Atlantic Hurricane Season of 1999

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ABSTRACT

The 1999 Atlantic basin hurricane season produced 4 tropical storms and 8 hurricanes for a total of 12 named tropical cyclones. Seven of these affected land. Hurricane Floyd—the deadliest U.S. hurricane since Agnes in 1972—caused a disastrous flood event over the U.S. mid-Atlantic and northeastern coastal states, resulting in 56 U.S. deaths and 1 death in the Bahamas. Heavy rain from a tropical depression contributed to some 400 inland flood deaths in Mexico.

1. Introduction

There were 12 named tropical cyclones in the Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico during 1999. These cyclones are listed in Table 1, along with their dates, maximum 1-min surface wind speed, minimum central surface pressure, U.S. damage, and directly attributable deaths. Four of the tropical cyclones were tropical storms and eight reached hurricane intensity. The four tropical storms were at the 1950–99 average of 4.0, and the eight hurricanes were above the average of 5.9. In addition, there were four tropical depressions that did not reach tropical storm intensity. Five hurricanes attained category 4 intensity on the Saffir–Simpson hurricane scale (Simpson 1974). This is the most category 4 hurricanes in a single season since 1886.

After each cyclone has dissipated, a ''best track'' is determined, using all available data. The best track consists of 6-hourly center positions, maximum 1-min wind speed, and minimum central surface pressure. A record of Atlantic basin best tracks (Jarvinen et al. 1984) is maintained at the National Hurricane Center for tropical storms and hurricanes. Figure 1 is a map showing the best track positions of this year's named storms along with an indication of depression, storm, or hurricane stage.

Many of the tropical cyclones affected land. Bret, Floyd, and Irene made U.S. hurricane landfalls in Texas, North Carolina, and Florida, respectively. Floyd also hit the Bahamas as a hurricane. Dennis was nearly a hurricane at landfall in North Carolina. Tropical Storm Harvey went across Florida, Hurricane Jose hit the northern Leeward Islands, and Tropical Storm Katrina moved inland over Nicaragua. Lenny moved eastward over the northern Leeward Islands as a hurricane and its extensive rain and ocean swells affected much of the southern and eastern Caribbean.

Flooding from Floyd caused a disaster in the eastern United States and particularly in North Carolina. The U.S. death toll of 56 from Floyd was the highest since Hurricane Agnes of 1972 (122 deaths). The deadliest tropical cyclone of the season was a tropical depression, whose heavy rain and flooding caused 400 deaths in Mexico.

Between May and November, 59 tropical waves moved westward across Dakar, Senegal's longitude. Many were tracked all the way across Central America to the eastern North Pacific basin. The origins of 11 of this season's 12 named tropical cyclones, or 92%, were associated with these waves. This compares to the 1967–99 average of 62% of the named tropical cyclones that originated from tropical waves. So, there are normally more systems originating from upper-tropospheric cold lows or along frontal zones than was observed during 1999.

2. Description of tropical storms and hurricanes

a. Tropical Storm Arlene, 11–18 June

Arlene remained at sea. The storm passed about 100 n mi east of Bermuda, but tropical storm force winds remained offshore.

On 8 June, water vapor imagery first showed the cir-

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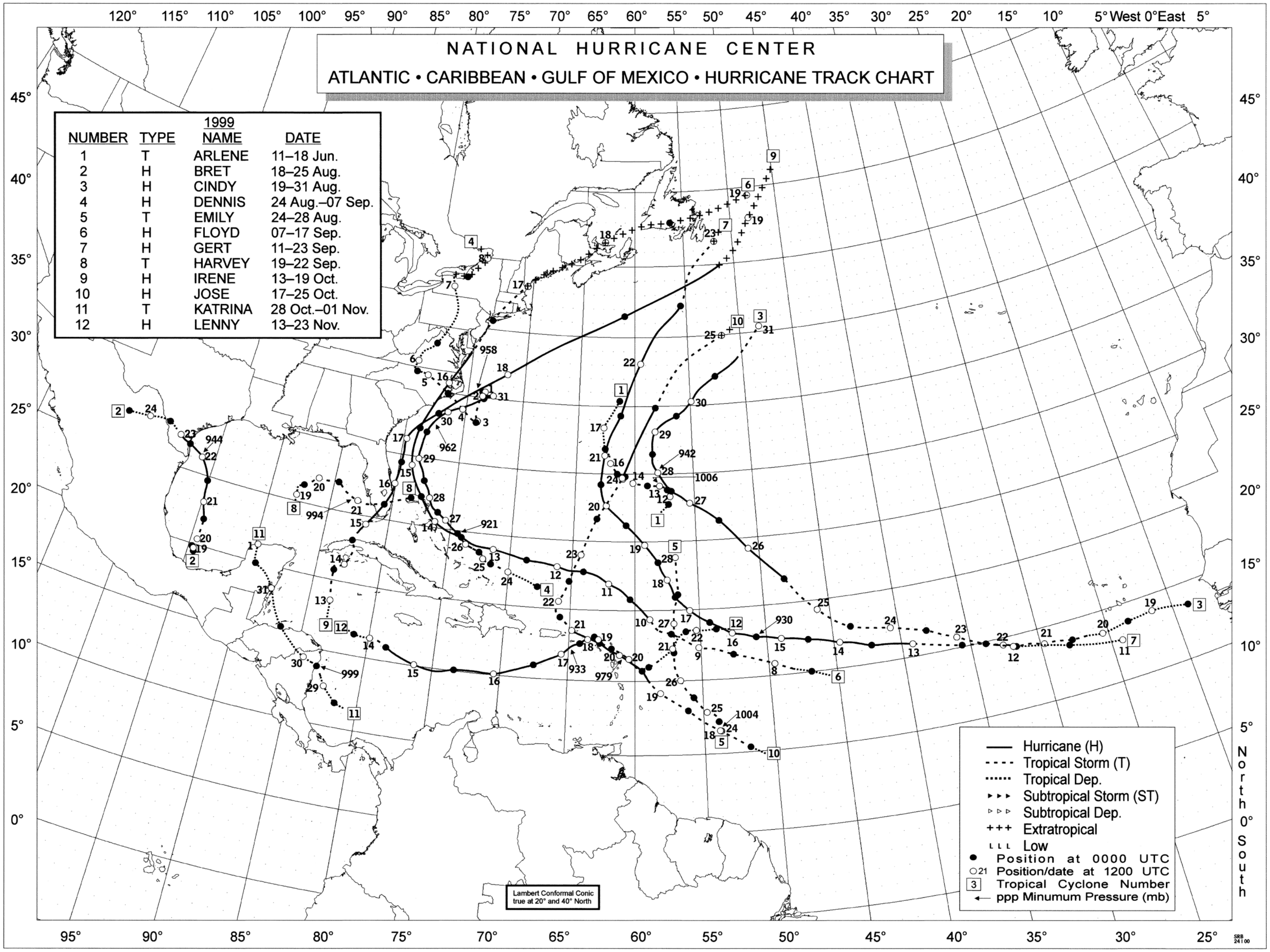

FIG. 1. Tracks of tropical storms and hurricanes in the Atlantic basin during 1999.

culation of an upper low located a few hundred miles north of Puerto Rico. Simultaneously, a large-amplitude tropical wave passed through the tail end of a frontal zone southeast of the upper low and a low-level cloud swirl became visible near 22°N, 61°W, close to the wave axis and southeast of the upper low. The low-level cloud swirl then moved slowly northwestward for 2 days with development inhibited by westerly shear from the upper low.

Meanwhile, steady convection had been maintained in the diffluence region to the east of the upper low. By 10 June, the low-level circulation moved underneath the cold low, near 24°N, 63°W. Shortly thereafter, the upper low moved eastward into the convective area. As the upper low accelerated northeastward late on 10 June, satellite microwave imagery revealed the development of a new circulation in the convection. During the morning of 11 June, the convection developed a well-defined banding pattern, and it is estimated that a tropical depression formed from this activity at 1800 UTC 11 June, about 465 n mi southeast of Bermuda.

Soon after reaching depression status, the cyclone slowed and drifted northward for 24 h. By 1200 UTC 12 June, satellite classifications (Dvorak 1984) indicated that tropical storm strength had been attained. Arlene intensified for 12 h until westerly shear began to expose the low-level circulation center. The maximum intensity was reached at 0000 UTC 13 June, when the winds were estimated to be 50 kt and the minimum central pressure was estimated to be 1006 mb. From 13 to 15 June, Arlene moved generally west-northwestward while weakening slightly under the westerly shear.

Steering currents became poorly defined and Arlene moved little on 15 June. The best track indicates that Arlene executed a small cyclonic loop, although this apparent motion may have been due to a reformation of the center closer to the convection on the east side of the cyclone. A northwestward motion resumed late on 15 June, followed by a gradual turn to the north and then northeast over the next 3 days as Arlene moved around the western periphery of the Atlantic subtropical ridge. Convection began to diminish on 16 June when the environmental vertical wind shear changed to northeasterly and Arlene moved over cooler waters. Arlene's closest approach to land was on 17 June, when it passed about 100 n mi to the east of Bermuda. The storm weakened to a depression on 17 June, and dissipated ahead of an approaching frontal zone on 18 June.

The maximum wind speed of 50 kt on 13 June is based on Dvorak satellite estimates. There was U.S. Air Force Reserve Hurricane Hunter aircraft reconnaissance on 15 and 16 June, but the estimated maximum winds had decreased slightly to 45 kt by this time.

Arlene's center passed about 100 n mi to the east of Bermuda and no significant weather occurred there.

b. Hurricane Bret, 18–25 August

Bret was a small hurricane that made landfall along a sparsely populated section of the south Texas coast with maximum sustained winds of 100 kt. Bret was the first hurricane to strike Texas since Hurricane Jerry in October 1989 and was the strongest Texas hurricane since Hurricane Alicia in 1983.

1) SYNOPTIC HISTORY

A tropical wave moved from Africa to the tropical Atlantic Ocean on 5 August. On 18 August, continuity and soundings from Merida, Mexico, place this weak tropical wave in the vicinity of the Yucatan Peninsula. Also, a weak surface low-formed over the peninsula. This low originated from a thunderstorm complex associated with a westward moving upper-level cyclonic circulation.

Later on 18 August the surface low moved over the Bay of Campeche. Early morning visible satellite imagery showed a low-level cloud circulation center and, a few hours later, a Hurricane Hunter reconnaissance mission confirmed the existence of a closed circulation. With some deep convection and banding present, the system became a tropical depression at 1800 UTC on 18 August over the Bay of Campeche.

The depression did not strengthen right away due to vertical wind shear caused by an upper-level trough over the extreme western Gulf of Mexico. However, the trough moved away and the depression became Tropical Storm Bret late on 19 August while beginning to move slowly northward. Bret steadily strengthened. On the morning of 22 August, it reached 125 kt (a category 4 hurricane on the Saffir–Simpson hurricane scale) just offshore from Brownsville, Texas. Figure 2 is a visible satellite image of Bret on the morning of 22 August. Responding to the presence of a weak midtropospheric ridge over the northwest Gulf of Mexico and to a midtropospheric cyclonic circulation over the Rio Grande valley, Bret turned northwestward and its forward speed slowed from near 10 kt to about 5 kt.

Bret's center crossed the Texas coast midway between Brownsville and Corpus Christi and near the middle of Padre Island at 0000 UTC 23 August. By the time of landfall, it had weakened to a category 3 hurricane with 100-kt winds and a pressure of 951 mb. After moving inland, Bret's movement became more westward. Bret continued to weaken while it moved across south Texas and into the high terrain of north-central Mexico, where it dissipated on 25 August.

2) METEOROLOGICAL STATISTICS

The maximum 1-min surface wind speed of 125 kt early on 22 August is based on a reconnaissance aircraft Global Positioning System (GPS) dropwindsonde vertical wind speed profile (Hock and Franklin 1999). Profiles from Bret's eyewall show that winds reached near 150 kt within 300 m above the surface and were about 125 kt near the surface.

Bret's pressure dropped 35 mb to 944 mb in the 24

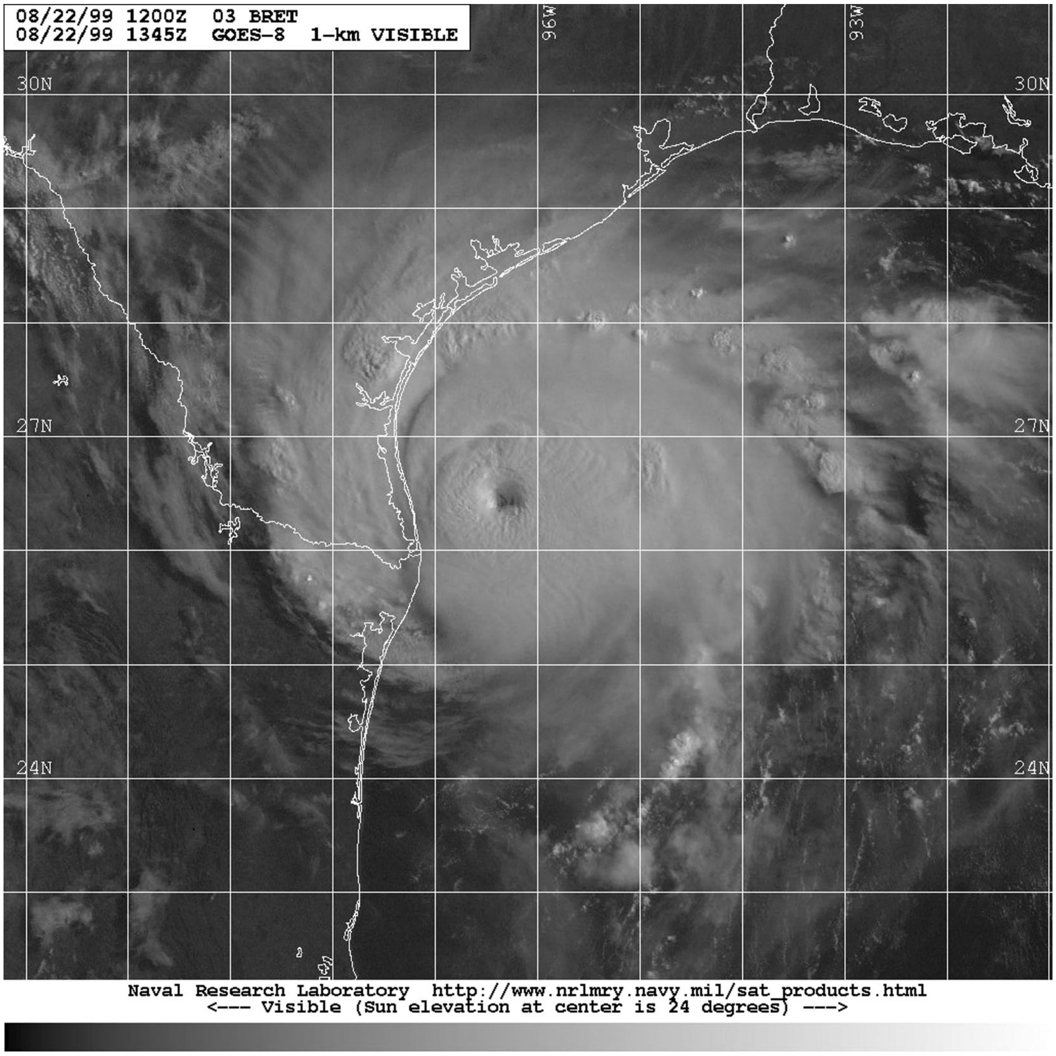

FIG. 2. *GOES-8* visible satellite image of Hurricane Bret at 1345 UTC 22 Aug 1999, near the time of 125-kt maximum wind speed. (Courtesy of Naval Research Laboratory, Monterey, CA.)

h ending at 1200 UTC 22 August and dropped 21 mb during the 6 h ending at 0000 UTC of the same day. This episode of intensification coincides with the hurricane's track over a maximum in the sea surface temperature (SST) field over the west-central Gulf of Mexico. Analyses from Applied Physics Laboratory, The Johns Hopkins University, shows 31°C SST values along Bret's track during the intensification. In addition, values of the upper oceanic heat content (described by Shay et al. 2000) under portions of the hurricane's circulation in the western Gulf of Mexico were high.

