Atlantic Hurricane Season of 1998

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ABSTRACT

The 1998 hurricane season in the Atlantic basin is summarized, and the individual tropical storms and hurricanes are described. It was an active season with a large number of landfalls. There was a near-record number of tropical cyclone–related deaths, due almost entirely to Hurricane Mitch in Central America. Brief summaries of forecast verification and tropical wave activity during 1998 are also presented.

1. Introduction

Nineteen ninety-eight was an active year for tropical cyclones (TCs) in the Atlantic basin. Fourteen tropical storms developed; 10 of these tropical storms became hurricanes. The long-term average numbers of tropical storms and hurricanes per season are 10 and 6, respectively. From 1995 through 1998, 33 hurricanes occurred, the largest 4-yr total ever observed (going back to at least the start of reliable records in the mid-1940s). Three of the 1998 hurricanes strengthened into major hurricanes [maximum winds $\geq$96 kt (49 m s^{-1}); categories 3, 4, and 5, on the Saffir–Simpson hurricane scale; Simpson (1974)]. It was a hurricane season that will long be remembered for a staggering number of fatalities, over 9000, due to disastrous Hurricane Mitch in Central America. Mitch was the fourth most intense hurricane ever observed in the Atlantic basin, and the strongest ever observed in the month of October. There were many TC landfalls; seven tropical storms or hurricanes struck the United States. Hurricane Georges left a path of devastation across the islands of the northern Caribbean Sea, and caused hundreds of deaths in the Dominican Republic.

After a slightly later than normal start with Alex in late July, followed by a couple more quiet weeks, the season more than made up for lost time. In a remarkable 35-day span from 19 August to 23 September, 10 named TCs formed. On 25 and 26 September, *four* hurricanes, Georges, Ivan, Jeanne, and Karl, were on the map at the same time in the Atlantic basin, for the first time since 1893.

Table 1 lists the tropical storms and hurricanes of 1998, and Fig. 1 is a map of their tracks. As was the case in 1995 and 1996, most of the TCs originated in the deep Tropics south of latitude 20°N.

Figure 2 shows the sea surface temperature anomalies from the long-term mean for August through October of 1998. Practically all of the 1998 TCs occurred during these months. During this period nearly all of the Atlantic Ocean's surface from the equator to 60°N was warmer than normal. Of particular interest is the tropical region from the Caribbean Sea eastward to near the coast of Africa. Here, sea surface temperatures were as much as 1°C above normal. The warmer than normal waters may have been a contributing factor to the above normal TC activity. The increase in hurricane activity since 1995 is consistent with the multidecadal sea surface temperature fluctuations identified by Landsea et al. (1999). They showed that the North Atlantic oscillates between warm and cold states that last 25–40 yr each. The last cold episode extended from 1971 to 1994. Since 1995, the north Atlantic appears to have switched back to a warm phase and Atlantic hurricanes have also increased to a level of activity similar to that of the late 1920s to late 1960s.

It has been known for some time (e.g., Riehl and Shafer 1944; Gray 1968) that the vertical shear of the horizontal wind is a major controlling factor in TC genesis and intensity change. Figure 3 shows the anomalies of the vertical shear from the long-term mean for August, September, and October of 1998. Superimposed on this chart are positions where TCs developed during these 3 months (initial tropical depression stage), and crosses showing where they reached tropical storm strength. No system developed in an area where the mean shear was above normal. Also, no tropical cyclone strengthened into a tropical storm where the mean shear was stronger than normal except Klaus, which became a tropical storm over subtropical latitudes in an area where the shear was slightly higher than average.

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TABLE 1. Atlantic hurricane season statistics of 1998.

No.	Name	Class*	Dates**	Maximum 1-min wind (kt)	Minimum sea level pressure (mb)	U.S. damage ($ millions)	Direct deaths
1	Alex	T	27 Jul–2 Aug	45	1002		
2	Bonnie	H	19–30 Aug	100	954	720	3
3	Charley	T	21–24 Aug	60	1000	50	20
4	Danielle	H	24 Aug–3 Sep	90	960		
5	Earl	H	31 Aug–3 Sep	85	985	79	3
6	Frances	T	8–13 Sep	55	990	500	1
7	Georges	H	15 Sep–1 Oct	135	937	5910	602
8	Hermine	T	17–20 Sep	40	999	0.085	
9	Ivan	H	19–27 Sep	80	975		
10	Jeanne	H	21 Sep–1 Oct	90	969		
11	Karl	H	23–28 Sep	90	970		
12	Lisa	H	5–9 Oct	65	995		
13	Mitch	H	22 Oct–9 Nov	155	905	40	9086
14	Nicole	H	24 Nov–1 Dec	75	979		

* 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.

Experience has shown that winds or heights at the 500-mb level usually provide a reasonably good approximation of the TC steering flow. Figure 4a is a map of the mean 500-mb heights for August and September of 1998 with the tracks of the TCs during those months superimposed. Figure 4b shows the anomalies of this height field from the long-term mean. There was a large negative height anomaly centered near the Canadian Maritimes, a large positive anomaly over the eastern Atlantic, and a ridge of slightly higher than normal heights extending westward to near southern Florida. Over the Atlantic, the TC tracks generally followed the periphery of the subtropical ridge, although there was a subtle weakness in the ridge in the vicinity of 40°W where two systems, Ivan and Jeanne, recurved much farther east than the others. Over the Gulf of Mexico, the steering flow appears rather weak and, in fact, TC motion tended to be slow and/or erratic in that area.

