^{-1} in the southeast quadrant at 2220 UTC. The plane also reported a minimum pressure of 935 mb, a closed eyewall of 20 km in diameter and an ''excellent'' stadium effect (outward slope with height of the convective clouds in the eyewall) at 2323 UTC. In addition, satellite objective T numbers were near 6.5 on the Dvorak scale, corresponding to a maximum wind speed of 65 m s^{-1} and a pressure of 935 mb. Visible satellite images revealed a spectacular cloud pattern with a clearly distinct eye during that time.

3) CASUALTY AND DAMAGE STATISTICS

Hortense devastated portions of Puerto Rico but most of the damage was not done by winds or storm surge. Instead, torrential rains produced flash floods and mudslides that killed at least 18 people. A report from FEMA indicates that nearly 11 500 homes were severely damaged by Hortense and agricultural losses were near $127 million. In addition, there was significant inland flooding in the low-lying areas as well as serious coastal flooding in Nagabo, Guayanilla, and Ponce.

In the Dominican Republic, three people were killed, 21 were reported missing, and there was significant damage primarily in the northeastern portion of the country. A school and a church were demolished by winds or falling trees. Numerous houses were damaged and several electrical poles went down. There was a 2.7-min storm surge along the northeast coast. Roads were blocked due to flooding both from the storm surge and from torrential rains. In Samana, 80% of the agriculture was damaged.

4) WARNINGS

A hurricane watch and a tropical storm warning were issued for Puerto Rico when Hortense was still in the developing stage over the Leeward Islands. Hortense became sheared and weakened over the eastern Caribbean and the official intensity forecast called for no significant change in strength. Consequently, the hurricane watch for Puerto Rico was discontinued but the tropical storm warning remained in effect. However, it was emphasized in the tropical cyclone discussions issued by the NHC that there was low confidence in the intensity forecast. Hortense reintensified and a hurricane warning was issued for Puerto Rico about 14 h before landfall.

Hurricane warnings were in place for the entire island because hurricanes can often wobble along the track. These wobbles are in general difficult if not impossible to forecast but are taken into consideration when issuing watches and warnings. Hortense jogged to the north of the main track when it was located just south of Puerto Rico. That wobble or jog brought the center of the hurricane over the extreme southwestern portion of the island.

From the time the tropical cyclone was located over the Lesser Antilles, NHC advisories as well as San Juan Forecast Office statements indicated that 125–255 mm of rain, with larger totals over mountains, were expected along the path of Hortense. Indeed, most of the damage produced by Hortense was caused by rainfall, which was largest over the high terrain.

i. Hurricane Isidore, 24 September–1 October

1) SYNOPTIC HISTORY

Hurricane Isidore formed from a tropical wave that had a well-defined cyclonic circulation of clouds and was clearly marked at midlevels in the Dakar sounding data when it crossed the west coast of Africa on 22 September 1996. Deep convection increased and satellite analysts provided the first Dvorak scale T numbers on the 23d, while the circulation passed to the south of the Cape Verde Islands. Thunderstorms became more concentrated, Dvorak T numbers from the Tropical Prediction Center's (TPC's) Tropical Analysis and Forecast Branch (TAFB) increased to 2.0, and ship reports suggested the formation of a surface circulation by 1200 UTC on the 24th. This indicates the start of the tropical depression stage of Isidore.

The tropical cyclone was initially situated to the south of a deep-layer anticyclone. It moved toward the west-northwest at 8–10 m s^{-1} and intensified. An intense convective band wrapped around the center and the system became a tropical storm on the 25th. Further intensification ensued, an eye began to appear intermittently and Isidore reached hurricane intensity on the following day.

The mature and dissipating stages of Isidore were influenced by a well-defined mid- through upper-level low that was quasi-stationary near 25°N, 45°–50°W through the 25th. The low then weakened and lifted northward to near 35°N, but was reinvigorated there by its interaction with a midlatitude short-wave trough that passed by to the north on the 27–28th. The steering currents on the east side of the low gradually turned Isidore generally toward the north. The forward speed slowed to about 5 m s^{-1} during the turn on the 29th, but then increased to 10 m s^{-1} on 1 October. During this period, Isidore reached its estimated maximum intensity of 51 m s^{-1} winds (Fig. 10). The eye disappeared on the 29th and upper-level westerly to southwesterly winds of around 30 m s^{-1} contributed to a shearing and weakening of Isidore, down to a tropical storm with an exposed low-level cloud center on the 29th, and then to a tropical depression on the 1st. Deep convection dispersed and Isidore transformed to extratropical status on the 2d.