Bret was a small hurricane. At its peak, hurricane force winds were confined to a radius of 30–40 n mi from the center in the north semicircle and only 10–20 n mi in the south semicircle. Thus only a small segment of the Texas coast was affected by the core of the hurricane. Kennedy County received most of the hurricane force winds, which were as high as 100 kt over a small portion of the coast of Padre Island. With the center moving inland over a sparsely populated area, few surface reports were available substantiating strong winds. Table 2 lists a selection of surface observations. The highest reported sustained wind is 63 kt at Rincon del San Jose on Padre Island. That instrument failed at 2230 UTC on 22 August just before the center passed nearby. The Port Aransas Coastal Marine Automated Network (C-MAN) station reported maximum sustained winds of 41 kt as the center of the hurricane passed about 60 n mi to the south.

Bret was slow moving and radar estimates suggest maximum storm total rainfall of over 760 mm in Kennedy County. None of the observed rainfall totals in Table 2 come close to that value. Aransas Pass is north of the area of peak rainfall and reported a storm total of 320 mm. The heavy rains accompanying the weakening tropical cyclone caused notable river flooding in

TABLE 1. 1999 Atlantic hurricane season statistics.

No.	Name	Class*	Dates**	Maximum 1-min wind (kt)	Minimum sea level pressure (mb)	U.S. damage ($ millions)	Direct deaths
1	Arlene	T	11– 18 Jun	50	1006		
2	Bret	H	18–25 Aug	125	944	60	
3	Cindy	H	19–31 Aug	120	944		
4	Dennis	H	24 Aug–07 Sep	90	962	157	4
5	Emily	T	24–28 Aug	45	1004		
6	Floyd	H	07–17 Sep	135	921	4500	57
7	Gert	H	11–23 Sep	130	930		2
8	Harvey	T	19–22 Sep	50	994	15	
9	Irene	H	13–19 Oct	95	958	800	
10	Jose	H	17–25 Oct	85	979		2
11	Katrina	T	28 Oct–01 Nov	35	999		
12	Lenny	H	13–23 Nov	135	933	330	17

* T = tropical storm wind speed 34–63 kt; H = hurricane wind speed 64 kt or higher.
** Dates begin at 0000 UTC and include tropical depression stage (wing speed $<$34 kt).

the Rio Grande Valley. The Rio Grande River at Laredo and the Aransas River near Skidmore and at Oso Creek crested slightly above flood stage. A 24-h rainfall total of over 350 mm was reported from the Mexican state of Nuevo Leon. The state of Tamaulipas is believed to have received similar amounts.

The Sea, Lake, and Overland Surges from Hurricanes (SLOSH) storm surge model suggested that a narrow region along central and north Padre Island experienced a storm surge of 2.5–3 m. A report from Port Mansfield Pass suggests that 1–1.5 m of water inundated this coastal location. Several cuts were observed in the dunes surrounding Padre Island. The largest of these, near mile marker 50 near the eye's passage, was mistaken as the Mansfield Pass by aircrews inspecting the damage. Other substantial beach erosion was reported near Port Mansfield.

In Aransas County around 2145 UTC 22 August, a tornado reportedly uprooted trees, destroyed a recreational vehicle, a barn, and a shed. Other reports indicate that a tornado touched down in Kingsville around 2245 UTC on 22 August and a tornado was reported in Alice, but the time was not known. Neither led to reported damage.

3) CASUALTY AND DAMAGE STATISTICS

Despite Bret's intensity, damage was fairly light. Much of this is due to its landfall over a sparsely populated region in south Texas and the hurricane's small size. The nearest population centers to the south and north of landfall were Brownsville and Corpus Christi. These cities are about 100 n mi apart and were both spared the brunt of the hurricane's core. Brownsville's maximum reported sustained wind was only 29 kt and Corpus Christi's maximum was only 39 kt (see Table 2). There were no deaths.

Property insurance damage claims total $30 million as reported by the Property Claims Services Division of the Insurance Services Office. A standard practice of multiplying by a factor of 2.0 gives an estimated damage total of $60 million. This is a conservative multiplier, based on a sample of past landfall damage estimates.

c. Hurricane Cindy, 19–31 August

Cindy had a long track across the Atlantic, but with no direct impact on land.

The origin of Cindy was a tropical wave that crossed the west coast of Africa early on 18 August. It was accompanied by 4.5-mb, 24-h surface pressure falls and a 50-kt, 700-mb wind speed maximum, as indicated in Dakar, Senegal, rawinsonde data. Shortly after moving over the eastern tropical Atlantic, deep convection became better organized. By the evening of 18 August, thunderstorm activity consolidated near the center of a broad circulation and it is estimated that a tropical depression formed early on 19 August, centered about 250 n mi east-southeast of the Cape Verde Islands.

Persistent 20–30-kt easterly vertical shear, as depicted in analyses (not shown) from the Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin, prevented the system from becoming significantly better organized during the next 36 h. By the afternoon of 20 August, the shear relaxed and convection appeared at the center of the depression. The system is estimated to have become Tropical Storm Cindy at this time. Cindy's track followed the western periphery of the Atlantic subtropical ridge during its existence.

Cindy continued to become better organized on 21 August as banding features developed and a central dense overcast formed over the center. Cindy reached hurricane strength early on 22 August, about 400 n mi west of the Cape Verde Islands. Then easterly shear became more pronounced and Cindy weakened to a tropical storm later that day. By the afternoon of 25 August, the easterly shear again slackened and Cindy restrengthened to a hurricane about 1100 n mi southeast of Bermuda. Cindy continued to intensify during the next several days as indicated by more prominent band-

TABLE 2. Selected surface observations for Hurricane Bret, 18–25 Aug 1999.

	Minimum sea level pressure		Maximum surface wind speed					
Location	Day/time, (UTC)	Pressure (mb)	Day/time, (UTC)[a]	Sustained (kt)[b]	Gust (kt)	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Texas								
Brownsville Airport	22/2131	1002.4	22/1830	29	47			51
Cameron City Airport	22/2035	999.7	22/1841	36	46			89
Harlingen Airport	22/2310	999.0	22/2208	38	48			65
Port Isabel						0.3		
McAllen Airport	23/0023	1003.1	22/2209	28	37			74
South Padre Island	22/1815	998.6	22/1915	38	48			99
Arroyo Colorado			22/1900	43	57			
Port Mansfield	22/2000	985.4	22/2200	42	66			
Rincon del San Jose			22/2230	63[e]	78[e]			
Falfurrias Airport	22/0330	976.6	23/0330		85[e]			
Edinburg								87
El Sauz								51
Falcon								30
Garciasville								69
Harlingen								75
Hebbronville								116
Laguna Atascosa								106
La Joya								118
Los Fresnos								65
McAllen								79
Mercedes								26
Monte Alto								103
Rancho Viejo								37
Raymondville								78
Rincon								46
Rio Grande City								105
Santa Ana National Wildlife Refuge								97
Santa Rosa								90
Weslaco								174
Zapata								63
Bob Hall Pier							0.8	0
Corpus Christi	23/0322	1002.4	23/0326	39	48			132
Kingsville Naval Air Station (NAS)		1001.7	22/1843	35	44			78
Rockport	22/2228	1006.4	23/1506	34	41		0.6	58
Victoria	23/0900	1008.8	24/1811	22	28			18
Alice	23/1217	998.3	23/1748	39	48			101
Cotulla	23/1753	1006.4	23/2332	33	40			108
McMullen Target			22/2124	38				
Aransas Pass			23/2115		57			320
Freer								68
Benavides								130
Calliham								51
Concepcion								187
Fowlerton								103
George West								135
Point Comfort								5
Portland								202
Robstown								136
Sinton								139
Tilden 9 S								81
Tilden 4 SSE								15
Victoria CP&L								13
Alice								76
Tilden 9 S								81
Tilden 4 SSE								15
Freeport							0.7	
Galveston	23/0425	1010.5	23/1032	19	22			1
Angleton/Lake Jackson	23/0602	1010.2						7
Palacios	23/0353	1008.5	22/1012	23	27			11
NOAA Buoys and C-MAN stations								
Buoy 42019	22/2200	1007	23/1600	37				
Buoy 42020	22/1900	982.9	22/1900	58	73			

Table 2. (*Continued*)

Location	Minimum sea level pressure		Maximum surface wind speed			Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
	Day/time, (UTC)	Pressure (mb)	Day/time, (UTC)[a]	Sustained (kt)[b]	Gust (kt)			
Port Aransas C-Man				23/2200	41			

[a] Day/time is for sustained wind when both sustained and gust are listed.
[b] Standard National Weather Service (NWS) Automated Surface Observing System (ASOS) and C-MAN on-hour averaging periods are 2 min; buoys are 8 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above National Geodetic Vertical Datum (NGVD) or 1919 above mean sea level.
[e] Equipment failed or power outage experienced.

ing features and improved upper-tropospheric outflow. A ragged eye first appeared in visible satellite imagery on the morning of 27 August and, by that afternoon, a 25 n mi diameter banding-type eye became evident. The hurricane continued to strengthen and reached its estimated peak intensity of 120 kt about 375 n mi east-southeast of Bermuda on 28 August. Figure 3 shows a visible satellite image of Cindy near its time of peak intensity.

On 29 and 30 August, Cindy began to weaken in response to increasing westerly, then southwesterly, shear. The overall cloud pattern gradually degenerated, the eye became indiscernible, the cloud tops warmed, and the deep convection became displaced north and then east of the center. Cindy reached its westernmost longitude, about 58.5°W, on the afternoon of 28 August. The system turned northeastward on the next day followed by acceleration late on 30 August. Cindy's closest approach to Bermuda, about 325 n mi, occurred early on 29 August.

Cindy was downgraded to a tropical storm early on 31 August as it accelerated northeastward over progressively cooler waters. By that afternoon, Cindy's circulation became indistinct in satellite imagery when it merged with a large extratropical cyclone over the North Atlantic about 850 n mi west of the Azores.

Satellite-based intensity estimates on 28 August are the basis for the best-track maximum sustained wind speed of 120 kt and the minimum central pressure of 942 mb at 1200 UTC 28 August. The highest wind reported by a ship was a sustained 62 kt, from the *Mineral Colombia* located about 120 n mi east-northeast of the hurricane's center.

d. Hurricane Dennis, 24 August–7 September

Although Dennis never made landfall as a hurricane, it affected the North Carolina coast with hurricane force winds, heavy rains, prolonged high surf, and beach erosion. Its rain was particularly important in North Carolina as it saturated the ground and set the stage for the severe inland flooding from Hurricane Floyd. Dennis also produced tropical storm force winds over portions of the Bahamas.

1) Synoptic history

Dennis originated from a tropical wave that crossed the coast of Africa on 17 August. The system moved westward with little significant weather until 21 August, when its shower activity increased a few hundred miles northeast of the Leeward Islands. A low-level circulation developed over the next 2 days and the convection became better organized. A reconnaissance flight on 23 August failed to find a surface circulation, but aircraft data indicated a circulation was present aloft at 850 mb. Later, surface observations showed a closed circulation, and it is estimated that Tropical Depression 5 formed early on 24 August about 190 n mi east of Turks Island. Reconnaissance data and ship reports indicated further intensification, and the depression became Tropical Storm Dennis later that day, and a hurricane early on 26 August.

Dennis initially moved at 9–12 kt, but slowed to an erratic 3 kt on 25 August when steering currents weakened due to the passage of a midlatitude trough to the north. Once Dennis reached hurricane strength, it began a more steady northwestward motion near the eastern Bahamas. This motion continued into 28 August.

Westerly shear persisted, preventing additional significant strengthening until late on 27 August. After the shear decreased, Dennis reached a peak intensity of 90 kt on 28 August and maintained that speed until early on 30 August. Even at peak intensity, Dennis was not a tightly wound hurricane. The eye was 30–40 n mi wide and, on several center fixes, the Hurricane Hunter aircraft did not report an eye. The radius of maximum winds was, at times, as large as 70–85 n mi.

A second midlatitude trough caused Dennis to turn gradually northward on 28–29 August, and accelerate east-northeastward on 30–31 August. This turn kept the center about 60 mi south of the North Carolina coast. The east-northeast motion continued until the trough passed Dennis on 31 August. Then steering currents collapsed and the cyclone slowed to an erratic drift about 110 n mi east of Cape Hatteras, North Carolina. This erratic drift lasted into 2 September.