2. Tropical storm and hurricane summaries

a. Tropical Storm Alex, 27 July–2 August

A well-organized tropical wave emerged from the west coast of Africa on 26 July and moved westward at 15–20 kt (1 kt = 0.514 m s^{-1}). Early on 27 July, ship reports and satellite scatterometer winds supported the presence of a surface circulation in association with the wave. On this basis, it is estimated that the system attained tropical depression status around 1200 UTC 27 July about 300 n mi (1 n mi = 1.85 km) south-southwest of the Cape Verde Islands.

The depression changed little in organization on 27 July and most of 28 July. It had minimal deep convection near the center, as it moved on a general west-northwest track at 15–20 kt. During this period, satellite imagery characterized the depression as a large and elongated circulation that was still embedded within the intertropical convergence zone. By the evening of 28 July, deep convection increased near the center. Dvorak (1984) satellite intensity estimates indicate that the cyclone strengthened into Tropical Storm Alex by 0000 UTC 29 July.

Alex continued to move on a general west to west-northwest course at 10–15 kt in response to a deep-layer ridge over the tropical eastern Atlantic. During the next several days, Alex's development was hampered by a mid-to upper-level trough, and attendant cyclonic circulation, located to its north and west. By 30 July, satellite imagery indicated that the storm was experiencing southerly vertical wind shear. During the evening of 30 July, satellite imagery showed a burst of deep convection just east of the center. It is estimated that Alex reached a peak intensity of 45 kt from 1800 UTC 30 July to 0600 UTC 31 July, and a minimum central pressure of 1002 mb near 0000 UTC 31 July. Shortly thereafter, increased southerly vertical wind shear induced by the mid- to upper-tropospheric trough to the west of Alex curtailed further strengthening.

Over the next few days the vertical wind shear took its toll. The low-level center of Alex became fully exposed south of the remaining deep convection on 1 August. Alex turned toward the northwest later that day and continued to weaken gradually. It weakened to a depression by midday on 2 August. Later that afternoon, data from an Air Force Reserve Command (AFRC) "Hurricane Hunter" reconnaissance aircraft showed that the system no longer had a closed low-level circulation, and Alex had dissipated.

b. Hurricane Bonnie, 19–30 August

Bonnie was the third hurricane to directly hit the coast of North Carolina during the past three years.