2) METEOROLOGICAL STATISTICS

Isidore passed through the eastern part of the NOAA drifting buoy network. Observations from those platforms helped define the western part of the cyclone's low-level wind field. The hurricane's peak intensity is based on satellite-derived estimates. The ship *Magnific* reported southeast (140°) winds of 30 m s^{-1} at 1200

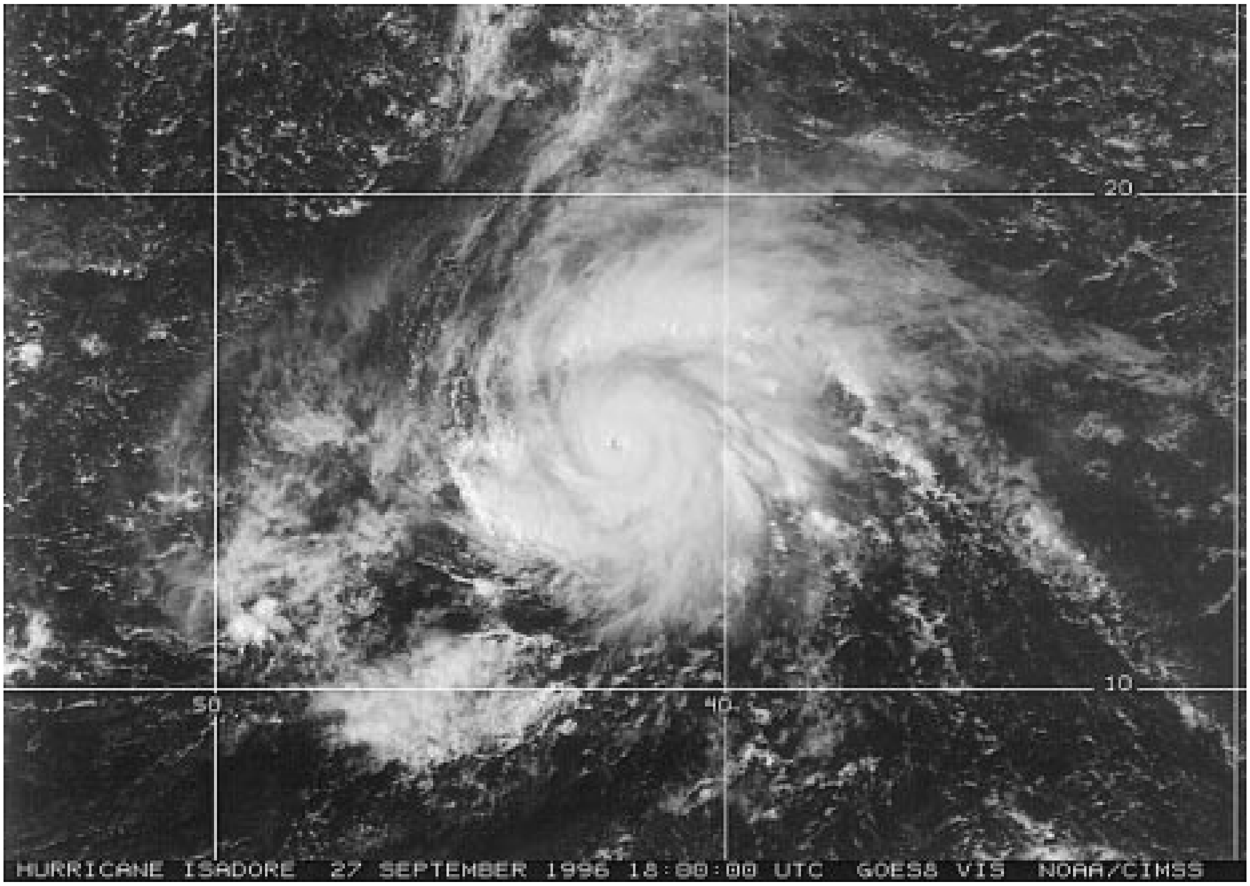

FIG. 10. Visible *GOES-8* satellite image of Hurricane Isidore at 1800 UTC 27 September 1996, just before peak intensity.

UTC on 30 September, while located at 25.1°N, 37.2°W, about 325 km from the center of Isidore. The reliability of that measurement is in doubt because the estimated maximum surface wind near the center was 26 m s^{-1} at that time. This was the only surface sustained wind report of 17 m s^{-1} or higher to be possibly associated with Isidore.

3) CASUALTY AND DAMAGE STATISTICS

No reports of casualties or damages due to Isidore were received.

j. Tropical Storm Josephine, 4–8 October

Josephine made landfall in the Apalachee Bay, Florida, area as a 31 m s^{-1} storm.

1) SYNOPTIC HISTORY

The origin of Josephine does not appear to be directly related to a tropical wave. On 29–30 September, a front that had moved over the southwestern Gulf of Mexico stalled over the area. A broad area of cloudiness and showers was noted over the southwest gulf beginning around this period. The disturbed weather appears to have been caused mainly by the front but could also be partially ascribed to a tropical wave that passed over the extreme southern gulf on 29 September. This wave led to the formation of Hurricane Hernan in the eastern Pacific. A broad area of low pressure developed near the Bay of Campeche on 1–2 October, but upper-tropospheric winds were only marginally favorable, and the associated deep convection was not persistent until the 3d. The surface circulation became better defined on the 4th, on which day the system received its initial Dvorak classification from the TAFB. Meanwhile, the strong pressure gradient between the low and a large high pressure system centered near the Great Lakes began to produce strong winds across the northern Gulf of Mexico.