During this time, Dennis was affected by the cold front associated with the midlatitude trough. A com-

TABLE 3. Selected surface observations for Hurricane Dennis, 24 Aug–7 Sep 1999.

Location	Minimum sea level pressure		Maximum surface wind speed			Storm surge	Storm tide	Total rain
	Days/time (UTC)	Pressure (mb)	Day/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)	(m)[c]	(m)[d]	(mm)
Bahamas								
Cat Island								102
North Carolina								
Alligator Bridge[e]			30/1100	48	56			
Atlantic (9.1-m tower)	30/1351	992.6	30/1532	48	75			
Beaufort	04/2049	984.8	04/1823	33	45			
Beaufort (10.1-m tower)	30/1302	992.8	30/1103	52	75			
Blockade Runner					72			
Brunswick County Airport			30/0810		61			
Brunswick Power Plant			30/0456	50[f]				
Calabash					35			40
Carolina Beach			30/0710		66			
Castle Hayne (Oxychem)			30/1100		54			
Castle Hayne (SW)			30/0900	35	67			
Cherry Point Marine Corps Air Station (MCAS)	04/2355	986.5	04/2005	41	53			235
Delco			30/1200	28	57			
East Waccamaw			30/1100		34			25
Elizabeth City	04/2313	1003.8	30/1654	34	45			178
Elizabethtown					37			
Flemington			30/0900	39	68			
Greenville			05/0140		43			
Harkers Island Bridge			30/1230		76			
Hatteras Inlet			30/1930	50[g]	64			
Hatteras Village			30/1515		85			
Jacksonville	05/0235	994.2	30/0835		41			
Kingston			04/2250		37			
Kure Beach			30/0740		58			
Kure Beach (Federal Point)			30/0530		71			
Manteo			30/1635		52			
New Bern	05/0000	986.8	30/1056	35	46			85
New River	04/2126	993.9	30/0956	33	50			146
Newport	04/2115	985.1	30/1204		54			251
North Topsail Beach			30/1240	44[g]	65			
Oak Island			30/0800	46	62			
Ocean Isle			30/0559		49			
Ocean Isle (Tubbs Inlet)			30/0753		46			
Ocracoke Island[e]	31/0740	995.1	31/0220	35[g]	58			486
Oregon Inlet			30/2030	53[g]	77			
Oriental							2.4	
St. James								152
Shallotte			30/0700		60			
Shallotte Inlet			30/0730		60			
Southport (elementary)					49			229
Southport (marina)								343
Southport (pilot boat dispatch)			30/0743		60			
Whiteville					37			50
Wilmington Airport	30/0953	996.1	30/0607	42	53			120
Wilmington (Battleship, NC)			30/0530		66			170
Wilmington (College Rd)					46			222
Wilmington (Corning)			30/1200		60			
Wilmington (Eastwood Rd)			30/0650		44			168
Wilmington (Masonboro Loop)					37			
Wilmington (New Hanover EOC)			30/0800	51	76			
Wilmington (WECT-TV)					46			129
Wrightsville Beach			30/0444		96			
Wrightsville Beach Fire Dept.			30/0630		73			
South Carolina								
Charleston Harbor							0.6	
Charleston Weather Forecast Office (WFO)			29/2050	29	40			31
Murrells Inlet								73
Myrtle Beach (Pavilion)			30/0600		45			
N. Myrtle Beach			30/0732	29	42			42
Virginia								
John Kerr Dam								86

TABLE 3. (*Continued*)

Location	Minimum sea level pressure		Maximum surface wind speed			Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
	Day/time (UTC)	Pressure (mb)	Day/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)			
Norfolk Airport	05/0551	1006.1	30/1651	37	46			84
Langely Air Force Base (AFB)		1007.1	04/2332	45	66			
Newport News		1006.5	04/2332	28	39			84
Norfolk NAS		1006.5						72
Oceana NAS		1006.5						74
Portsmouth								146
Richmond	05/0754	1006.5						55
Roanoke Rapids			30/1214	27	35			
Sewells Point							0.9	
Wakefield								117
Wallops Island			30/1717	33	40			
NOAA buoys and C-MAN stations								
41001	31/0400	976.0	30/2300	48[g]	63			
41002	30/1100	997.6		43[g]	59			
41004	30/0300	990.5	30/0330	54[g]	72			
41008	29/2000	1003.9	29/1700	31	43			
41009[e]	29/0900	1001.3	29/0700	29	37			
41010	29/0750	980.2	29/0500	57	72			
44014	30/2000	1002.3	30/2100	43	53			
Drifting buoy 41650[e]	27/0000	1009.8	27/1200	45				
Drifting buoy 41651[e]	25/2100	1010.8	25/2100	42				
Cape Lookout, NC (CKLN7)	04/2000	986.5	30/1400	60	79			
Chesapeake Bay, VA (CHLv2)	05/0600	1006.2	30/2100	49[g]	56			
Duck, NC (DUCN7)	04/2300	1005.6	30/2000	56	65			
Folly Beach, SC (FBIS1)	30/0100	1001.6	30/0000	24	35			
Frying Pan Shoals, NC (FPSN7)	30/0900	977.2	30/0945	81[g]	97			
Settlement Point, Bahamas (SPGF1)	28/2200	1002.6	29/0030	34[g]	46			
St. Augustine, FL (SAUF1)	29/1100	1004.9	29/1355	27	41			

[a] Day/time is sustained wind when both sustained and gust are listed.
[b] Standard NWS ASOS and C-MAN on-hour averaging periods are 2 min; buoys are 8 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above NGVD.
[e] Incomplete record.
[f] 100-ft tower, 15-min average.
[g] 10-min average.

bination of vertical shear and entrainment of cool dry air into the circulation decreased the convection and caused weakening. Dennis weakened to a tropical storm on 1 September, and on 1 and 2 September may have, in fact, been as much subtropical or extratropical as tropical. Despite the lack of convection, surface observations indicate maximum sustained winds were near 45 kt on 2 September, some of which were due to the pressure gradient between Dennis and a strong surface ridge north of the front. Winds in excess of 34 kt or greater were observed as far north as New Jersey.

A large high pressure cell over the eastern United States forced Dennis southward late on 2 September. This motion over warmer water probably helped initiate a deep convective burst on the next day. Then, Dennis turned northwestward toward the North Carolina coast as the ridge moved east into the Atlantic. This motion continued on 4 September along with reintensification. Dennis was just below hurricane strength when it made landfall at the Cape Lookout National Seashore just east of Harkers Island, North Carolina, on 4 September. Dennis continued inland and weakened to a depression over central North Carolina. Even in dissipation, Dennis continued to move erratically along a zigzag northward course. Dennis became extratropical on 7 September and was absorbed into a larger extratropical low on 9 September.

2) METEOROLOGICAL STATISTICS

Dennis's path brought it near the eastern Bahamas on 27–28 August. The only official report of tropical storm force winds in the Bahamas was from a C-MAN station at Settlement Point, Grand Bahama, which reported 34-kt sustained winds with gusts to 46 kt on 29 August. A selection of surface observations is listed in Table 3. Also, unofficial reports from amateur radio operators indicated sustained winds of up to 55 kt with gusts to 65 kt in the Abaco Islands.

Aircraft reconnaissance data suggest that Dennis maintained 90-kt surface wind speeds for 36 h from 28 to 30 August. Just before landfall on 4 September, an

TABLE 4. Selected surface observations for Hurricane Floyd, 7–17 Sep 1999.

Location	Minimum sea level pressure		Maximum surface wind speed			Storm surge	Storm tide	Total rain
	Day/time (UTC)	Pressure (mb)	Day/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)	(m)[c]	(m)[d]	(mm)
Bahamas								
Grand Bahama Island	15/0100	983.0	14/2000	52	65		1.6	
Little Harbor Abacos	14/1910	929.0						237
Nassau				55	68			
Florida								
Craig Field	15/1653	994.6	15/1929	37				
Daytona Beach	15/1353	991.8	15/1053	36	60			31
Fowey Rocks	14/2300	995.5	14/1600	36	44			
Fort Lauderdale Executive Airport	14/22532	994.9	15/0653	23	33			0
Fort Lauderdale International Airport	14/2253	994.6	14/2201	25	36			3
Fort Pierce	15/0735	989.5	15/0736	29	43			
Gainesville	15/1653	994.6	15/1407	33				
Jacksonville International Airport	15/1656	995.3	15/0907	40				
Lake Worth Pier	14/2200	993.4	14/1700	32	49			
Leesburg	15/1053	996.4	15/1153	20	27			
Melbourne Airport	15/0900	989.1	15/0501	45	59			34
Melbourne WFO			15/0655	32	52			
Miami	14/2256	995.8	15/0322	19	29			1
Ocala	15/1035	998.0	15/1535	28				
Orlando	15/0853	993.8	15/0853	24	42			32
Patrick AFB			15/0820	49	57			
Sanford			14/2024	25	37			81
Tamiami Airport	14/2253	996.4	14/1953	21	31			
West Palm Beach	15/0453	992.9	14/1941	27	38			10
Georgia								
Alma	15/950	999.7	15/1746	28				
Brooklet								10
Dover								10
Ludowici								13
Newington								22
Rocky Ford								5
Savannah Airport			15/1810	35	46			
St. Simon's Island	15/1804	993.2	15/1804	40				
South Carolina								
Allendale								17
Beaufort								46
Charleston City Office			16/0150	50	74			101
Charleston Harbor							3.1	
Charleston International Airport	15/0052	989.5	16/0046	44	58			99
Edisto Beach State Park			16/0029	33	47			
Florence Airport	16/0655	991.2	16/0158	36	54			103
Folly Beach			15/2300	47	62			
Grand Strand	16/0553	977.0	16/0523		57			
Ladson Oakbrook								109
Myrtle Beach Airport	16/0553	979.7	16/0455					408
Ridgeville								91
St. George								48
Walterboro								64
Williams								61
North Carolina								
Beaufort	16/0409	976.0	16/0405	42	58			141
Castle Hayne 2E			16/0715		81			
Castle Hayne 3SW			16/0845		104			
Cherry Point MCAS	16/0555	961.4	16/0405	56	71			83
Elizabeth City	16/1418	968.5	16/1346	34	56			67
Federal Point			16/0620		97			
Flemington			16/0625		80			
Frisco	16/0740	983.8	16/0805	51	61			9
Greenville			16/0800		51			
Holden Beach			16/0820	42	64			
Manteo			16/1000		53			
Masonboro Island							3.1	
Mount Olive			16/0520		65			
Myrtle Grove			16/0540		89			

TABLE 4. (*Continued*)

Location	Minimum sea level pressure		Maximum surface wind speed			Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
	Day/time (UTC)	Pressure (mb)	Day/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)			
Newport			16/0454		58			
New Bern	16/0543	961.1	16/0501	39	58			109
New River	16/0426	959.0	16/0556	44	68			210
Oak Island			16/0820	52	69		3.1	
Pleasure Island							3.1	
Rocky Mount/Wilson								385
Seymour Johnson AFB	16/0955	983.0	16/1055	45	60			
South River								89
Washington			16/0800		41			
Wilmington Airport	16/0755	959.7	16/0855	54	75			484
Wilmington Corning			16/0700		89			
Wilmington Emergency Operations Center (EOC)			16/0845		104			
Wrightsville Beach					120			
Virginia								
Fort Eustis	16/1455	985.2	16/1640	25	37			
Glouchester								286
Hampton								191
James City County								363
Langley AFB			16/1355	40	55			
Lower James City								326
Newport News	16/1558	983.4	16/1623	33	44			421
Norfolk Airport	16/1551	977.1	16/1303	27	40			
Norfolk NAS	16/1555	979.1	16/1609	38	48			
Oceana NAS	16/1556	975.7	16/1656	35				
Portsmouth	16/1600	978.3	16/1614	30	52			257
Richmond	16/1640	991.9	16/1405	29	44			166
Smithfield								318
Wakefield WFO								323
Weems								275
Yorktown								
Maryland								
Annapolis								295
Cambridge							0.8	
Chestertown								356
Lewisetta							1.1	
Martin State Airport		989.0						
Mid-Bay buoy			16/1710		60			
Ocean City	16/1853	976.8	16/1653	31	45			43
Patuxent NAS		991.0	16/1555	30	36			
Salisbury	16/1851	980.4	16/2150	28	42			129
Solomon's Island							0.9	
St. Inigoes		987.6						
Tall Timbers			16/2040		62			282
Thomas Point Light			16/1300	43	49			
Delaware								
Cape Henlopen			16/PM		56			
Greenwood								269
Lewes						0.8	2.1	0
Vermon								314
Wilmington	16/2106	986.0	16/2214	32	40			
New Jersey								
American Corners								259
Atlantic City	16/2054	980.2	16/2345	23	34	0.6	1.9	
Caldwell	16/2353	987.8	16/2353		38			259
Cape May						0.8	2.2	
Doylestown								256
Federalsburg								284
Neshanic								256
Newark International Airport	16/2351	985.1	16/2351	38	46			158
Pequannock								280
Sandy Hook	16/2306	981.0	17/0024	34	45	0.6	2.0	
Somerville								339
Teterboro Airport	16/2351	985.0	16/2351	24	38			217
Wayne/Iflows								310

TABLE 4. (*Continued*)