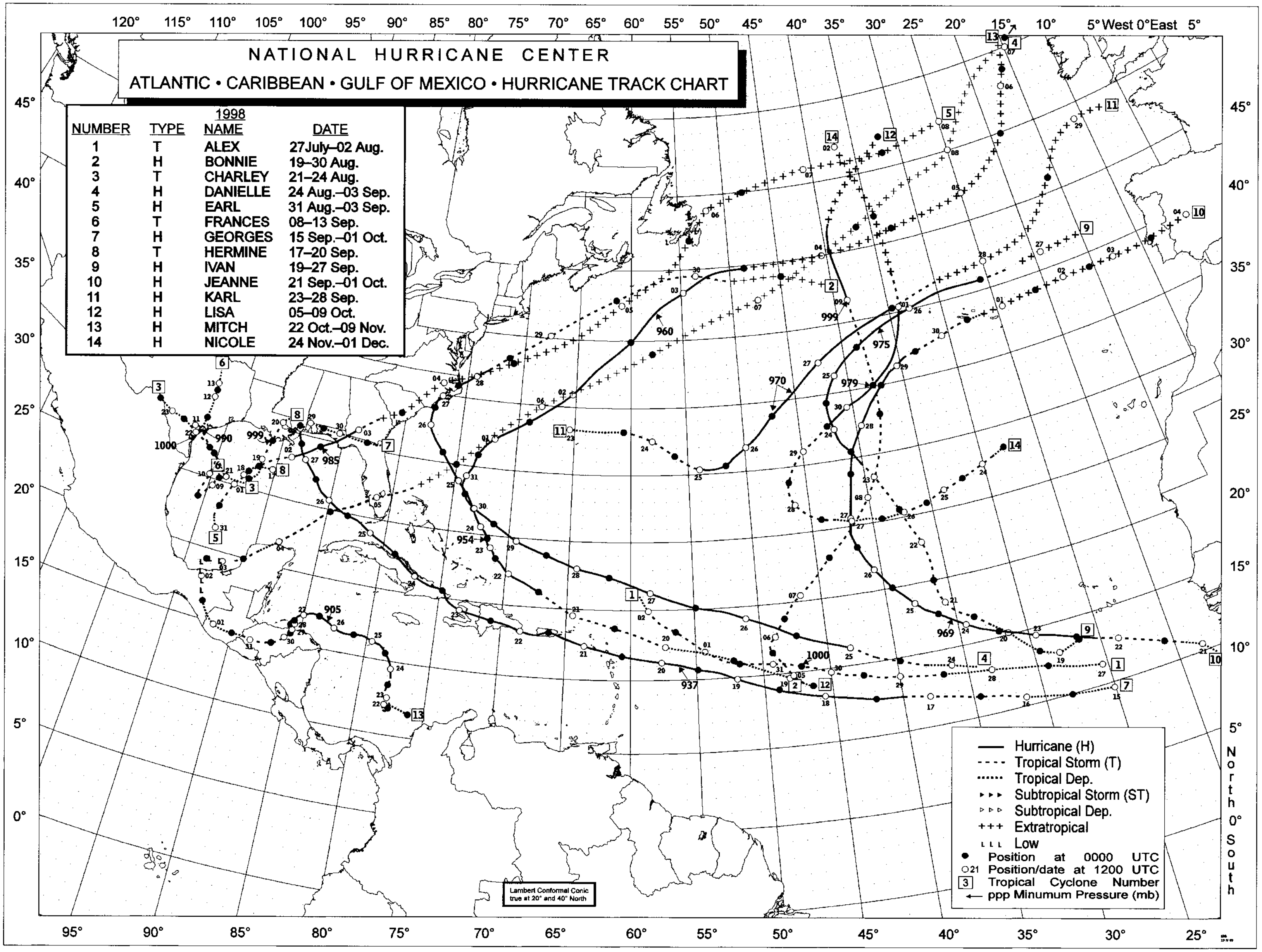

Fig. 1. Tracks of tropical storms and hurricanes in the Atlantic basin during 1998.

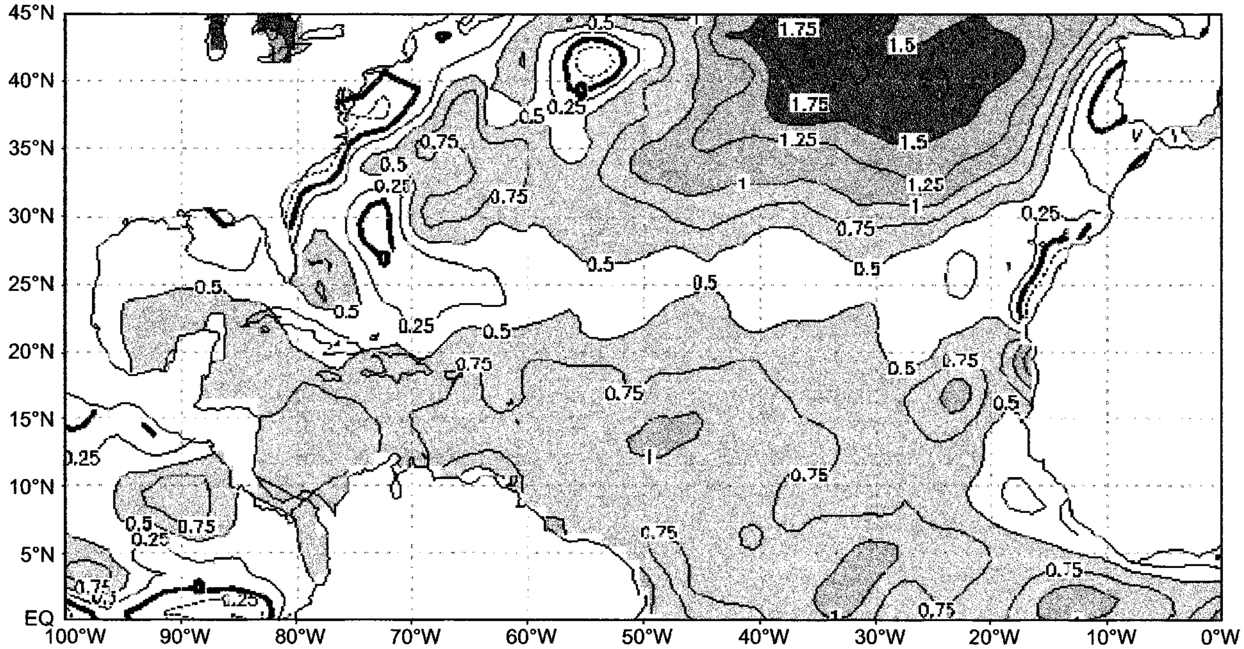

FIG. 2. Sea surface temperature departures from normal (average from 1961 to 1990) for the period 1 Aug–31 Oct 1998. Contour interval is 0.25°C. Shaded areas denote warm anomalies.

1) SYNOPTIC HISTORY

The source of Bonnie was a large and vigorous tropical wave that moved over Dakar, Senegal, on 14 August. The wave appeared in visible satellite imagery as a large cyclonic low- to midlevel circulation void of deep convection. The wave caused 24-h surface pressure changes of −3.5 and −4.0 mb at Dakar and Sal, respectively. There was a well-established 700-mb easterly jet that peaked at 50 kt just before the wave axis crossed Dakar, followed by a well-marked wind shift from the surface to the middle troposphere. The overall circulation left Africa just north of Dakar where the ocean was relatively cool. However, a strong high pressure ridge steered the system on a west-southwest track over increasingly warmer waters and convection began to develop. Initially, there were several centers of rotation within a much larger circulation. It was not until 1200 UTC 19 August that the system began to consolidate into a tropical depression. Although the central area of the tropical depression was poorly organized, the winds north of the circulation were nearly tropical storm strength, as indicated by ship observations and high-resolution low-cloud wind vectors provided in real time by the University of Wisconsin. Based on these