A U.S. Air Force Hurricane Hunter plane was dispatched into the system on the afternoon of the 4th, and data from the aircraft indicated that a tropical cyclone, Tropical Depression Ten, had formed. Based on aircraft, surface, and satellite data, the estimated time of genesis is 1800 UTC 4 October. Initially, steering currents were weak, and the depression moved slowly north-northeastward on the 4th and 5th. Southwesterly shearing was present over the system, and there was no significant increase in organization until the 6th. Even though the depression did not intensify during the first couple of days of its existence, the strong pressure gradient persisted over the northern gulf, producing gale force winds over that area. By midday on the 6th, aircraft observations indicated that the central pressure had dropped to 1001 mb. Banding features on satellite images became better defined, and it is estimated that the cyclone strengthened into Tropical Storm Josephine at 1800 UTC 6 October.

A strong midlatitude, deep-layer trough began to dominate the eastern half of the United States, and on the 6th and 7th the tropical storm was steered eastward to northeastward, at an increasing forward speed, on the southeast flank of this trough. Early on the 7th, Josephine strengthened significantly and was nearing hurricane intensity. This development trend proved to be temporary, however, as vertical shear began to increase over the northeast Gulf. The storm's intensity leveled off at 31 m s^{-1}, and Josephine's cloud structure was asymmetric, with nearly all of the deep convection northeast of the center. The center moved over Apalachee Bay around 0000 UTC on the 8th, and crossed the coast in a relatively uninhabited region of north Florida, in Taylor County, at about 0330 UTC.

Josephine was already beginning to lose its tropical characteristics when it crossed the coast, since the air temperature at Keaton Beach dropped about 6°C in an hour shortly after the storm moved inland. The system became an extratropical cyclone by the time it entered Georgia at 0600 UTC 8 October. The cyclone's forward speed increased dramatically, to near 21 m s^{-1}, and the extratropical low raced northeastward along and/or near the U.S. east coast, passing close to Cape Cod at 0600 UTC on the 9th. The low traversed Nova Scotia and Newfoundland on 9–10 October, and then emerged out over the North Atlantic. It moved eastward for a day or two, slowing its forward speed. Then the system tracked counterclockwise within a deep-layer cyclonic flow regime over the northeastern Atlantic on the 12th through the 15th. Finally, the extratropical remnant of Josephine merged with a larger extratropical cyclone in the vicinity of Iceland on 16 October.

2) Meteorological statistics

The minimum central pressure reported in Josephine, by the Hurricane Hunters, was 981 mb at 1135 UTC 7 October. Highest flight-level (850 mb) winds near that time were 34 m s^{-1}. The maximum flight-level wind reported by reconnaissance aircraft was 38 m s^{-1} at 0050 UTC 8 October. Josephine's maximum surface winds were estimated to be 31 m s^{-1} from 1200 UTC on the 7th up to landfall. Aircraft observations indicated that, at most, a partial eyewall was present on three center fixes during the above period.

Storm surge flooding was significant from the Tampa area northward to eastern Apalachee Bay, with maximum values near 2.8 m above normal tide levels.

Table 7 lists selected surface observations associated with Josephine.

3) Casualty and damage statistics

Total insured losses from Josephine in Florida, Georgia, South Carolina, North Carolina, and Virginia are estimated to be $65 million. This gives a rough estimate of $130 million for the total storm damage. There were no deaths that could be directly attributed to Josephine.

4) Warnings

A tropical storm warning was issued for the Gulf of Mexico coast from Apalachicola to Venice, Florida, at 0900 UTC 7 October, about 19 h prior to landfall. This was upgraded to a hurricane warning at 1200 UTC on the 7th, as Josephine neared hurricane intensity. A tropical storm warning was also issued for the Atlantic coast from Cape Canaveral, Florida, to Little River Inlet, South Carolina, at 1500 UTC on the 7th.

k. Tropical Storm Kyle, 11–12 October

Kyle was a small, short-lived tropical storm that formed over the northwestern Caribbean Sea in mid-October. It moved onshore near the border of Guatemala and Honduras as a weakening tropical depression and quickly dissipated. There were no significant effects on land associated with this system.

1) Synoptic history

Satellite imagery and rawinsonde data show that a tropical wave moved off the west coast of Africa on 27 September. The wave was tracked in satellite imagery to the Lesser Antilles on 5 October and to the western Caribbean Sea on the 9th where it interacted with a frontal cloud band. Surface analysis indicated a broad 1010-mb low over the northwest Caribbean Sea at 0000 UTC 11 October. At this time, anticyclonic flow aloft was seen in animation of satellite imagery above disorganized convective activity.

A well-defined convective cloud band developed and poststorm analysis suggests that a tropical depression formed from the disturbance near 1200 UTC 11 October while centered about midway between Swan Island and the coast of Belize. Steering currents were weak and the depression began drifting toward the southwest.

The tropical cyclone quickly intensified and is estimated to have become a tropical storm at 1800 UTC on the 11th. A small central dense overcast was evident in satellite imagery by the time the first reconnaissance

TABLE 7. Tropical Storm Josephine selected surface observations, October 1996.