Location	Minimum sea level pressure Day/time (UTC)	Minimum sea level pressure Pressure (mb)	Maximum surface wind speed Day/time (UTC)[a]	Maximum surface wind speed Sustained (kt)[b]	Maximum surface wind speed Gust (kt)	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
White House								330
Pennsylvania								
Philadelphia	16/2136	985.0	16/2136	32	42	0.9	2.8	
New York								
Central Park	16/2250	983.8	16/1450	25	36			128
Farmingdale Airport	16/2353	981.6	16/2053	23	37			80
Islip/MacArthur Airport	17/0156	983.4	16/2356	27	37			
JFK International Airport	16/2351	982.5	17/0051	30	41			83
LaGuardia Airport	16/2351	983.7	17/0051	30	41			125
Montgomery Airport			16/2039	29	44			
Montauk Point Airport	17/0254	986.9	17/0454	22	37			
Newburgh/Stewart	17/0045	992.6	16/2245	34	54			
Upton NWS								89
Westhampton Airport	17/0153	984.8	17/0153	28	43			
White Plains Airport	17/0050	985.8	16/2350	25	42			159
Massachusetts								
Beverly					31			
Blue Hill Conservatory					40			
Boston							3.3	
Boston/Logan Airport					38			
Brewster			17/0545		63			
Buzzards Bay			17/0300	47	57			
Fox Point barrier						1.3		
Hadley								244
Hyannis					62			
Lawrence					32			
Martha's Vineyard					34			
Nantucket					32		0.4	
New Bedford barrier			17/0600		64	0.8		
Norwood					27			
Orange					29			
Plymouth					33			
Southwick								233
Taunton					38			
Westfield					37			
Worcester					30			
Rhode Island								
Block Island					39			
Newport					35		0.8	
Providence					35		1.8	
Westerly					31			
Connecticut								
Bridgeport Airport	17/0154	981.8	16/2254	29	39			
Bristol								274
Burlington								240
Danbury Airport	17/0153	987.1	17/0153	15	21			
Groton/New London	17/0145	986.8	17/0045	30	43			
Hartford Airport	17/0253	985.4						
Meriden	17/0156	984.5						
Meridan Markham Airport	17/0155	986.4	17/0155	20	34			
New Haven Airport	17/0145	983.8		33				
Southington								232
Willimantic	17/0352	985.8			31			
Windsor Locks					37			
New Hampshire								
Manchester					28			
NOAA buoys and C-MAN stations								
41004			16/0200	54	72			
41009	15/0900	980.9	15/1000	52	70			
41008			15/2100	24	31			
41010	15/09001	939.6	15/0700	72	91			
44009	16/1900	976.0	16/1800	39	52			
44014	16/1600	981.4	16/1615	50	66			
44025	17/0000	980.0	17/0600	33	43			

TABLE 4. (*Continued*)

Location	Minimum sea level pressure Day/time (UTC)	Pressure (mb)	Maximum surface wind speed Day/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
BUZM3			17/0300	47	57			
CLKN7	16/0500	974.9	16/0450	63	79			
DSLN7	16/0730	985.8	16/0750	69	82			
DUCN7	16/0900	977.0	16/0850	67	83			
FPSN7	16/0600	958.7	16/0512	86	97			
SAUF1	15/1200	992.9	15/1200	58				

[a] Day/time is for sustained wind when both sustained and gust are listed.
[b] Standard NWS ASOS and C-MAN averaging periods are 2 min; buoys are 8 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above NGVD.

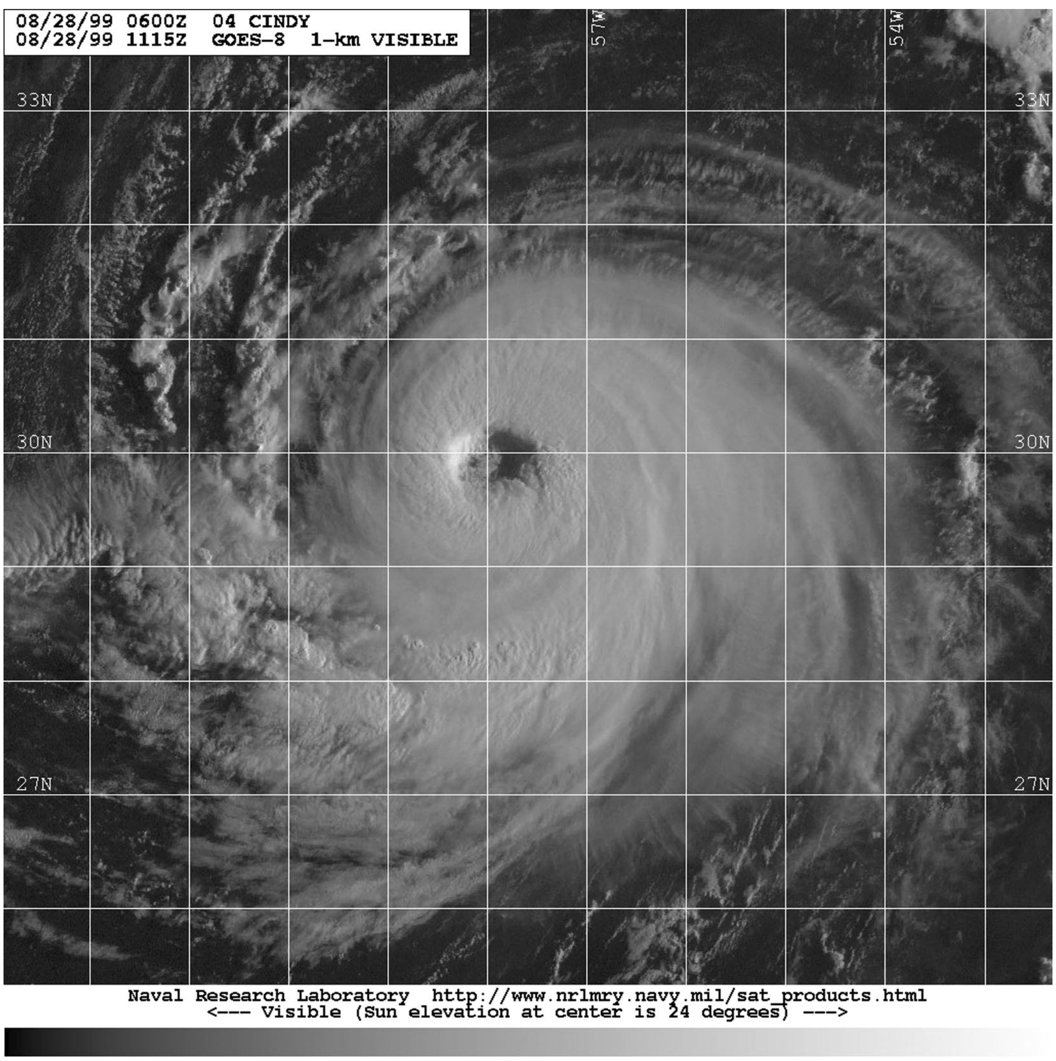

FIG. 3. *GOES-8* visible satellite image of Hurricane Cindy at 1115 UTC 28 Aug 1999, near the time of 120-kt maximum wind speed. (Courtesy of Naval Research Laboratory, Monterey, CA.)

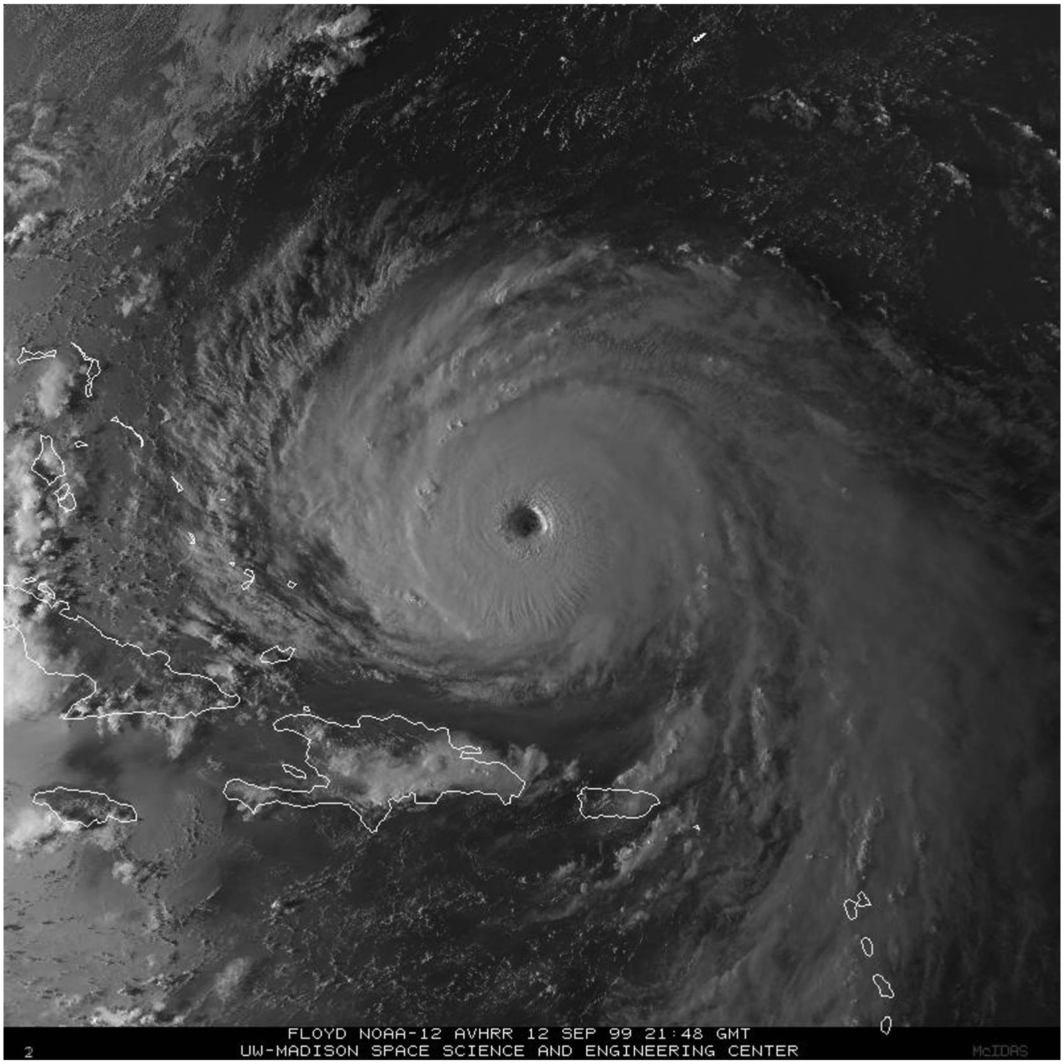

FIG. 4. *NOAA-12* visible satellite image of Hurricane Floyd at 2148 UTC 12 Sep 1999, several hours prior to the 135-kt maximum wind speed. (Courtesy Space Science and Engineering Center, University of Wisconsin—Madison.)

aircraft measured 71-kt wind at 850 mb and a 984-mb pressure. Vertical wind profiles from several hundred GPS dropwindsondes (Franklin et al. 2000) indicate that the average ratio between surface and 700-mb flight-level winds is about 0.90 and the ratio between surface and 850-mb winds is about 0.80. Thus, Dennis is estimated to be a 60-kt tropical storm at landfall.

Dennis tracked parallel to the Florida and Georgia coasts, with tropical storm force winds near the coasts. A 41-kt gust was reported from the St. Augustine, Florida, C-MAN station. On 29 August, the core of Dennis passed just east of National Oceanic and Atmospheric Administration (NOAA) buoy 41010, which reported a 57-kt sustained wind with a gust to 72 kt and a minimum pressure of 980.2 mb.

Dennis's first pass near the mid-Atlantic coast on 30 August caused sustained tropical storm force winds with gusts to hurricane force in coastal North Carolina and gusts to tropical storm force in coastal South Carolina from Charleston northward. The maximum reported sustained winds were 53 kt with gusts to 77 kt at Oregon Inlet. Gusts to 96 kt at Wrightsville Beach and 85 kt at Hatteras Village suggest that sustained hurricane force winds may have occurred along the coasts of New Hanover and Dare Counties. Sustained hurricane force winds of 81 kt with gusts to 97 kt were measured at the Frying Pan Shoals C-MAN station (145-ft elevation) with a minimum pressure of 977.2 mb.

The landfall of Dennis on 4 September produced tropical storm force winds over portions of eastern North Carolina and coastal southeastern Virginia. The large circulation of Dennis also affected shipping over the western Atlantic. On 30 August, the ship *Zim U.S.A.* reported a sustained wind speed of 65 kt while located about 120 n mi east-southeast of the center of the then 90-kt tropical cyclone.

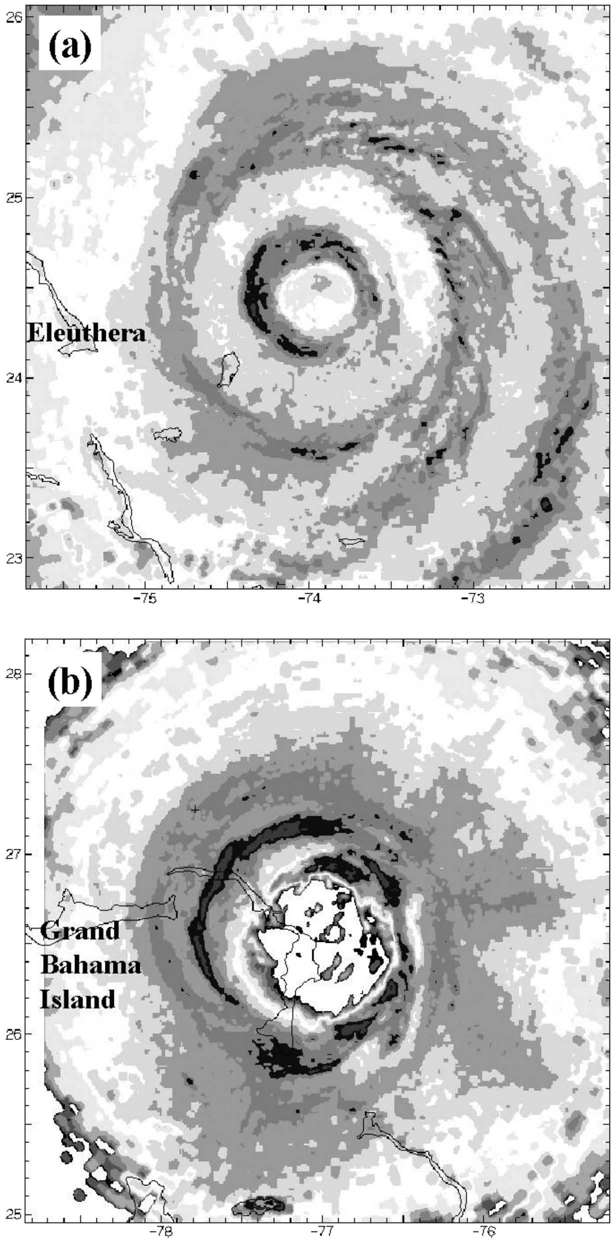

FIG. 5. Airborne radar reflectivity from NOAA WP-3D aircraft: (a) 2342 UTC 13 Sep 1999 and (b) 2028 UTC 14 Sep 1999. (Courtesy of M. Black, Hurricane Research Division, NOAA, Miami, FL.)