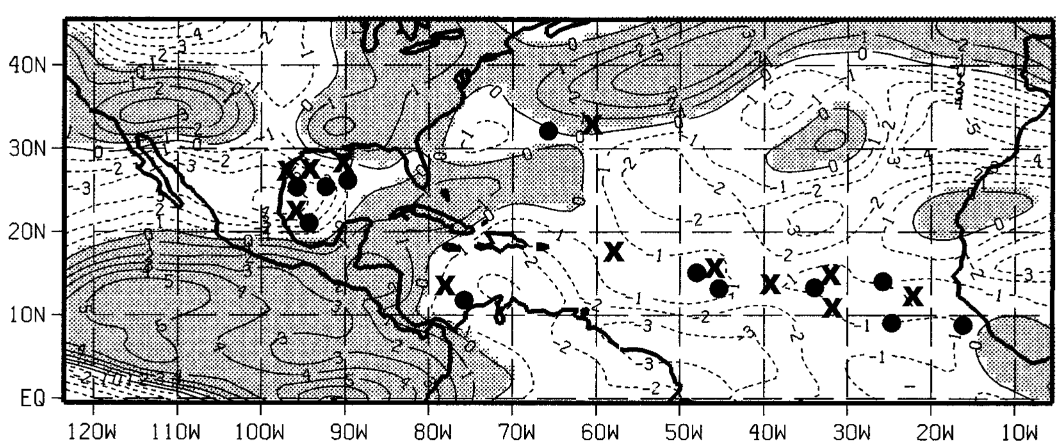

FIG. 3. Anomalies of the magnitude of the vertical shear (850 mb minus 200 mb) of the wind from normal (1958–98 mean) for Aug–Oct of 1998. Contour interval is 1 m s^{-1}. Dots show locations where TCs developed (tropical depression formed) and crosses show locations where the cyclones reached tropical storm strength during these three months. Shaded areas denote wind shears higher than the long-term mean.

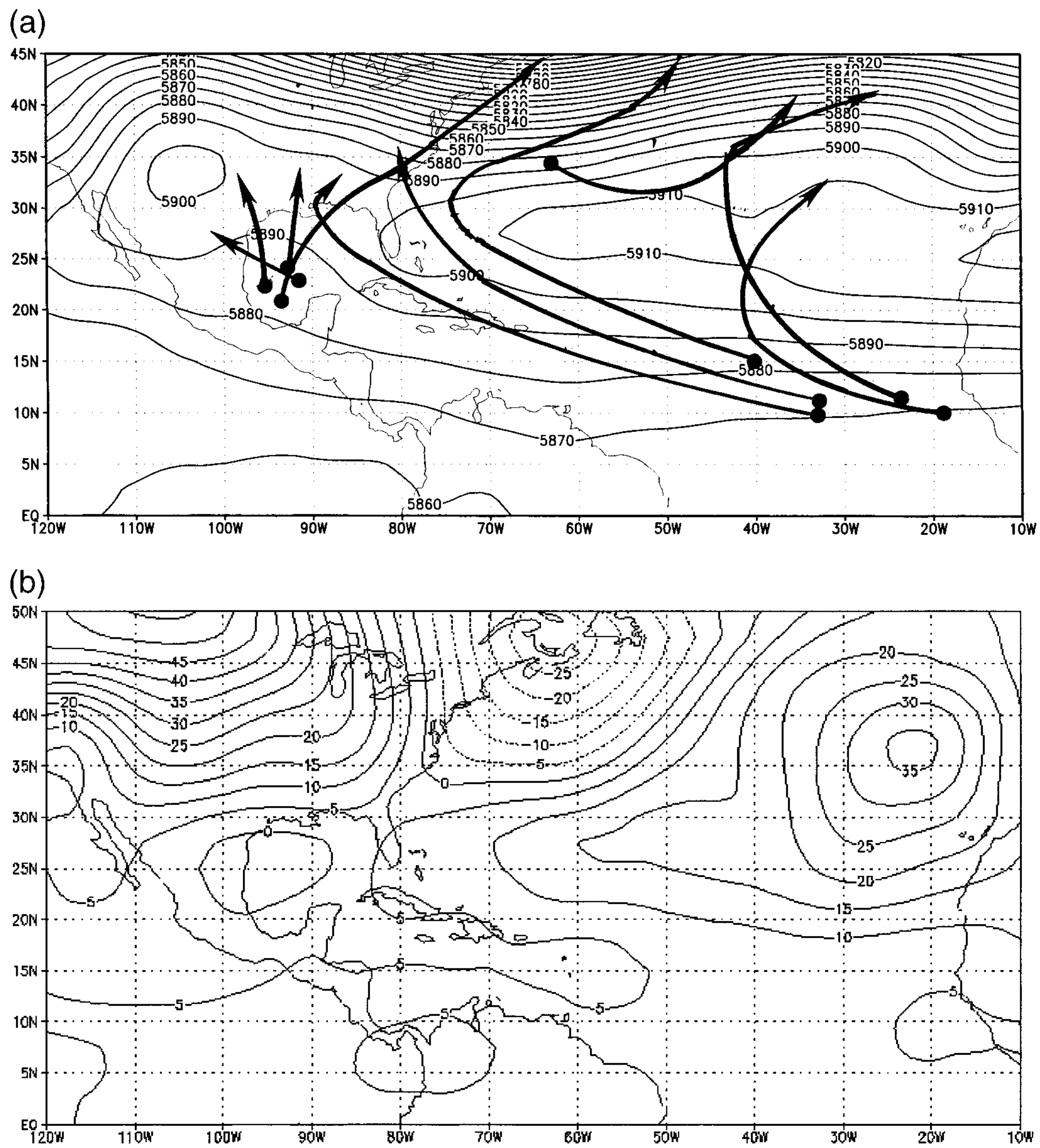

FIG. 4. (a) Mean 500-mb-height contours for Aug–Sep of 1998, with tracks of TCs that occurred during this period superimposed. Contour interval is 10 m. (b) Anomalies of the mean 500-mb height field for Aug–Sep 1998 from normal. Contour interval is 5 m.

winds and satellite intensity estimates, the depression strengthened into Tropical Storm Bonnie by 1200 UTC 20 August. Bonnie moved on a general west to west-northwest track around the circulation of the Azores–Bermuda high toward the northern Leeward Islands.