Location	Press. (mb)	Date/time (UTC)	Sustained wind (m s^{-1})[a]	Peak gust (m s^{-1})	Date/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Florida								
Arcadia/Horse Ck								143.8
Brooksville	995.9	08/0037	11	19	07/1917			40.10
Cedar Key C-MAN	992.6	08/0000	18	22	08/0200			
Clearwater tide gauge			19	26	08/0100			
Dekle Beach							1.8	
Foley (Taylor County)								215.9
Fort Myers	999.7	08/1007	19	24	08/0947			48.80
Horseshoe Beach				23	08/0223			
Inverness								74.40
Jacksonville airport	992.2	08/0256		21	08/0654			156.2
Jacksonville Naval Air Stn.				19	08/0650			149.4
Jacksonville Cecil Field	993.2	08/0337		22	08/0124			148.8
Keaton Beach C-MAN	991.9	08/0100		15[e]	08/0000			
Lake Iamonia (Leon County)								145.4
Lakeland	999.3	07/2351	10	14	07/2351			38.40
Macdill AFB	997.3	07/2355	15	25	08/0410			89.20
Madison								129.5
Mayport Naval Station	993.2	08/0555		20	08/0758			106.4
Melbourne	999.0	08/0750	8	18	08/0715			39.90
Mill Creek (Madison County)								156.0
Monticello								114.3
New Port Richey	996.3	08/0023	13	19	08/0005			64.30
Old Port Tampa			18	29	08/0524			
Orlando (MCO)	997.3	08/0804	13	18	08/0323			19.80
Perry								128.8
Punta Gorda	999.3	08/0954	19	25	08/1016			65.8
Ruskin								
Secatan (Taylor County)								200.1
St. Petersburg	996.6	07/2355	15	20	08/0051			73.7
St. Pete pier			14	20	08/0054			
St. Petersburg uncom. ASOS	995.9	08/0014	19	22	08/0344			
Sarasota/Bradenton Airport	998.3	07/2250	14	21	08/0150			65.3
Steinhatchee							2.1	
Sunshine Skyway	993.0	08/0154	20	32	07/2345			
Suwannee							2.8	
Tallahassee	993.5	08/0229	13	18	08/0229			197.9
Tampa airport	996.6	08/0029	12	24	08/0257			
Tampa Palms (Ira Brenner)								140.5
Venice	1000.2	07/2300	17	22	08/0000			
Winter Haven	998.3	08/1026	14	18	08/0627			70.1

[a] National Weather Service standard averaging period is 1 min; ASOS and C-MAN are 2 min; buoys are 8 min.
[b] Date/time is for sustained wind when both sustained and gust are listed.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above national geodetic vertical datum.
[e] May not have been peak value.

aircraft investigated the cyclone during the afternoon. Maximum sustained surface winds of 23 m s^{-1} are estimated to have occurred from 1800 UTC on the 11th to 0000 UTC on the 12th. The minimum central pressure of 1001 mb occurred near this time.

Upper-level southwesterly shear soon increased, resulting in a decrease of the deep convection. It is estimated that Kyle weakened to a tropical depression by 1200 UTC 12 October. The center of the rapidly dissipating depression moved onshore near the border between Guatemala and Honduras 6 h later.

2) METEOROLOGICAL STATISTICS

The maximum wind speed recorded from aircraft in Kyle was 25 m s^{-1} from a flight level of 457 m at 1908 UTC 11 October. The minimum observed central pressure was 1001 mb at 2145 UTC on the 11th, and was extrapolated from 457 m.

3) CASUALTY AND DAMAGE STATISTICS

No reports of casualties or damages were received by the NHC.

4) WARNINGS

A tropical storm warning and hurricane watch were issued from Felipe Carillo Puerto, Mexico, to Cabo Camaron, Honduras, including Belize and the adjacent islands at 2100 UTC 11 October. The hurricane watch was discontinued at 1200 UTC on the 12th, and the tropical storm warnings were discontinued 3 h later.

l. Hurricane Lili, 14–27 October

Lili was the sixth category three Atlantic hurricane on the SSHS during 1996. It moved across central Cuba and the central Bahamas with sustained winds in the 41–46 m s^{-1} range.

1) SYNOPTIC HISTORY

A tropical wave moved from Africa to the Atlantic Ocean on 4 October accompanied by a large cyclonic rotation of low clouds and a midtropospheric jet. The wave moved westward under an unfavorably strong vertical shear environment and, on 11 October, passed through the Windward Islands where a marked wind shift and large 24-h pressure changes were observed. It reached the southwestern Caribbean on the 13th, where a pre-existing area of low surface pressure was located.

The system developed a well-defined low-level circulation and became a tropical depression at about 1200 UTC on the 14th, just east of Nicaragua, and began moving northwestward at about 4 m s^{-1}.

Over the next two days, the depression turned north and then north-northeastward in response to a weak mid- to upper-level low over the Gulf of Mexico. Although there appeared to be considerable convective banding and falling surface pressures, aircraft data showed that the depression did not strengthen to a storm until early on the 16th, when the center was close to Swan Island. With a well-established outflow over the circulation, Lili strengthened to a hurricane on the 17th.

Moving slowly, the center executed a small cyclonic loop just north of Swan Island on the 16th and wobbled again on the 17th as it approached the Isle of Youth, Cuba. The center passed over the eastern side of the Isle of Youth near 0100 UTC on the 18th and made landfall on the south coast of mainland Cuba in Matanzas Province at 0930 UTC. The maximum sustained surface winds had strengthened to near 44 m s^{-1} at landfall as Lili turned eastward for a 12-h crossing of central Cuba on the 18th.