Few detailed observations of storm surge are available from areas affected by Dennis. Storm tides up to 1.5 m above normal were reported along much of the North Carolina coast on both 30 August and 4 September. Areas along the Neuse River reported tides 3 m above normal tide level on 30 August, while areas along the Pamlico River reported similar heights on 4 September. Portions of the South Carolina and southeastern Virginia coasts experienced tides about 1 m above normal. Amateur radio reports from the Bahamas indicate similar tide heights as the eye passed over the Abacos. Because Dennis meandered off the North Carolina coast for several days, the above normal tides were prolonged. This led to extensive beach erosion along portions of the North Carolina and southeastern Virginia coasts.

Dennis affected the mid-Atlantic states twice within a week, and other weather systems affected the region during the same period. The maximum reported rainfall was 486 mm at Ocracoke, North Carolina, with 150–250 mm reported elsewhere over portions of eastern North Carolina. Amounts of 75–150 mm occurred elsewhere over eastern North Carolina, extreme eastern South Carolina, and over portions of southeastern Virginia. Rainfalls were generally 75 mm or less elsewhere over eastern South Carolina and less than 25 mm in Florida and Georgia.

Dennis significantly contributed to saturating the ground of the mid-Atlantic coastal states and this set the stage for the severe flooding caused by Hurricane Floyd 2 weeks later. Rainfall data from the Bahamas indicates a maximum total of 102 mm at Cat Island. Heavier amounts likely occurred on Eleuthera and in the Abaco group near the eye of Dennis.

One tornado was reported with Dennis on 4 September. This F2 tornado in Hampton, Virginia, caused 15 injuries, 6 of them serious.

3) CASUALTY AND DAMAGE STATISTICS

Four deaths reported in Florida were related to high surf spawned by the hurricane. No deaths are known due to winds, rains, storm tides, or tornadoes associated with Dennis.

The Property Claims Services Division of the Insurance Services Office reports insured losses due to Dennis totaled $60 million in North Carolina and Virginia. As in Bret, a two-to-one ratio was applied to the insured losses, giving $120 million total property damage. Press reports indicate that agricultural losses in North Carolina and Virginia were $37 million, making a total estimated damage from Dennis of $157 million.

e. Tropical Storm Emily, 24–28 August

A tropical depression formed from a tropical wave early on 24 August about 360 n mi east of the Windward Islands. A reconnaissance aircraft reached the area later that day and found a small circulation with a 1004-mb central pressure and 55-kt flight level winds. The 45-kt surface winds estimated for that time represent Emily's peak intensity.

Emily was in a strong shearing environment because the circulation of the much larger Cindy was gradually approaching from the east. This shearing limited Emily's development by displacing the sporadic deep convection from the circulation center. Cindy also affected Emily's motion by disrupting the easterly trade wind flow such that Emily moved slowly toward the northwest, and then north. Emily was absorbed by the much larger circu-

TABLE 5. Selected surface observations for Hurricane Irene, 13–19 Oct 1999.

	Minimum sea level pressure		Maximum surface wind speed				
Location	Day/time (UTC)	Pressure (mb)	Day/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)	Storm surge (m)[c]	Total rain (mm)
Cuba							122
Havana Casablanca			14/2020		68		272
Playa Giron							221
Topes de Collantes							221
Juguey Grande							180
Jovellanos							183
Melena del Sur							180
Union de Reyes							163
Batabano							157
Guines							140
Cienfuegos							137
Nueva Gerona							122
Colon							
Florida							
Big Pine Key			15/0000	69	89		
Key West International Airport	15/1010	987.6	15/0518	38	47		182
Marathon Airport		989.6					
Key West			15/1630	38	47	0.5	
Vaca Key			15/0800			0.6	249
Tavernier							
Miami Beach			15/1950	52			
Tamiami Airport	15/2353	990.9	15/2130	45	60		
Homestead AFB	15/2257	990.9	15/1809	42	74		279
Miami International Airport	15/2256	990.1	15/2008	41	61		
Pompano Beach Airport	16/0253	991.0	15/2202	40	50		
Fort Lauderdale Executive Airport	16/0153	909.5	15/2048	40	50		340
Fort Lauderdale International Airport	16/0123	990.9					
Opalocka Airport	16/0053	989.9	15/2257	39	49		276
West Palm Beach Airport	16/0453	990.9	16/0211	37	53		
North Perry Airport	15/2029		15/2029	37	50		
Winter Heaven	16/1927	1003.1	15/2033		42		
Fort Myers Page Airport	15/2328	1000.1	16/0228		38		
Fort Myers Regional Airport	16/0017	1000.0	15/2305		38		
Bunnel (X47)			16/2222		38		52
St. Augustine Airport	17/—-	997.7	17/0020		47		41
Mayport Navy Base	17/0820	996.8	17/0302		48		74
Craig Field			17/0311		38		43
Orlando International Airport	16/2053	1000.2	16/1553	33	42		98
Melbourne Airport			16/1050	40	58		
Patrick AFB unofficial			16/1048	50	59		
Vero Beach Airport			16/0910	39	62		
Fort Pierce	16/1053	989.1	16/0753	37	45		
Bunnell X47			16/2222		38		63
Flagler Beach Volunteer Fire Department	16/unkn	998.7					
Georgia							
St. Simons Island	17/0907	997.3	17/0303		47	0.6	
Fernandina Beach						0.9	
South Carolina							
Charleston International Airport							158
Johns Island							107
Charleston City Office							
North Carolina							
Frisco	18/0139	986.0	17/2215	33	41		80
Beaufort			18/0326		35		119
Cherry Point			18/0210		39		73
Wilmington Airport	18/0202	994.6					140
Cape Fear							170
Elizabethtown							162
New Bern							140
Snowhill							279
Ernul							
Virginia							186
Norfolk	18/0552	997.3	18/1152		35		190

TABLE 5. (*Continued*)

Location	Minimum sea level pressure Day/time (UTC)	Minimum sea level pressure Pressure (mb)	Maximum surface wind speed Day/time (UTC)[a]	Maximum surface wind speed Sustained (kt)[b]	Maximum surface wind speed Gust (kt)	Storm surge (m)[c]	Total rain (mm)
Oceana NAS	18/0756	996.6	18/1056		42		
Newport News Airport	18/0654	998.6	18/1054		34		
Wallops Island	18/0754	998.5	18/0754		34		305
Cheasepeake							255
Portsmouth							3
NOAA Buoys and C-MAN stations							
Buoy 41009	15/0900	984.8	16/1100	45	60		
Gray Reef buoy (41008)			17/0800		51		78
Sombrero Key C-MAN	15/1700	990.5	15/1530	57	69		
Molasses Reef C-MAN	15/2100	991.5	15/2020	53	64		
Long Key C-MAN	15/2000	988.7	15/2000	50	61		
Sand Key C-MAN	15/1200	987.0	15/0610	43	57		
Dry Tortugas C-MAN			15/0850	41	51		225
Fowey Rock Light C-MAN	15/2300	991.9	15/2200	57	73		241
Lake Worth C-MAN	16/0300		16/0300	44	53		370
Frying Pan Shoals tower			17/2250	49	61		
Diamond Shoals (DSLN7)	18/02002	983.0	17/2250	45	49		
Cape Lookout (CLKN7)	18/0100	989.0	18/0303		40		
Duck Pier (DUCN7}	18/0700	994.0	17/0300	40	49		90
NWS COOP observer rainfall							340
Fort Lauderdale							334
Hollywood							306
Homestead General Airport							212
North Dade County							
NWS unofficial							392
Cooper City							377
West Pembroke Pines							353
Saga Bay							343
South Miami							443
Boyton Beach							297
Plantation							295
Tamiami Trail/Krome Ave.							264
Everglades/U.S.27							247
Lauderdale Lakes							242
El Portal							237
Pompano Beach							233
Lake Worth				44	53		227
Biscayne Bay/320 St.							223
Weston							210
North Miami Beach							198
West Boca Raton							193
Opa-Locka							188
Saw Grass Mills							192
North Palm Beach							180
Leisure City							164
Jupiter							
South Florida Water Management District							
Belle Glade			16/2303		81		
20–25 mi SW of Clewinston			15/2226		79		
Lake Ockeechobee (middle)			16/0522		70		
25 mi west of Palm Beach			15/0055		59		
west of Lake Ockeechobee			15/2239		56		
35 mi west of Boca Raton			15/2314		50		
Krome Ave (near Homestead)			15/2003		50		
La Belle			15/1712		43		
Kissimee			16/1510		40		

[a] Day/time is for sustained wind when both sustained and gust are listed.
[b] Standard NWS ASOS and C-MAN averaging periods are 2 min; buoys are 8 min.
[c] Storm surge is water height above normal astronomical tide level.

lation of Cindy on 28 August several hundred nautical miles northeast of the Leeward Islands.

f. Hurricane Floyd, 7–17 September

Floyd was a large and intense Cape Verde hurricane that pounded the central and northern Bahama Islands, threatened the southeast U.S. coast from Florida through South Carolina, finally struck the coast of North Carolina, and moved along the U.S. east coast into New England. It neared the lower threshold of category 5 intensity as it approached the Bahamas, and produced a flood disaster of immense proportions in the eastern United States, particularly in North Carolina.

1) Synoptic history

Floyd can be traced to a tropical wave that emerged from western Africa on 2 September. The wave proceeded westward across the eastern tropical Atlantic at about 15 kt, with little change in structure. On 6 September, a curved band of deep convection began to develop and Tropical Depression 8 formed on 7 September about 1000 mi east of the Lesser Antilles.

A deep-layer ridge prevailed to the north of the cyclone such that the associated steering current was west-northwestward at 12–15 kt for 2 days. The cloud pattern became sufficiently well organized for the system to become Tropical Storm Floyd early on 8 September and about 750 n mi east of the Leeward Islands. Floyd slowly strengthened and became a hurricane on 10 September about 200 n mi east-northeast of the northern Leeward Islands.

As Floyd was nearing hurricane status, a midtropospheric trough near 60°–65°W caused a slowing of the forward speed, and a turn toward the northwest. This motion continued until 11 September, keeping the hurricane well to the northeast of the Leeward Islands. On 11 September, Floyd's upper-level outflow was disrupted over the southern semicircle by the above-mentioned trough and by an anticyclone over the eastern Caribbean Sea. Consequently, after strengthening to 95 kt early on 11 September, the hurricane weakened to 85 kt by 12 September. Early on 12 September, rising mid- to upper-tropospheric heights to the north of Floyd forced the hurricane to turn toward the west. Maximum sustained winds increased to 135 kt and the central pressure fell about 40 mb by early on 13 September. Figure 4 is a visible satellite image of Floyd about 8 h prior to the maximum wind speed reaching 135 kt.

A possible contributor to the significant strengthening of Floyd was the presence of enhanced upper oceanic heat content along its track. Analyses from the Physical Oceanography Division, Atlantic Oceanographic and Meteorological Laboratory (AOML), NOAA, showed relatively high values of heat content just to the east of the Bahamas a day or two before Floyd passed through the area.

Floyd moved toward the central Bahamas until late on 13 September when it turned west-northwestward. The eye passed just 20–30 n mi northeast and north of San Salvador and Cat Islands on the night of 13 September. Floyd's eyewall passed over central and northern Eleuthera on the morning of 14 September, and after turning toward the northwest, Floyd struck Abaco Island on the afternoon of 14 September. By the time the hurricane hit Abaco, it had weakened somewhat from its peak, but Floyd was still a borderline category 3/4 hurricane.

A mid- to upper-tropospheric trough over the eastern United States eroded the subtropical ridge over the extreme western Atlantic and Floyd continued to turn gradually to the right. The center of the hurricane paralleled the central Florida coast, passing about 95 n mi east of Cape Canaveral on 15 September. By later that afternoon, Floyd was east of the Florida–Georgia border and headed northward toward the Carolinas.

Although there was a fluctuation in intensity, caused by an eyewall replacement event discussed in the next section, overall, the intensity of Floyd diminished from 13 to 15 September. Two large-scale factors probably contributed to the weakening: the entrainment of drier air at low levels from the northwest, and increasing south-southwesterly vertical shear.

After turning toward the north-northeast with its forward speed increasing to near 15 kt, Hurricane Floyd made landfall near Cape Fear, North Carolina, early on 16 September as a category 2 hurricane, with estimated maximum winds near 90 kt. Floyd was losing its eyewall structure as it made landfall. Continuing to accelerate north-northeastward, Floyd's center passed over extreme eastern North Carolina on the morning of 16 September and over the greater Norfolk, Virginia, area a little later. Floyd then weakened to a tropical storm and moved swiftly along the coasts of the Delmarva Peninsula and New Jersey later on. By the time it reached Long Island on 17 September, its forward speed had increased to near 29 kt. The system decelerated as it moved into New England.

By late on 16 September and early on 17 September, Floyd merged with a frontal zone along the Atlantic seaboard. Floyd took the form of a frontal low and became extratropical by the time it reached the coast of Maine on the morning of 17 September. The cyclone turned toward the northeast and then east-northeast, moving over the coast of New Brunswick late on 17 September, Prince Edward Island early on 18 September, and Newfoundland late on 18 September and early on 19 September. Floyd's extratropical remnant merged with a large extratropical low over the North Atlantic and was no longer a distinct entity by later on 19 September.

2) Meteorological statistics

The peak intensity of Floyd, 135 kt, is based upon an estimate of 90% of the highest aircraft reconnaissance

TABLE 6. Selected surface observations for Hurricane Lenny, 13–23 Nov 1999.