The first reconnaissance plane into Bonnie arrived late on 20 August and measured a 1004-mb minimum pressure and 61-kt winds at 500-m elevation, northeast of the center. Bonnie skirted the Leeward Islands and most of the associated weather remained to the north over the open Atlantic. During that period, Bonnie's circulation was very asymmetric.

Under favorable upper-level winds, Bonnie gradually strengthened and became a hurricane at 0000 UTC 22 August, when it was located about 200 n mi north of the eastern tip of Hispaniola. At that time, the Hurricane Hunters found a nearly complete eyewall and peak flight-level winds of 76 kt. Bonnie moved on a general west-northwest heading and reached 100-kt maximum winds and 954-mb minimum pressure about 150 n mi east of San Salvador in the Bahamas. Figure 5 shows a visible satellite image of Bonnie near that time.

The ridge to the north of Bonnie temporarily weakened and the steering currents collapsed. The hurricane then drifted northward for a period of 18–24 h. Thereafter, the subtropical ridge reintensified, forcing Bonnie to move northwestward and then northward toward the coast of North Carolina, during which time the hurricane

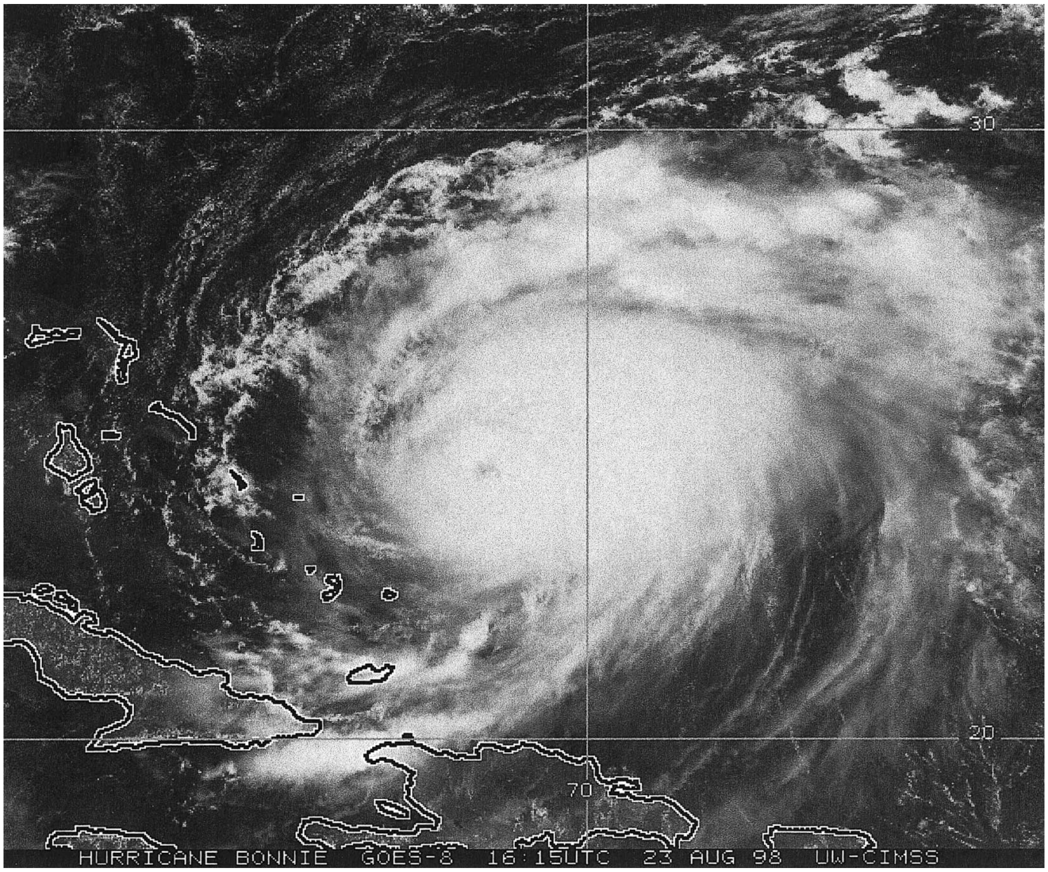

FIG. 5. Visible *Geostationary Operational Environmental Satellite-8* (*GOES-8*) satellite image of Hurricane Bonnie at 1615 UTC 23 Aug 1998, near the time of peak intensity.

maintained winds near 100 kt. After slight weakening of the hurricane, the eye of Bonnie passed just east of Cape Fear around 2130 UTC 26 August and then made landfall near Wilmington, as a category 2 hurricane, around 0330 UTC 27 August.

The hurricane slowed down and weakened over eastern North Carolina. It dropped to tropical storm status based on surface observations and Weather Surveillance Radar-1988 Doppler (WSR-88D) winds. Bonnie turned northeastward over water ahead of a middle-level trough and rapidly regained hurricane strength as indicated by aircraft reconnaissance data. Thereafter, the hurricane moved on a general northeast to east track and became extratropical near 1800 UTC 30 August, about 240 n mi south-southeast of Newfoundland.