A major trough in the westerlies moved to the eastern United States as Lili approached Cuba and this resulted in the hurricane accelerating mostly northeastward to a forward speed of near 13 m s^{-1} by late on the 19th.

The hurricane maintained its strength over Cuba. The pressure was measured by aircraft at 975 mb just before landfall and the same pressure was measured again when the eye moved back over water. Accelerating toward the Bahamas, there was further strengthening and Lili went through the central Bahamas early on the 19th with sustained winds of near 46 m s^{-1}. The eye, 55–75 km wide, moved over Great Exuma and San Salvador and the eyewall affected portions of Long Island, Rum Cay, and Cat Island.

Shortly thereafter, at 0000 UTC on the 20th and just east of the Bahamas, the hurricane reached its peak strength, with an estimated 51 m s^{-1} maximum sustained wind and a central surface pressure of 960 mb. Figure 11 is a visible satellite image of Lili as it neared its maximum intensity.

Lili continued moving northeastward, its center passing about 240 km southeast of Bermuda on the 20th. By now, the strongest winds were on the southeast side of the center and Bermuda's sustained winds did not reach tropical storm force. Lili's winds gradually decreased from the 51 m s^{-1} maximum on the 20th to 33 m s^{-1} on the 21st.

On the 22d, having turned eastward, the forward motion decelerated to almost stationary as a midlevel shortwave high pressure ridge came into longitudinal phase with Lili. Lili drifted erratically eastward across the central North Atlantic until the 24th, when another acceleration toward the northeast began. Lili reintensified to 44 m s^{-1} on the 25th and finally weakened to a tropical storm on the 26th, as the center was passing about 555 km northwest of the Azores. Lili is estimated to have become extratropical on the 27th. It remained a 28 m s^{-1} extratropical storm until crossing Great Britain on the 28th. Its remnants crossed the northern European mainland on the 29th.

2) METEOROLOGICAL STATISTICS

Aircraft data was available from 11 aircraft reconnaissance missions into Lili over a 5-day period, from the 15th to the 20th, and resulted in 37 center penetrations. Seven of the missions were performed by the Hurricane Hunters. The other four missions were performed by the NOAA research aircraft when Lili's center was near Cuba. The maximum wind speed measured aboard the aircraft was 58 m s^{-1} at the 700-mb level, at 0855 UTC on the 19th in the southeast quadrant. The minimum surface pressure from the aircraft was 960 mb at 1218 UTC on the 19th.

Table 8 lists a selection of significant surface observations. The highest sustained wind from Cuba was a 10-min average of 41 m s^{-1} reported from Cayo Largo del Sur, an island located about 95 km east of the Isle of Youth. The center was over mainland Cuba and about 75 km north of the island at the time of the report. A 41 m s^{-1} 10-min wind was also reported from San Salvador in the central Bahamas at the time that the center was located about 28 km miles to its north-northwest.

Two hours after the report from San Salvador, at 1200 UTC on the 19th, a ship, the *Chiquita Bremen,* observed