Location	Minimum sea level pressure		Maximum surface wind speed			Storm surge	Storm tide	Total rain
	Day/time (UTC)	Pressure (mb)	Day/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)	(m)[c]	(m)[d]	(mm)
St. Maarten								
Philipsburg Meteorological Office	19/0200	972.1	19/1730	73	90			474
Met. Office FMC8 Rain Gauge								700
Antigua								
V.C. Bird International Airport	20/0100	994.5	19/2046	35	50			465
English Harbour			19/XXXX		69			
U.S. Virgin Islands								
St. Croix								
Hamilton Airport		981.7	17/2035	60	80			204
Maria Hill@		969.9	17/1836	72	97			
USDA Met Station Frederkstad								71
Lime Tree Bay National Ocean Service (NOS) gauge							0.9	
St. Thomas								
Cyril E. King Airport		993.2	18/0417	46	61			110
USGS/National Park Service								87
Charlotte Amalie/NOS gauge							0.5	
St. John								87
Health Center/NWS Sensor			17/XXXX		80			
USGS/Meteorological station Lind Point								75
Coral Bay/COOP observer	17/1900	986.7	17/1710		65			61
Puerto Rico								
Luis Munoz Marin International Airport		1000.0	17/1423	29	34			64
La Puntilla, San Juan/NOS gauge							0.5	
Ceiba/Roosevelt Roads	17/1355	1001.0	17/1345	29	42			108
Magueyes Island, Lajas/NOS gauge							0.3	239
Puerto Rico NWS COOP observer rainfall								
Toro Negro Orocovis								315
Pico Del Este								298
Jayuya								290
Rio De La Plata								267
Aibonito								251
Villalba 3NE								215
Rio Blanco Naguabo								202
Maunabo								189
Rio Orocovis								177
Gurabo Agricultural Expt Station								170
Cayey 1E								168
Lago De Matrullas								168
Rio Fajardo, near Fajardo								165
Lago El Guineo								161
Pueblo Del Rio Gurabo								153
Cerro La Punta/Jayuya								151
Juncos 1NNE								133
La Plaza 7S Caguas								131
Rio Cerrillos Ponce								130
Rio Maunabo								127
Barrio Beatriz/Caguas								114
Montones Las Piedras								112
Bisley Station El Yunque								108
Bairro Arriba/Caquas								76

[a] Day/time is for sustained wind when both sustained and gust are listed.
[b] Standard NWS ASOS and C-MAN on-hour averaging periods are 2 min; buoys are 8 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above NGVD.

flight-level (700 mb) winds of 149 kt on 13 September. The minimum dropsonde-measured central pressure was 921 mb on the same day.

Floyd is estimated to have been a 90-kt hurricane at landfall in North Carolina, based on a 10-m anemometer measurement of sustained winds of 83 kt on 16 September near Topsail Beach, North Carolina. There were also unofficial reports of peak wind gusts to 120 kt (at eight stories elevation) at Wrightsville Beach and 104 kt at the Wilmington Emergency Operations Center.

Table 4 lists a selection of surface observations from land stations and data buoys. Floyd's eye passed over

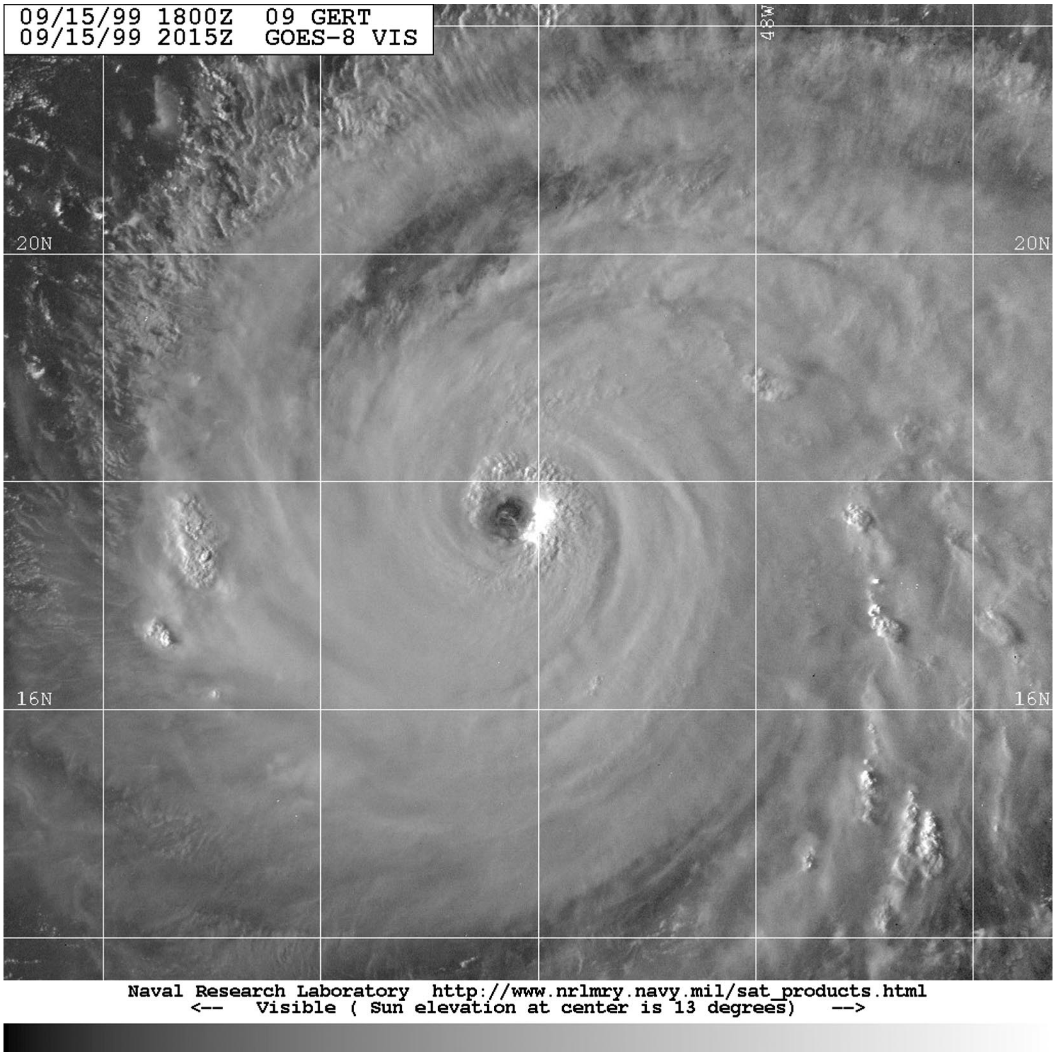

FIG. 6. *GOES-8* visible satellite image of Hurricane Gert at 2015 UTC 15 Sep 1999, near the time of 130-kt maximum wind speed. (Courtesy of Naval Research Laboratory, Monterey, CA.)

NOAA data buoy 41010, located about 105 n mi east-northeast of Cape Canaveral on 15 September. That buoy reported maximum 8-min averaged winds of 72 kt at an anemometer height of 5 m. At least two factors would imply a higher value for the 1-min, 10-m wind speed: 1) extrapolating upward from 5- to 10-m elevation, and 2) the presence of waves above 15 m in height. The best track intensity of Floyd when it passed over the buoy was 100 kt, as indicated by dropsonde and aircraft flight level wind data. The center of the hurricane passed about 25 n mi west of the Frying Pan Shoals C-MAN station located about 30 n mi southeast of Cape Fear on 16 September. This station reported winds sustained at 86 kt for a 20-min period at an anemometer height of 44 m.

On 13 September, just after Floyd reached its maximum strength, a sequence of microwave satellite images (not shown), as well as aircraft radar, gave evidence of a concentric eyewall replacement cycle. Willoughby and Black (1996) describe Hurricane Andrew's concentric eyewalls. First, during the deepening phase, there was a dominant inner eyewall with an eye diameter of 20–25 n mi. Later on, after peak intensity was reached, there was an indication of concentric eyewalls. Figure 5a shows a radar image from a NOAA WP-3D research aircraft late on 13 September that shows the inner and outer eyewalls. Then, there was an apparent eyewall replacement, as suggested by measured vertical wind profiles and radar imagery from a NOAA WP-3D research aircraft as well as by the microwave images. The inner eyewall was dissipating while Floyd was centered near Eleuthera. This corresponded to a weakening of the hurricane to near 105 kt. The outer convective ring became the new eyewall by the time Floyd was centered over Abaco with a 50 n mi eye. This is shown in Fig. 5b, an aircraft radar image at 2028 UTC on 14 September. Afterward, the new eye failed to contract significantly, while Floyd restrengthened just slightly as it reached Abaco. After the disintegration of the inner eyewall, the large-scale environment, as noted previously, became less favorable. Consequently, after leaving the Bahamas, Floyd never regained its former intensity.

Heavy rainfall preceded Floyd over the mid-Atlantic states due to a preexisting frontal zone and the associated overrunning. Hence, even though the tropical cyclone moved fairly quickly, precipitation amounts were very large. Myrtle Beach, South Carolina, recorded 408 mm. At Wilmington, North Carolina, the storm total of 484 mm included a 24-h record of 383 mm. Newport News, Virginia, also reported over 400 mm and amounts over 300 mm were reported in Maryland, Delaware, and New Jersey. Rainfall totals in the 200–250-mm range extended across southern New York and into New England. Storm surge values up to 3.1 m were reported along the North Carolina coast.

A number of tornadoes were sighted in eastern North Carolina. There was a confirmed tornado in Bertie County and another in Perquimans County. The latter tornado destroyed two houses and damaged three or four others. At least 10 tornadoes were reported by spotters in the Newport/Morehead City County Warning area, and these apparently caused some structural damage. Four tornadoes or funnel clouds were seen in the Wilmington area, but no damage was apparent.

3) CASUALTY AND DAMAGE STATISTICS

There were 57 deaths directly attributable to Floyd, 56 in the United States and 1 on Grand Bahama Island. The death toll by state is as follows: North Carolina, 35; Pennsylvania, 6; New Jersey, 6; Virginia, 3; Delaware, 2; New York, 2; Connecticut, 1; and Vermont, 1. Most of these deaths were due to drowning in freshwater flooding. Floyd was the deadliest hurricane in the United States since Agnes of 1972.

In the United States, the Property Claims Services Division of the Insurance Services Office reports that insured losses due to Floyd totaled $1.325 billion. In comparison to most hurricane landfalls, Floyd caused an inordinately large amount of freshwater flood damage, which probably alters the two to one damage ratio. The damage estimate is $4.5 billion.

4) WARNINGS

It is notable that hurricane warnings were issued for the U.S. east coast from south Florida northward to Plymouth, Massachusetts. The last time such an event occurred was during Hurricane Donna of 1960. According to information provided to the Federal Emergency Management Agency, over two million people were evacuated for Floyd in the United States. This is reported to be the largest evacuation in U.S. history.

g. Hurricane Gert, 11–23 September

Gert was a 130-kt hurricane that moved across the central North Atlantic Ocean. It briefly produced hurricane force winds at Bermuda and high waves along the southeast coast of Newfoundland.

1) SYNOPTIC HISTORY

A tropical wave moved from west Africa to the Atlantic on 10 September, accompanied by convective banding and some evidence of a low-level cloud circulation. The developing tropical cyclone's track was south of the Atlantic subtropical ridge and toward the west-northwest from 10–16 September. The best track starts on 11 September, south of the Cape Verde Islands, when the system became a tropical depression. It reached tropical storm strength on 12 September and became a hurricane on 13 September. Gert continued to strengthen to 130 kt by 16 September. Figure 6 is a visible satellite image of Gert near the time of 130-kt wind speed.

There was a weakness in the ridge ahead of Gert and along Floyd's track. While intensifying, Gert responded to this weakness and slowly turned north and then north-northeastward during 16–21 September. Its center came within about 300 n mi to the northeast of the Leeward Islands during this turn. With some fluctuations in intensity, winds remained near 115 kt through 19 September, after which weakening commenced. Gert weakened to 60 kt by 23 September, having moved to near southeastern Newfoundland. It then became extratropical and merged with another extratropical low pressure system.

2) METEOROLOGICAL STATISTICS

Dvorak satellite wind speed estimates place the time of Gert's peak intensity of 130 kt near 0000 UTC on 16 September. Nearly 24 h of reconnaissance data, starting about 0800 UTC on 16 September, indicated that the wind speed weakened to 120 kt and then reached 125 kt early on 17 September.

The center of Gert passed about 115 n mi east of Bermuda on 21 September. The maximum 10-min wind speed reported from the airport was 39 kt with a peak gust to 64 kt. A gust to 76 kt was reported from an exposed coastal location. There were three instances of 1-min mean winds speeds between 66 and 70 kt from a harbor location during the morning of 21 September. A rainfall total of 13 mm was reported from Bermuda. Gale conditions were also experienced on the Avalon Peninsula on southeast Newfoundland.

3) CASUALTIES AND DAMAGES

Bermuda experience some coastal erosion along its east and south sides.

Two persons drowned on 20 September, when a large and unexpected wave swept them out to sea. They had been standing at the water's edge at Schoodic Point in Acadia National Park, Maine. The local marine patrol described the wave as a ''rogue wave.'' This event is believed to be related to large swells generated by Gert, even though the hurricane was located more than 1000 n mi south-southeast of Maine at the time. There were also news reports of 8-m-high waves sweeping over the coast of the southeast tip of Newfoundland. Three persons were swept into the water while trying to secure their boat. All were rescued.

h. Tropical Storm Harvey, 19–22 September

Tropical Storm Harvey formed in the eastern Gulf of Mexico and moved across southern Florida. It produced heavy rainfall over portions of southwest Florida.

1) Synoptic history

The tropical wave that produced Harvey moved off the west coast of Africa late on 4 September. From 4 to 14 September, the wave's trek across the tropical Atlantic into the eastern Caribbean Sea was uneventful, due, in part, to the disruptive effects of the upper-level outflow from Hurricane Floyd. By 16 September, convective activity began to increase over the western Caribbean Sea and a broad area of low pressure formed. Upper-air observations from the northwest Caribbean showed an associated midlevel circulation near the Cayman Islands. The broad area of low pressure drifted northwestward into the Gulf of Mexico over the next few days. Early on 19 September, satellite imagery showed increasing deep convection near and east of the circulation center and a tropical depression formed about 350 n mi west-southwest of St. Petersburg, Florida.

Upper-level outflow around the depression improved. By early on 20 September, surface winds were near 40 kt and the system became Tropical Storm Harvey, about 300 n mi west-southwest of St. Petersburg. Over the next 24 h, Harvey's central pressure dropped a modest 7 mb and the storm is estimated to have reached a peak intensity of 50 kt on 20 and 21 September. Satellite images showed that the system did not become better organized during this period because of westerly vertical wind shear. Data from a NOAA Gulfstream IV high-altitude aircraft on the afternoon of 20 September showed 25–35-kt westerly upper-level winds over the cyclone. This contributed to the displacement of Harvey's center to the northwest edge of the deep convection and restricted the outflow over the western semicircle. Satellite imagery also suggested that dry air was being entrained into the circulation from the northwest.