2) METEOROLOGICAL STATISTICS

The Hurricane Bonnie event was characterized by a high density of observations. During Bonnie, the National Oceanic and Atmospheric Administration (NOAA) Gulfstream jet and P-3 aircraft deployed a very large number of Global Positioning System (GPS) dropsondes (Hock and Franklin 1999) over a large portion of the Atlantic as a part of a major synoptic flow experiment. These observations were primarily used to initialize the numerical models.

The maximum winds measured were 116 kt at the 700-mb level at 0113 UTC 25 August and then again at 1659 UTC 26 August. These measurements were taken during AFRC and NOAA reconnaissance missions, respectively. Table 2 displays selected surface observations during Bonnie, primarily over the area where the hurricane made landfall. There were several important observations from amateur observers relayed to the Tropical Prediction Center/National Hurricane Center (TPC/NHC) and to the local National Weather Service forecast offices. These include reports of peak wind gusts of 104 kt near North Carolina State Port at 0138 UTC and 100 kt at Wrightsville Beach at 1951 UTC 27 August. Rainfall totals of about 200–280 mm were recorded in portions of eastern North Carolina. Storm tides of 1.5–2.4 m above normal were reported mainly in eastern beaches of Brunswick County, North Carolina, while a storm surge of 1.8 m was reported on the Albemarle Sound in Pasquotank and Camdern Counties. A tornado was reported in the town of Edenton, North Carolina, in Chowan County.

TABLE 2. Hurricane Bonnie selected surface observations, Aug 1998.

Location	Pressure (mb)	Day/time (UTC)	Sustained wind (kt)[a]	Peak gust (kt)	Day/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
U.S. Virgin Islands								
St. Thomas Airport	1006.1	21/1128	23	33	21/0851			7.40
Puerto Rico								
Ceiba	1006.8	21/1121	24	33	21/0156			13.00
Carolina								27.90
Grand Turk								88.90
South Carolina								
Charleston International Airport	1007.0	26/1856	25	33	26/2034			
Charleston City Office			25	39	26/1230			
Myrtle Beach			38	52	26/1715			
North Carolina								
Wilmington	969.9	27/0053	49	64	26/1827			229.60
Kure Beach				77	26/1630			
Florence Airport			34	44	26/2150			
Elizabeth City	995.7	28/0030	51	63	28/0333			36.10
Ocracoke	990.5	27/1815		66	27/1457			167.60
Oregon Inlet	989.1			54	27/2015			
Emerald Isle	976.9			62				
Newport	985.1	27/1030		52	27/0553			241.60
Greenville				63	27/0915			208.30
Morehead City								271.80
Cherry Point			41	61	27/0114			277.60
Jacksonville				62	27/1133			279.40
Frisco			49	69	27/1109			
New Hanover							2.1–2.7	
Tide Gauge on Masonboro Island							2.8	
Wrightsville Beach							2.1–2.2	
Coastal Pasquotank						1.8		
Chowan County						1.5–1.8		
Virginia								
Cape Henry			70	90	28/0300			
Chesapeake Light Station			68	81	28/0350			
Currituck County Emergence Operations Center (EOC)				81	28/0400			
Oceana Naval Air Station (NAS)	999.0		38	54	28/0357			
Langley Air Force Base (AFB)	1005.0		46	58	27/2355			
Norfolk Airport	1000.4	28/0024	40	56	28/0141			172.00
Portsmouth	1000.0	28/0105		55	28/0222			62.00
Norfolk NAS	1002.0		36	48	27/2315			124.70
Sewells Point							1.8	
New Jersey/Delaware								
Delaware Light	1005.2	28/1800	32	40	28/1700			
Reedy Point							1.9	
Cape May							1.8	
Atlantic City							1.5	
Sandy Hook							1.7	
C-MAN stations								
Frying Pan Shoals	964.0	26/1630	76[e]	90	26/2130			
Cape Lookout	994.2	27/1300	48	75	27/1211			
Diamond Shoals	996.8	27/2200	68	79	27/2034			
Duck, NC	993.5	28/0100	45	55	27/2000			
Chesapeake Light	995.7	28/0600	72[e]	86	28/0532			
Buoys								
41002	998.7	26/0300	42[e]	57	26/0426			
41004	990.5	26/1300	38	49	26/1600			
44004	994.3	29/0600	36[e]	46	29/0131			
44014	989.9	28/1000	37	47	28/0200			
44137	998.2	30/0000	50		30/0300			
44144	990.8	30/0300	47		30/0300			
Georges Bank buoy	990.2	29/1600	35	45	29/1700			

[a] National Hurricane Center standard averaging period is 1 min; Automated Surface Observing System (ASOS) and C-MAN are 2 min; buoys are 8 min.

[b] Day/time is for sustained wind when both sustained and gust are listed.

[c] Storm surge is water height above normal astronomical tide level.

[d] Storm tide is water height above National Geodetic Vertical Datum (NGVD).

[e] 10-min average wind.

3) Casualty and damage statistics

Three people died as a consequence of Bonnie. A 12-year-old girl was killed when a large tree fell on her home in Currituck County, North Carolina. Another person was caught in rip currents and drowned in Rehoboth Beach, Delaware. A third person died on Cape Cod when choppy seas overturned a rowboat. This last death may have been only indirectly related to Bonnie.