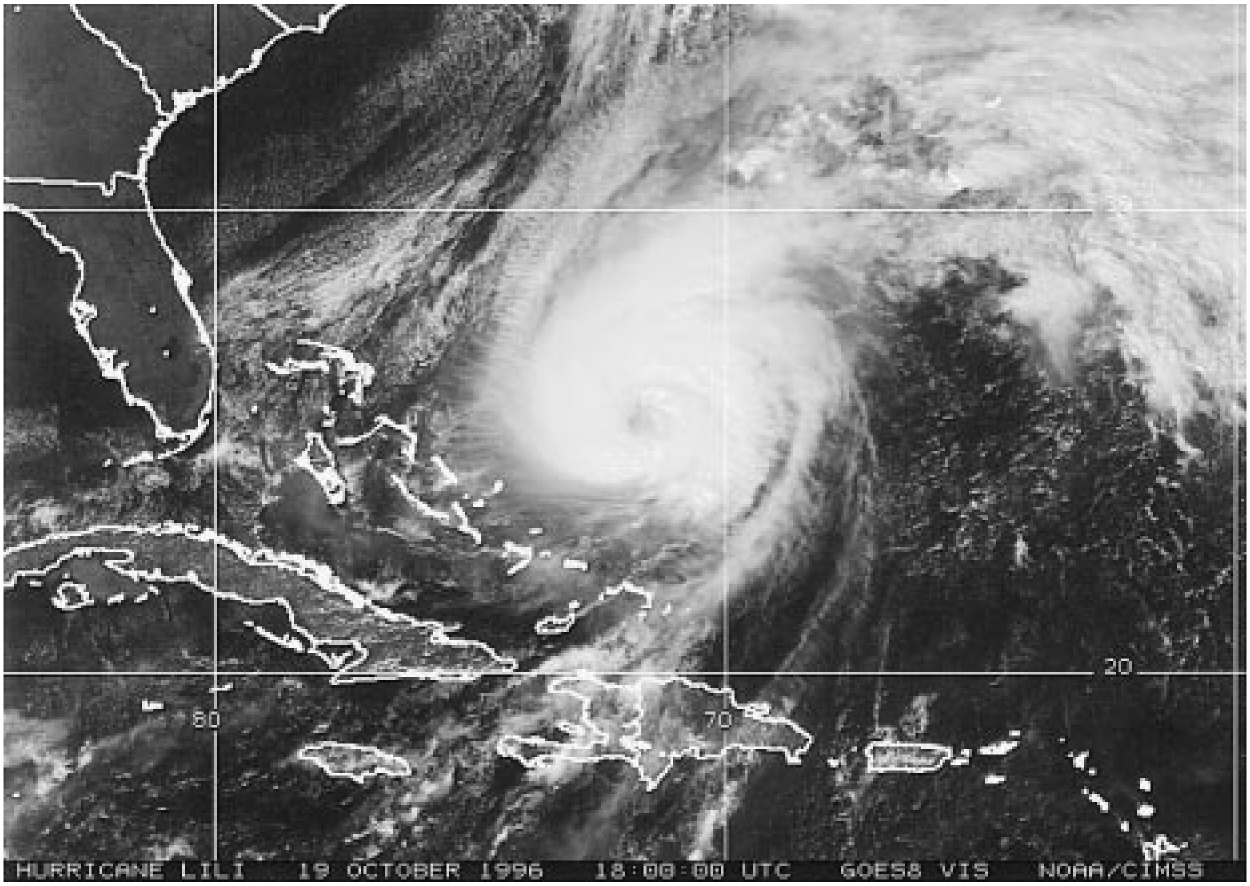

FIG. 11. Visible *GOES-8* satellite image of Hurricane Lili at 1800 UTC 19 October 1996, shortly after it reached peak intensity.

a wind gust of 51 m s^{-1} while located about 37 km south of the center.

There was heavy rainfall over portions of Cuba with over 660 mm accumulated at La Moza.

Sustained wind speeds to about 23 m s^{-1} with gusts to as high as 40 m s^{-1} (from Alderney, a Channel Island) were reported from Great Britain, when Lili was extratropical, on the 28th and 29th.

3) Casualty and damage statistics

During the formative state of the tropical cyclone, heavy rain and flooding occurred over portions of Central America. The Associated Press reported five drowning deaths in Honduras and three deaths in Costa Rico. In addition, thousands were left homeless in both of these countries and there was flooding in Nicaragua as well.

In Cuba, there was extensive damage to agriculture and thousands of people were made homeless according to Reuters News. Reuters also reported that six were killed in Great Britain during Lili's extratropical stage. Four died in traffic accidents and two fishermen were swept into the sea there.

In the Bahamas, reports from Georgetown on Great Exuma Island suggest that many houses were substantially damaged and many boats were sunk. A storm tide of 4.6 m above mean sea level was estimated on the north side of Great Exuma.

4) Warnings

Hurricane warnings were issued for the Isle of Youth, Cuba, almost 24 h before hurricane conditions began. The lead time for the mainland Cuba landfall was 30 h. The hurricane warning lead time for the central Bahamas was somewhat less: 15–18 h. A hurricane watch was issued for Cuba 52 h before the center reached the Isle of Youth and Lili was only a tropical depression at the time of issuance.

A point of interest is at 1200 UTC on the 18th, when the center had just made landfall in Cuba and was accelerating in the general direction of southeast Florida and perhaps less than 24 h away. No warnings were issued for the Miami and Fort Lauderdale metropolitan areas. This was possible because of the confidence in the guidance models that showed the hurricane turning northeastward and missing south Florida. Tropical storm

TABLE 8. Hurricane Lili selected surface observations, October 1996.

Location	Press. (mb)	Date/time (UTC)	Sustained wind (m s^{-1})[a]	Peak gust	Date/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Cuba								
Abreusk, Guillermo Moncada								596.7
Agramonte, Union de Reyes								
Limonar								326.4
Cayo Largo del Sur	986.1	18/1050	41 (10 min)	54	18/1050			
Jucaro			21 (10 min)	26	18/1945			230.1
Cienfuegos				50	18/1550			
Guines								224.5
Havana			15 (10 min)	36	18/1050			
La Moza								661.4
Nueva Gerona, Isle of Youth			31 (10 min)	36	18/0448			
Punta del Este, Isle of Youth	977	18/0200						
Santo Domingo				50	18/1855			
Trinidad								21.2
Virgen del Camino								7.0
Florida								
Dry Tortugas DRYF1	1005.4	18/2000	11 (2 min)	13	18/1800			
Key West	1003.5	18/2053	9	11	18/1904			40.9
Molasses Reef MLRF1	1003.1	18/2200	11 (2 min)	13	18/1500			
Sand Key SANF1	1003.5	18/2000	13 (2 min)	17	18/1100			
Sombrero Key SMKF1	1003.4	18/2000	14 (2 min)	17	18/1400			
Bahamas								
Lee Stocking Island airport[e]			18 (60 min)	27				
Lee Stocking Island hill[e]			21 (60 min)	31				
San Salvador	963.5	19/1000	41 (10 min)		19/1000			
Warderick Wells[e]			20 (60 min)	23				

[a] Averaging period is 1 min unless otherwise indicated.
[b] Date/time is for sustained wind when both sustained and gust are given.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above national geodetic vertical datum.
[e] Courtesy of the Caribbean Marine Research Center.

warnings were issued for the Florida Keys, however, and Table 8 shows that sustained winds did not quite reach tropical storm force there.

m. Hurricane Marco, 16–26 November

Hurricane Marco drifted aimlessly over the western Caribbean Sea for about a week, threatening several land areas but never making landfall.