After turning from a north to a northeast heading on the afternoon of 19 September, Harvey moved slowly eastward on 20 September. By early on 21 September, the system turned southeastward and the forward speed increased to 9 kt in response to midlevel northwesterly flow. Harvey's track bent back to the east by midmorning of 21 September and the cyclone accelerated in advance of a midlatitude trough approaching from the west. Harvey made landfall near Everglades City, Florida, around 1700 UTC on 21 September with maximum sustained winds of 50 kt and a minimum central pressure of 999 mb. It crossed Florida and moved offshore over the Atlantic near Fort Lauderdale. Later that afternoon, Harvey was absorbed by a developing extratropical cyclone centered just off the coast of South Carolina. This extratropical cyclone then moved over portions of the Canadian Maritime Provinces, causing heavy rainfall. Several weather stations along the Fundy coast of New Brunswick received over 200 mm, and up to 302 mm fell in northern Nova Scotia, making for the worst flooding in 30 years. Between 50 and 100 mm of rain fell in Labrador.

2) Meteorological statistics

Harvey's maximum sustained winds of 50 kt are based on a reconnaissance aircraft wind speed of 58 kt at a flight level of 457 m. The ship *Liberty Sun* reported 47 kt on 20 September. The Molasses Reef C-MAN recorded a sustained wind of 47 kt, with a gust to 59 kt, and Fowey Rocks Light reported 45-kt sustained winds with a gust to 51 kt.

The highest official sustained surface wind observed over land was 32 kt at the Key West Airport on 21 September. The Turkey Point Nuclear Power Plant recorded a 10-min, 46-kt wind, at a 9-m elevation, while the highest gust, 48 kt, was recorded at Tenraw in the Everglades (25.6°N, 81.9°W). The lowest pressure observed in south Florida was 999.4 mb at the Fort Lauderdale Airport, also on 21 September.

The highest storm-total rainfall recorded in Harvey was 255 mm at the Naples Conservancy in Collier County. Naples Lakewood measured about 250 mm of rain as did Naples/Collier County Emergency Management at their operations center. Substantial street flooding was reported in portions of Collier and Lee Counties. Rainfall totals of 140 and 171 mm were observed at Immokalee and Everglades City, respectively. Storm total rainfall across Miami-Dade, Broward, and Palm Beach Counties ranged from 19 mm (West Palm Beach Airport) to 72 mm (Coral Springs).

The maximum recorded storm surge was 0.7 m at Fort Myers with estimates from 0.5 to 1.0 m elsewhere in Charlotte County. Storm surge up to 0.6 m occurred elsewhere in southwest Florida and in the Florida Keys. Tidal flooding was reported in Everglades City including the county airport where a portion of the runway was flooded, resulting in the closure of the airport. Minor coastal flooding was reported along the south-facing portions of the Florida Keys and the west-facing shores of Florida Bay. Sections of Highway A1A in the Keys were closed due to the flooding. The combined effect of wave action and the storm surge resulted in minor beach erosion in Sarasota County, along the south-facing shores of the Keys, and in the backcountry of Everglades National Park.

There were two tornadoes. An F0 touched down briefly in Collier County near Paradise Point taking the roof off one house, while the other touched down in Dade County with no reported damage.

The Canadian Hurricane Centre reported that some areas of southeastern New Brunswick and northern Nova Scotia received over 250 mm of rain over a 30-h period from Harvey's extratropical remnants. Oxford, Nova Scotia, reported 302 mm and 50–100 mm fell in Labrador.

3) CASUALTY AND DAMAGE STATISTICS

There are no known casualties. Property damage estimates supplied by the Property Claims Services Division of the Insurance Services Office, indicate that Harvey caused about $7.5 million in insured losses in southern Florida. The total estimated damage from Harvey is $15 million.

i. Hurricane Irene, 13–19 October

Irene was a wet October tropical cyclone that moved over the Florida Keys and southeast Florida. It dumped nearly 400 mm of rain and resulted in severe flooding conditions.

1) SYNOPTIC HISTORY

A broad area of low pressure accompanied by disorganized clouds and thunderstorms prevailed over the southwestern Caribbean Sea from 8 to 10 October. This system did not show signs of tropical cyclone development until a tropical wave reached the western Caribbean Sea on 11 October. On 12 October a U.S. Air Force Reserve reconnaissance plane found an incipient low-level circulation and a broad low pressure area of 1006 mb just to the northeast of the coast of Honduras. However, the circulation was too ill-defined to be classified as a tropical depression. Satellite imagery during the night showed that the thunderstorms increased and banding features and upper-level outflow became quite distinct. Surface and upper-air data from Grand Cayman, and satellite intensity estimates, indicate that a tropical depression formed in the northwestern Caribbean Sea early on 13 October and reached tropical storm status 6 h later. Irene moved on a general northward track, then slowed before curving to the north-northeast just to the southwest of the Isle of Youth, Cuba, where it made its first landfall on 14 October. Radars from Cuba and Key West showed the center of Irene moving on a north-northeast track over western Cuba. The center of the tropical cyclone then crossed the Havana and Ciudad Havana provinces late on 14 October. Irene reached hurricane status over the Florida Straits and the calm of the center moved over Key West near midday on 15 October. Most of the hurricane force winds were confined to the east of Irene's center over the lower to middle Florida Keys. Irene made its fourth landfall near Cape Sable, Florida, and then moved across southeast Florida bringing tropical storm conditions and 250–500 mm of rain. During the period while Irene was crossing Florida, sustained hurricane force winds appeared to be limited to squalls offshore of the east coast of Florida, as reported by reconnaissance aircraft and indicated by surface observations and Doppler radar.

Irene moved back over water in northern Palm Beach County near Jupiter a little after 0000 UTC on 16 October. It retained hurricane strength and moved on a general northward track paralleling the Florida east coast heading for the Carolinas. An upper-level trough, sweeping eastward across the eastern United States, forced Irene on a fast northeastward track. The core of Irene missed the mainland Carolinas but produced very heavy rains inland. It then brushed North Carolina's Outer Banks before moving out to sea.

During a 12-h period beginning on the evening of 18 October, Irene's central pressure dropped from 978 to 958 mb and the winds increased from 70 to 95 kt. This may be attributable to a combination of a trough interaction and the tropical cyclone moving over the warm waters of the Gulf Stream. Thereafter, Irene continued to accelerate and, on 19 October, was absorbed by a much larger extratropical low near Newfoundland. The resultant system became an intense extratropical storm over the North Atlantic.

2) METEOROLOGICAL STATISTICS

Irene was monitored by three Cuban weather radars located at Havana, Isle of Youth, and Pinar del Rio. Operationally, Irene was upgraded to hurricane status just before landfall over the Isle of Youth. However, numerous observations from Cuba and a postanalysis of satellite imagery indicate that Irene was most likely a tropical storm while crossing Cuba. Peak wind gusts reported from Cuba were 68 kt at the Havana forecast office.

A selection of surface observations is given in Table 5. The highest sustained wind observed was 69 kt at Big Pine Key in the Florida Keys. Observations from the South Florida Water Management District indicate that gusts to hurricane force were experienced near Lake Okeechobee. Based on the Miami Weather Surveillance Radar-1988 Doppler signatures, these gusts were likely produced by small-scale mesocyclone-induced downbursts. Four weak tornadoes occurred in Broward and Palm Beach counties.

There was serious urban flooding in southeast Florida with a maximum rainfall amount reported in south Florida of 443 mm in South Miami. Coastal sections of

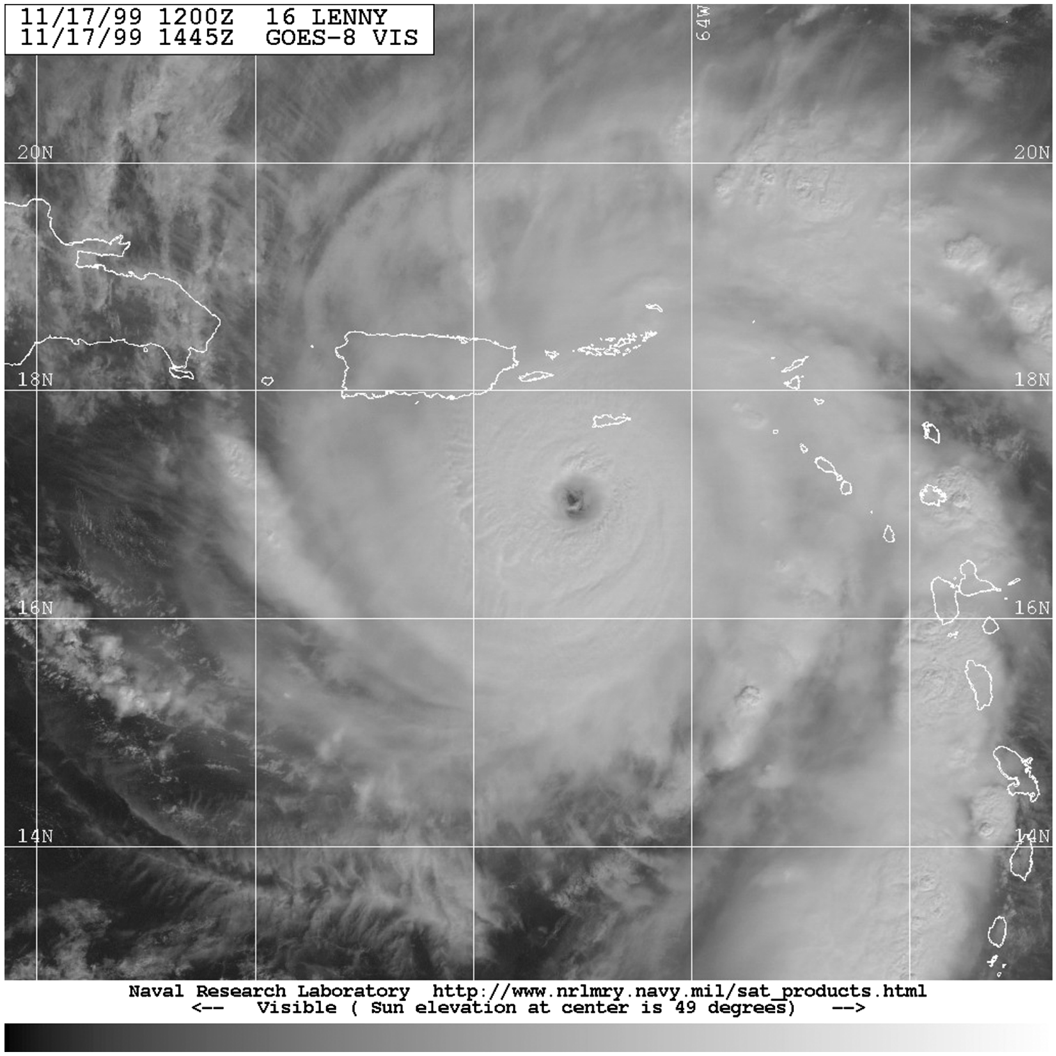

FIG. 7. *GOES-8* visible satellite image of Hurricane Lenny at 1445 UTC 17 Nov 1999, several hours prior to the 135-kt maximum wind speed. (Courtesy of Naval Research Laboratory, Monterey, CA.)

North Carolina and Virginia also recorded amounts in the 200–300-mm range, with lesser amounts in Georgia and South Carolina.

The rapid intensification of Irene on 18 October off the North Carolina coast was documented by a reconnaissance plane investigating the hurricane during that period. Their report indicated a very small closed eyewall of about 3 n mi in diameter and 114 kt winds at a flight level of 850 mb.

3) CASUALTY AND DAMAGE STATISTICS

There were eight deaths indirectly caused by Irene. Five people were electrocuted (four in Broward County and one in Miami-Dade County) when they walked into puddles that concealed downed power lines. There were three drownings when vehicles were driven into canals obscured by flooding (one in Palm Beach County and two in Broward County). In addition, there were three persons injured by tornadoes in Broward County.

Irene caused considerable damage due to flooding in south Florida. In some residential areas, flooding lasted for a week, displacing several hundred people and isolating thousands more. The total losses (agricultural and property) were estimated near $600 million mostly in Dade, Broward, and Palm Beach Counties. Additional losses to near $200 million occurred in the rest of Florida. An estimated 700 000 customers lost electricity.

j. Hurricane Jose, 17–25 October

1) SYNOPTIC HISTORY

Jose originated from a tropical wave that moved off the west coast of Africa on 8 October. The wave moved slowly westward across the tropical Atlantic for several days. By 15 October, when the system was located about midway between Africa and the Lesser Antilles, shower activity became better organized. The disturbance became a tropical depression on 17 October, about 550 n mi east of the southern Windward Islands. There was well-defined upper-tropospheric outflow over the depression. Moving west-northwestward, the depression strengthened into Tropical Storm Jose on 18 October.

Jose turned northward when a mid- to upper-tropospheric trough produced a weakness in the Atlantic subtropical ridge. Jose became a hurricane late on 19 October about 100 n mi east of the Leeward Islands. As it neared these islands, Jose reached its peak intensity of 85 kt at 1200 UTC 20 October. Turning back to a west-northwest heading, Hurricane Jose struck the northern Leeward Islands, passing over Antigua around midday on 20 October. The eye then moved near St. Barthelemy and St. Martin early on 21 October.

Southwesterly vertical shear caused weakening, as Jose moved over the northern Leeward Islands. Jose weakened to a tropical storm by the time it reached Tortola in the British Virgin Islands, on the morning of 21 October. A little later on 21 October, the cyclone turned back toward the northwest and the center passed about 40 n mi northeast of the eastern tip of Puerto Rico. With a large mid- to upper-tropospheric trough positioned over the western North Atlantic, Jose turned northward, then north-northeastward on 22 October. The storm continued north-northeastward at a faster forward speed on 23 October. Its structure was still disrupted by southwesterly shear. Early on 24 October, however, microwave satellite data indicated that the deep convection again was over the low-level center and Jose regained hurricane strength. The hurricane passed about 250 n mi east of Bermuda around midday on 24 October, and the forward speed increased markedly. The rejuvenation of the tropical cyclone was short lived and Jose weakened back to a tropical storm by 25 October. It continued to accelerate into the North Atlantic, losing tropical characteristics later that day. It then merged with a larger midlatitude low and associated front.