There are numerous reports of many trees down, roof and structural damage, and widespread power outages primarily in eastern North Carolina and Virginia where a federal disaster was declared for several counties. The area hardest hit appears to have been Hampton Roads, Virginia, where the damage probably reached well into the hundreds of millions of dollars. The Property Claims Services Division of the Insurance Services Offices reports that Bonnie caused an estimated $360 million in insured property damage to the United States. This estimate includes $240 million in North Carolina, $95 million in Virginia, and $25 million in South Carolina. A conservative ratio between total damage and insured property damage, based on past landfalling hurricanes, is two to one. Therefore, the total U.S. damage estimate is $720 million.

4) Warnings

A hurricane warning was issued from Murrells Inlet, South Carolina, to the North Carolina–Virginia border, including the Pamlico and Albermarle Sounds, at 0900 UTC on 25 August, about 39 h prior to the landfall of Bonnie on the coast of North Carolina.

c. Tropical Storm Charley, 21–24 August

1) Synoptic history

The origin of Tropical Storm Charley is unclear. It may have evolved from a large swirl of clouds that left the coast of Africa on 9 August, mainly to the north of Dakar, Senegal. Charley's immediate precursor consisted of a small area of deep convection first noted a few hundred miles to the northeast of the Leeward Islands on 15 August. Intermittent convective activity continued while the system moved just north of west for the following few days. On 19 August, animation of satellite pictures showed a cyclonic rotation of the clouds over the southeastern Gulf of Mexico.

The first formal position estimate from satellite analysts came on the evening of 19 August. Dvorak T numbers for gauging intensity were first assigned the next day (1.5) over the central Gulf [see Dvorak (1984) for description of T numbers]. By the morning of 20 August, surface winds had begun to increase. NOAA's central Gulf buoy 42001 measured sustained winds as high as 31 kt and gusts to 45 kt at 1700 UTC. These stronger winds were fleeting, however, and an investigation of the system late that day by AFRC reconnaissance aircraft did not indicate a closed low-level circulation center.

A center ''fix'' was made aboard reconnaissance aircraft around 1300 UTC the next day, indicating that the system became a tropical depression around 0600 UTC on 21 August. At that time, the depression was centered about 275 n mi off of the south Texas coast. The TC moved toward the west-northwest to northwest at about 10 kt during its 3-day lifetime.

Although the center was not well formed initially, the amount of deep convection steadily increased, particularly over the northern semicircle. This portion of the cyclone swept over the oil platforms of the northern Gulf; data from these platforms (e.g., Table 3) suggest that the depression reached tropical storm status by 1800 UTC on 21 August. Winds of hurricane force were noted at a flight level of 300 m in intense convection to the northeast of the center early on 22 August. Charley was likely then at its peak strength, near 60 kt. Subsequent wind speeds measured by reconnaissance aircraft were considerably lower, and it is estimated from these and other observations that surface winds were closer to 40 kt when Charley's center made landfall near Port Aransas about 1000 UTC on 22 August.

The surface circulation weakened further after landfall and likely dissipated early on 24 August along the Rio Grande near Del Rio, Texas. Although the winds diminished inland, and a closed surface circulation could no longer be identified, a slow-moving circulation aloft persisted in the Del Rio vicinity and generated flooding rains that were most devastating in that area on 23 and 24 August. By late on 25 August, most of the remnant cloud system had deteriorated and precipitation diminished.

2) Meteorological statistics

Charley's primary legacy will be the rainfall and associated flooding near Del Rio. On 23 August, 427 mm of rain fell in Del Rio. This easily surpassed the previous daily record of 223 mm set on 13 June 1935. A nearby site recorded 447 mm for the 24-h period ending in the morning hours of 24 August. Along the coast, maximum rainfall totals were near 125 mm except for an unofficial report of 230 mm near the mouth of the San Bernard River in Brazoria County. River flooding along the Rio Grande occurred well downstream from Del Rio, in the Laredo area. Storm tides of 0.6–1.1 m above normal astronomical levels were reported along the coast.

The Automated Surface Observing System (ASOS) sites at Rockport (RKP) and Galveston (GLS), Texas, were the only two surface reporting stations on land to measure sustained tropical storm force winds. They recorded 2-min winds of 36 kt and 34 kt, respectively. A gust to 55 kt was reported from the Port O'Connor Coast Guard Station. A minimum pressure of 1000 mb is estimated at landfall from the observation of 1000.7 mb at RKP an hour later.

TABLE 3. Tropical Storm Charley selected surface observations, Aug 1998.

Location	Pressure (mb)	Day/time (UTC)	Sustained wind (kt)[a]	Peak gust (kt)	Day/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Louisiana								
Lake Charles ASOS			32	38	21/1918			30.00
Cameron							0.7	
Texas								
Jefferson City Airport (ASOS)			29	37	20/2054			40.60
Corpus Christi NWSO	1005.8	22/1059	27	32	22/1040			10.70
Corpus Christi NAS			27	36	22/0756			1.80
Rockport ASOS	1000.7	22/1059	36	42	22/0806			58.70
Victoria ASOS			30	37	22/1122			66.80
Port Aransas (incomplete record)			29	36	22/1100			
Aransas Pass				46	22/0800			
Cotulla ASOS				37	22/2013			
Seadrift				39	22/0800–0900			
Skidmore				39				
Tynan				35				
Port O'Connor Coast Guard Station				55				
Refugio 3SW								185.40
Woodsboro 10S								127.00
Port O'Connor							0.6–0.9	
Palacios				42				
Galveston ASOS			34	38	22/0823			
Freeport								132.30
Matagorda								111.80
Pleasure Pier							1.5	
Offshore oil rigs								
KS58			35	48	21/1645			
KH08			35		21/1642			
K7R8			40	50	21/1647			

[a] National Hurricane Center standard averaging period is 1 min: ASOS and C-MAN are 2 min; buoys are 8 min.
[b] Day/time is for sustained wind when both sustained and gust are listed.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above NGVD, except for Pleasure Pier where observation is relative to mean low water.