1) SYNOPTIC HISTORY

A cold front moved into the northwestern Caribbean on 9 November, followed by an abnormally strong high pressure system that dominated the eastern United States. The front became nearly stationary and interacted with a series of westward-moving tropical waves. The intertropical convergence zone became active in the southwestern Caribbean as monsoonal southwesterly flow from the eastern Pacific reached the area. As early as 13 November, surface analysis showed a weak low pressure area just north of Colombia and, by the next day, there was a well-defined but broad low-level circulation between Jamaica and Honduras. At that time, the system did not meet the criteria for tropical depression status because the convection was neither concentrated nor organized near a center of circulation. In fact, there were several smaller centers of circulation embedded within a much larger system. The broad area of low pressure drifted northward for a couple of days, and in combination with a high pressure system over the United States, produced gale force winds over Florida, Cuba, the Bahamas, and the Gulf of Mexico.

The convection gradually became organized south of Jamaica and a poststorm analysis of the surface and reconnaissance aircraft data indicates that the system became a tropical depression at 1800 UTC 16 November. The poorly defined tropical depression moved generally southward and encountered a much better upper-level environment for strengthening. It became a tropical storm at 0600 UTC 19 November and then moved on a slow east-northeast track. Marco briefly reached hurricane status at 0600 UTC 20 November, with maximum winds of 33 m s^{-1} and a minimum pressure of 983 mb. Thereafter, Marco was hit by strong upper-level westerlies and weakened rapidly to a tropical depression at 1800 UTC 23 November. It was then located just to the southeast of Jamaica.

TABLE 9. Comparison of mean 1996 Atlantic official track forecast errors (rounded to the nearest km) and CLIPER errors with 1986–95 10-yr average. A track forecast error is defined as the great-circle distance between a forecast position and a poststorm analysis best track position for the same time. Cases include all tropical storms and hurricanes. Also shown is the range of the track forecast errors (km) for each forecast period.

	Forecast period (h)					
	0	12	24	36	48	72
1996 average official	19	79	133	186	237	352
1996 average CLIPER	19	89	178	285	396	630
(Number of cases)	(290)	(286)	(260)	(236)	(217)	(183)
1986–95 average official	26	91	173	252	335	506
1996 official departure from 1986–95 average	−27%	−13%	−23%	−26%	−29%	−30%
1986–95 average CLIPER	26	106	214	331	448	654
1996 average CLIPER departure from 1986–95 average	−27%	−16%	−17%	−14%	−12%	−4%
1996 official error range	0–106	0–374	15–365	11–446	0–596	15–1135

Once a midlevel ridge rebuilt over the Bahamas and Florida, Marco turned toward the west and west-northwest and regained tropical storm strength. The tropical cyclone was south of the western tip of Cuba when it interacted with a cold front and dissipated by 1800 UTC 26 November. The remnants of Marco drifted southward and produced heavy rains over Honduras and Belize.

Marco was characterized by its numerous intensity fluctuations. For several consecutive days, Marco became disorganized during the afternoon when the low-level center was practically exposed. The central pressure rose each afternoon as well. This was followed by a significant redevelopment of the convection and a drop in pressure during the nights and early mornings. These fluctuations could be attributed to the interaction of Marco with a series of fast-moving short-wave troughs and ridges observed on water vapor imagery. These features increased and then relaxed the shear while moving through the area.

For about eight consecutive days before Marco developed, the National Weather Service's Medium-Range Forecast Model consistently forecast the formation of a tropical cyclone in the western Caribbean. This formation was also suggested by both the United Kingdom Meteorological Office and European Centre for Medium-Range Weather Forecasts global models a couple of days later.

2) METEOROLOGICAL STATISTICS

Marco was upgraded to a hurricane based on a 32 m s^{-1} 1-min sustained wind reported by a U.S. Navy ship. Shortly thereafter, a reconnaissance plane reported a minimum pressure of 983 mb and a 1-s wind of 46 m s^{-1} at the 850-mb flight level. This was a pressure drop of 11 mb in 1 h and 40 min. During that flight, the crew reported a volatile center structure with severe turbulence, extreme rainfall, and hail. Satellite images showed very cold convective tops at that time. During the early morning flight of 22 November, the reconnaissance plane observed another pressure drop from 996 to 985 mb in about 2 h, and a 9-km diameter eye. The vessel *Jo Spruce* reported sustained winds of 29 m s^{-1} and a pressure of 1007.5 mb at 1200 UTC 25 November. This observation was used operationally to upgrade Marco to a tropical storm for the second time.