2) METEOROLOGICAL STATISTICS

The estimate of a peak intensity of 85 kt is based on a wind of that speed measured at 10 m by a reconnaissance aircraft GPS dropwindsonde. The highest measured wind speed from a surface reporting station was 70 kt with a gust to 89 kt at Antigua. Sustained winds of 65 kt were measured at St. Maarten. The highest sustained wind reported from the Virgin Islands was 52 kt with a gust to 60 kt at St. John. Higher wind speeds likely occurred over portions of the British Virgin Islands. In Puerto Rico, winds were mostly below tropical storm force. There was an unofficial measurement of sustained winds of 30–39 kt with a gust to 48 kt from Costa Azul Beach in Luquillo.

Very heavy rain fell well after the passage of the center over the northern Leeward Islands, in association with bands of thunderstorms extending east and southeast of the center. Rainfall totals were as high as 350 mm over portions of the islands.

3) CASUALTY AND DAMAGE STATISTICS

Two deaths were caused by Jose, one in Antigua and one in St. Maarten. Damage in Antigua was characterized as ‘‘minor.’’ In St. Maarten, the heavy rains caused extensive flooding and mud slides that damaged roads and homes, especially in low-lying areas. United States (Puerto Rico and the U.S. Virgin Islands) damage totals were less than $5 million.

k. Tropical Storm Katrina, 28 October–1 November

Katrina was briefly a 35-kt tropical storm while moving onshore on the Caribbean coast of Nicaragua.

1) SYNOPTIC HISTORY

Satellite imagery shows that the remnants of a cold front moved slowly southward across the western Caribbean Sea beginning on 22 October. A broad area of low pressure gradually formed over much of the Caribbean during this time and cloudiness and thunderstorms became concentrated over the southwestern Caribbean Sea on 26 October. On the next day, low-level cloud lines began to show a closed circulation just north of Panama. On 28 October, a reconnaissance aircraft reported a well-defined low-level closed circulation about 150 n mi east of Bluefields, Nicaragua, indicating that a tropical depression had formed.

Katrina was a tropical storm for about 6 h late on 30 October, while making landfall on the coast of Nicaragua just south of Puerto Cabezas. For the rest of its 4 days, Katrina was a tropical depression that moved on a mostly northwestward track across Nicaragua and Honduras, back over the waters of the northwest Caribbean, and then across northern Belize and the Yucatan Peninsula. The depression dissipated on 1 November just north of the Yucatan Peninsula when it was absorbed by a cold front.

2) METEOROLOGICAL STATISTICS

The system was monitored by reconnaissance aircraft on 28 and 29 October while located in the southwestern Caribbean Sea. The basis for naming Katrina a tropical storm was a 43-kt flight-level wind observation on 29 October. Satellite-based rainfall estimates suggest that 250–375 mm of rain may have occurred over portions of Nicaragua and Honduras, with lesser amounts for the Yucatan Peninsula. San Andres, Colombia, an island about 100 n mi east of Nicaragua, reported 91 mm of rain in 6 h on 28 October.

3) Casualties and damages

It is possible that the rainfall described above caused some flash flooding over mountainous terrain over Central America. No reports of damages or casualties were received.

l. Hurricane Lenny, 13–23 November

Hurricane Lenny was the fifth category 4 hurricane of the 1999 season. This hurricane had a major impact around the Caribbean Sea. Moreover, Lenny is the first storm to have an extended west-to-east track across the central and eastern Caribbean Sea in the roughly 150-yr record of Atlantic tropical cyclones.

1) Synoptic history

A broad area of low pressure was first identified in the southwest Caribbean Sea early on 8 November. Although thunderstorm activity remained poorly organized, locally heavy rains and strong gusty winds occurred over the northwestern Caribbean Sea and adjacent Central America and Mexico for several days. Early on 13 November, satellite imagery showed that the system was gradually becoming better organized. Based on 30-kt surface winds and a 1003-mb central pressure from aircraft reconnaissance that afternoon, a tropical depression formed about 150 n mi south of the Cayman Islands. By mid morning of 14 November, the overall organization of the depression was improving and the depression became a tropical storm on the morning of 14 November.

Later that day, a reconnaissance mission found maximum flight-level winds of 84 kt and a central pressure of 988 mb. Lenny became a hurricane about 150 mi southwest of Kingston, Jamaica. Satellite imagery showed a banding-type eye, 15–20 n mi in diameter.

Lenny's extended west-to-east motion across the Caribbean is unprecedented. For its first 48 h, Lenny moved on an east to east-southeastward course. This motion was induced by the flow around the southern portion of a deep-layer trough located over the western Atlantic. Several short-wave troughs helped to amplify the mean western Atlantic trough through the period, increasing the westerly steering flow. From 1200 UTC 15 November to 1800 UTC 16 November, Lenny's mean forward speed was 14 kt toward the east. The unusual nature of this steering pattern is illustrated by an anomaly chart of November mean 500-mb heights. This chart (not shown) shows a very large negative anomaly (minimum height of -60 m) centered a few hundred nautical miles north of Puerto Rico.

During a 24-h period beginning midday on 16 November, the central pressure dropped 34 mb. Lenny's maximum sustained surface winds of 135 kt and minimum central pressure (933 mb) occurred at 1800 UTC 17 November when the hurricane was centered about 20 n mi south of St. Croix in the U.S. Virgin Islands. However, the 135-kt winds were confined to the southeast quadrant of the hurricane over water. Figure 7 is a visible satellite image of Lenny just before reaching 135-kt wind speed.

Lenny moved into a col between two midlevel ridges late on 17 November and its forward motion slowed. The hurricane drifted east-northeastward before turning southeastward early on 19 November. Despite what appeared in satellite imagery as a favorable upper-level outflow pattern, Lenny weakened, perhaps due to oceanic upwelling. Lenny was gradually weakening when its center passed very slowly over St. Maarten during the afternoon of 18 November, over Anguilla later that evening, and over St. Barthelemy early on 19 November. Lenny weakened to a tropical storm on 19 November just south of St. Barthelemy. It made its final landfall in Antigua late on 19 November.

Lenny continued to move southeastward and the forward motion increased to near 8 kt. The motion turned again toward the northeast as Lenny weakened to a depression on 21 November. The depression turned back to the east early on 21 November and dissipated on the morning of 23 November about 600 n mi east of the Leeward Islands.

2) Meteorological statistics

The estimated peak intensity of Lenny, 135 kt, is based on 90% of the 149-kt flight-level (700 mb) wind speed reported at 1702 UTC 17 November. A GPS dropwindsonde measured 183 kt at 891 mb, a record dropwindsonde wind speed in a hurricane. The lowest pressure recorded by the aircraft was 934 mb at 1929 UTC 17 November. However, the minimum central pressure of 933 mb was assigned based on the lower 700-mb height from the 1702 UTC fix.

Table 6 lists a selection of surface observations from land stations. The highest official sustained surface wind speed observed over land was 73 kt at the St. Maarten Meteorological Office in Philipsburg on 19 November. However, the meteorological antenna fell down during the strongest winds. Hamilton Airport on St. Croix recorded sustained 1-min winds of 60 kt, with a gust to 80 kt. The lowest official pressure observed in the northern Leeward Islands was 972.1 mb at the St. Maarten Meteorological Office.

The maximum sustained surface wind speed reported via amateur radio operators was 81 kt on St. John in the U.S. Virgin Islands on 17 November. During the peak of the hurricane, Saba recorded a gust of 145 kt (792-m elevation) before the anemometer blew away. The highest measured gust of 97 kt on St. Croix coincides with Lenny's closest approach. The minimum central pressure at St. Croix, 980 mb, was also recorded at this time.

Lenny's slow drift across the northern Leeward Islands resulted in very large rainfall amounts over a 36-

h period. For many locations, heavy rain over several days was the primary impact of Lenny. Portions of French St. Martin, St. Barthelemy, and Guadeloupe received record rains. The highest rainfall total in Dutch St. Maarten was 700 mm, recorded at the meteorological office in Philipsburg. Even higher amounts are likely to have occurred in French St. Martin. V. C. Bird International Airport in Antigua reported 465 mm.

Rainfall totals up to 200 mm occurred across the U.S. and British Virgin Islands and resulted in widespread flooding. The largest official rainfall total in Puerto Rico was 239 mm on Magueyes Island, Lajas.

Fredericksted in St. Croix was inundated by an estimated 4–6-m storm surge. The maximum reported storm tide was 0.9 m at the NOAA National Ocean Service gauge in Lime Tree Bay on St. Croix.

Lenny's approach from the west produced unprecedented wave and storm surge impact on westward-facing coasts and harbors. The meteorological service in Dutch St. Maarten reported that southern and western coastal areas were significantly impacted by wave action. The Météo-France meteorological station in Gustavia on St. Barthelemy estimated waves up to 4.9 m in the harbor on 17 November. A platform near La Desirade, just east of Grande-Terre, Guadeloupe, recorded a significant wave height of 3.0 m at 2300 UTC 20 November and estimates range up to 4 m in the harbor.

Lenny generated large waves and swells that propagated across much of the southern and eastern Caribbean, affecting the Guajira Peninsula of Colombia, Aruba, Bonaire, Curacao, and much of the remainder of the Leeward and Windward Islands.

3) Casualty and damage statistics

Lenny was responsible for 17 direct deaths: 3 in Dutch St. Maarten, 2 in Colombia, 5 in Guadeloupe, 1 in Martinique, and 6 offshore. Two of the deaths in St. Maarten were caused by flying debris while the other was the result of a collapsed roadway. The remainder of the onshore fatalities, based on media reports, are presumed to be due to freshwater flooding. Two of the offshore deaths occurred when the sailing yacht *Vdar* was lost somewhere in the southern Caribbean Sea.

Lenny's heavy rain, and wave and storm surge produced considerable damage on many of the islands in the northeast Caribbean. St. Croix sustained moderate damage. Many boats were washed ashore along the north coast of the island. Several boats sank In Christiansted Harbor and structures in the south and east portions of the island suffered roof damage. Lenny also impacted the agricultural areas of the island. Both the Dutch and French portions of St. Maarten/Martin were severely impacted with many buildings damaged and boats damaged or lost. In St. Lucia, at least 70 homes were reported damaged. In Saba, the airport tower and several other buildings were severely damaged. Guadeloupe sustained a large amount of damage along the west coast due to the wave action, and inland due to heavy rains. In Grenada, 10 homes were destroyed and 21 small boats were lost. There were also reports of damage in St. Vincent and the Grenadines, and Montserrat.

Insured losses of $165 million have been reported from Puerto Rico and the U.S. Virgin Islands. Using a factor of 2.0, the total U.S. damages from Lenny is estimated at $330 million.

3. Tropical Depression 11

Four tropical depressions that did not strengthen to tropical storms were tracked. Tropical Depressions 2, 7, and 11 occurred over the southwest Gulf of Mexico, in early July, early September, and early October, respectively. Depression 12 was over the tropical Atlantic, east of the Lesser Antilles in early October. Only Tropical Depression 11 had a significant impact on land.

Tropical Depression 11 caused heavy rains and a high death toll in Mexico. Its origin can be traced to a tropical wave that moved westward from the west coast of Africa on 22 September. Little development occurred until the wave reached the western Caribbean on 30 September, when a broad low pressure area developed. Further development was slow while the system moved across the Yucatan Peninsula into the Gulf of Mexico, and it was not until 4 October that the system became a tropical depression about 125 n mi east-northeast of Veracruz, Mexico.

Steering currents were weak, and the depression meandered erratically over the Bay of Campeche throughout its lifetime. There was one notable reformation of the center early on 6 October, based on reconnaissance aircraft data. A broad surface trough dominated the central and eastern Gulf of Mexico, and the depression merged with this trough about 130 n mi northeast of Veracruz on 6 October. While ship reports and reconnaissance aircraft data indicate that tropical storm force winds were present as the cyclone dissipated, these appear to have been associated with a wind surge moving southward over the western Gulf and not with the tropical cyclone.

Although the depression was poorly organized, it contributed to widespread and prolonged heavy rains over the states of Puebla, Tabasco, and Veracruz, Mexico. Press reports indicate the resulting severe flooding was responsible for an estimated 400 deaths.

4. Verification

The National Hurricane Center issues a 72-h track and intensity forecast, every 6 h, for all tropical cyclones in the Atlantic basin. These forecasts are verified by comparison with the best tracks described in section 1. This season's average official track and absolute intensity forecast errors are given in Table 7, along with the previous 10-yr averages. Absolute intensity errors are

TABLE 7a. National Hurricane Center Atlantic basin average track forecast error (n mi).

	Forecast period (h)				
	12	24	36	48	72
1999 official	37.3	70.3	106.4	139.9	211.4
1999 CLIPER model	47.0	97.1	153.3	207.1	306.8
1999 no. of cases	288	266	244	222	181
1989–98 official	47.6	88.7	127.1	163.9	242.2
1989–98 CLIPER model	55.4	113.2	174.8	253.3	341.9

TABLE 7b. National Hurricane Center Atlantic basin average absolute intensity forecast errors (kt).

	Forecast period (h)				
	12	24	36	48	72
1999 official	7.4	11.6	14.4	16.3	18.6
1999 SHIFOR model	9.0	13.9	17.3	20.4	23.0
1999 no. of cases	286	264	243	221	180
1989–98 official	6.8	10.4	13.3	16.0	19.5
1989–98 SHIFOR	8.5	12.0	14.6	17.1	19.8

errors without regard to sign that measure the magnitude of the errors and not the bias. Errors of the simple climatology and persistence (CLIPER) and statistical hurricane intensity forecast (SHIFOR) statistical models are also listed, as a basis for comparison.

The official track errors for 1999 were lower than their previous 10-yr averages and were also lower than the corresponding CLIPER model errors for a homogeneous set of cases. In contrast, the official 1999 absolute intensity errors were slightly larger than their previous 10-yr average, except at 72 h, where they were slightly smaller. As did the official track errors, the 1999 official intensity errors demonstrated skill over the statistical model.

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