3) CASUALTY AND DAMAGE STATISTICS

Marco never hit land but its large circulation brought heavy rains to Central America and Hispaniola. These rains produced floods and mudslides causing at least eight deaths. The interaction of Marco during its developing stage with the strong high over the U.S. resulted in gale force winds that produced beach erosion along the east coast of Florida.

4) WARNINGS

Because Marco moved very slowly, watches or warnings were in place for Jamaica for several days.

3. Forecast verification

For all tropical and subtropical cyclones identified operationally in the North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico, the NHC issues an ''official forecast'' of the center position and maximum 1-min wind speed. These forecasts are issued at 6-h intervals, for the periods of 12, 24, 36, 48, and 72 h. At the end of every year's hurricane season, the forecasts are verified by comparing the forecast positions and intensities to the postanalysis best track of each cyclone.

Table 9 lists the average official track forecast errors for 1996, and the average official forecast errors for 1986 through 1995. It can be seen that these errors were 13%–30% lower than the most recent 10-yr averages at all time periods. The number of cases is rather large, so these statistics are likely to be meaningful. Also shown in this table are the mean 1996 errors for the

TABLE 10. Comparison of average official and average absolute official maximum 1-min wind speed forecast errors (rounded to the nearest 0.1 m s^{-1}) and corresponding SHIFOR errors for tropical storms and hurricanes in the Atlantic basin for 1996 with 1990–95 6-yr average. Also shown is the range of wind speed forecast errors (m s^{-1}) for each forecast period. Error = forecast − observed.

	Forecast period (h)					
	0	12	24	36	48	72
1996 average official	−1.1	−1.0	−1.4	−1.9	−2.6	−3.0
1996 average absolute official	2.1	3.6	5.3	6.7	8.0	9.3
1996 average SHIFOR	−1.1	−1.0	−1.6	−2.5	−3.4	−5.2
1996 average absolute SHIFOR	2.1	4.7	6.5	7.8	9.4	11.2
(Number of cases)	(290)	(286)	(260)	(236)	(217)	(183)
1990–95 average official	−0.9	−0.6	−0.6	−0.9	−1.6	−1.8
1990–95 average absolute official	1.7	3.4	5.3	6.7	8.1	9.9
1996 average absolute official departure from 1990–95 average absolute official	+24%	+6%	0%	0%	−1%	−6%
1990–95 average SHIFOR	−0.9	−0.5	−0.7	−1.0	−1.3	−2.2
1990–95 average absolute SHIFOR	1.7	4.2	6.0	7.2	8.2	9.1
1996 average absolute SHIFOR departure from 1990–95 average	+24%	+12%	+8%	+8%	+15%	+23%
1996 official error range	−10.3 to +10.3	−12.9 to +12.9	−23.1 to +18.0	−23.1 to +18.0	−28.3 to +15.4	−33.4 to +25.7

climatology and persistence forecast model, CLIPER (Neumann 1972), and the most recent 10-yr average CLIPER errors. One can see that the mean 1996 CLIPER errors are lower than the longer-term averages at all time periods. This is consistent with the fact that 1996 featured a preponderance of tropical cyclones in the low latitudes, where steering currents tend to be relatively unchanging and the motion tends be more persistent than in the higher latitudes. Thus, to some degree, the high accuracy of the 1996 official forecasts may be attributed to having tropical cyclones that were relatively easy to forecast. On the other hand, the mean 1996 CLIPER errors were only slightly lower than average at 48 and 72 h, yet the mean 1996 official errors showed the biggest improvements at these forecast times. Overall, there has in fact been a gradual improvement in the official track forecasts of Atlantic tropical storms and hurricanes during the past quarter century or so (Lawrence et al. 1997).

Two different measures of intensity forecast errors for 1996 are shown in Table 10: the average error or bias (i.e., the average forecast minus observed maximum 1-min wind speed) and the average absolute error (i.e., the average absolute value of the forecast minus observed maximum 1-min wind speed). This table also lists the corresponding intensity forecast errors for the climatology and persistence forecast model Statistical Hurricane Intensity Forecast (SHIFOR) (Jarvinen and Neumann 1979). The average official errors, which range from −1.1 to −3.0 m s^{-1}, appear to be small, and indeed they are. However, they do indicate that there was a consistent negative bias in the official forecasts that increases in magnitude with increasing forecast times. An even greater negative bias was seen for the corresponding average SHIFOR forecasts. Since the average intensity forecasts take into account both underforecasts and overforecasts of maximum winds, the average absolute wind speed forecast errors are useful for determining forecast skill. The 1996 average absolute official wind speed forecast errors, also shown in this table, range from 4.7 m s^{-1} at 12 h to 11.2 m s^{-1} at 72 h. From 12 h through 72 h the average absolute official errors are lower than the average absolute SHIFOR errors for 1996. If improvement over SHIFOR is viewed as an indication of skill, then the official intensity forecasts, on average, exhibited skill out to 72 h in 1996.

Notwithstanding, the real challenge in intensity forecasting comes in cases of rapid intensification or decay, especially near landfall. For example, after a period of weakening, Hurricane Bertha strengthened abruptly just before making landfall on the coast of North Carolina, and this restrengthening was not anticipated in the official forecasts. Such intensity fluctuations can have significant impact on the hurricane warning process.

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