3) CASUALTY AND DAMAGE STATISTICS

Charley's death toll stands at 13 in Texas, with 6 people missing. All were apparently flood victims located well inland. The total consists of four people including two toddlers who were in a pickup truck that was swept away by rising water in Real County on 23 August. Seven other people from the truck were rescued. Nine deaths due to drowning occurred in Del Rio (Val Verde County) along the San Felipe Creek during the late night of 23 August. Emergency operations personnel in Mexico reported that seven people died in Ciudad Acuña, Mexico, across the border from Del Rio. Media reports indicate that three of these victims drowned while trying to cross a flooded gully.

Total U.S. losses due to the inland flood are estimated at $50 million. Property losses were reported in several counties and consisted of damages to residences, businesses, roads, bridges, and agriculture. About 1500 houses, 200 mobile homes, and 300 apartments were damaged or destroyed in Val Verde County, where about $40 million in losses occurred. Minor beach erosion was reported along portions of the Texas coast.

4) WARNINGS

The NHC issued a tropical storm warning from Brownsville to High Island, Texas, on its first advisory (as a tropical depression) at 1500 UTC on 21 August, about 19 h prior to landfall in that area. The warning was extended eastward to Cameron, Louisiana, 6 h later.

d. Hurricane Danielle, 24 August–3 September

Danielle had a long track across the Atlantic. Although it did not significantly impact land as a TC, it battered portions of the United Kingdom as an extratropical system.

1) SYNOPTIC HISTORY

A tropical wave, accompanied by disorganized cloudiness and showers, moved off the west coast of Africa on 21 August. Within 24 h, deep convection became somewhat more consolidated in clusters near an ill-defined center of cyclonic cloud rotation. Initial Dvorak technique classifications were assigned at 1100 UTC 22 August. Thereafter, the organization of the disturbance continued to improve gradually as cloudiness and showers became concentrated in a circular area. By 0600 UTC 24 August, the Dvorak T number was analyzed at 2.0 and it is estimated that Tropical Depression 4 formed around this time, centered a little less than 600 n mi west-southwest of the Cape Verde Islands. Strengthening continued, as satellite images showed convection becoming more tightly wrapped around the center, and the TC is estimated to have become Tropical Storm Danielle by 1800 UTC 24 August. Upper-tropospheric outflow was well defined over the area, and Danielle intensified further. The first visible satellite pictures on 25 August revealed a ''pinhole'' eye, indicating that the system had become a hurricane. Danielle was a quite compact system, with tropical storm force winds covering an area estimated to be only a little more than 100 n mi in diameter. Based on satellite data, this rapidly strengthening hurricane reached a peak intensity of near 90 kt around 0600 UTC 26 August, while centered about 900 n mi east of the Leeward Islands.

After Danielle reached its first peak in strength, southeasterly vertical shear appeared to disrupt its organization. By the time the first reconnaissance aircraft reached the hurricane around 0000 UTC 27 August, it was not as well organized in satellite imagery as it had been. This first aircraft mission found a maximum wind of 90 kt at the 850-mb flight level, but a remarkably high central pressure of 993 mb. Such values of wind and pressure show how much deviation from the typical wind versus pressure relationship can occur in compact hurricanes. In contrast to this, the much larger Hurricane Bonnie, which was in progress over the western Atlantic around the same time with a comparable maximum wind speed, had a minimum central pressure that was 25 mb lower than Danielle's.

Moderate vertical shear continued to preclude much strengthening of Danielle. However, aircraft data indicated that a second 90-kt intensity peak occurred around 1200 UTC on 27 August. For the next few days, some weakening took place even though the eyewall structure was generally maintained and atmospheric conditions seemed to be favorable for intensification. By 30 August, Danielle was barely a hurricane. Movement over waters cooled by the earlier passage of Hurricane Bonnie may have contributed to the weakening.

From the time the cyclone formed, and for about 6 more days, the motion was toward the west-northwest, with the forward speed gradually slowing from 18–20 kt over the eastern Atlantic to 9 or 10 kt on 30 August. By that time, Danielle was nearing the western periphery of the subtropical anticyclone that had steered it across much of the Atlantic. As it continued to decelerate, the hurricane turned toward the northwest and north, reaching its westernmost longitude, about 74°W, early on 31 August. The hurricane restrengthened, and reached a third 90-kt intensity peak around 1200 UTC that day.

In response to increasing southwesterly midtropospheric steering flow, ahead of a trough near the U.S. east coast, Danielle completed its recurvature and began to move northeastward on 1 September. It also regained 90-kt maximum winds for the fourth, and final, time. The center of the accelerating hurricane passed slightly less than 200 n mi northwest of Bermuda early on 2 September. Danielle began to lose its tropical characteristics on 3 September, as its center passed about 200 n mi south of Cape Race, Newfoundland. Danielle became an extratropical cyclone around 0000 UTC 4 September, although it was still a strong storm with hurricane force winds. The storm moved eastward to east-northeastward across the North Atlantic for the next couple of days, with only slow weakening. It turned northeastward about 300 n mi west of the British Isles on 6 September, its forward speed slowed to 6–10 kt. The cyclone became indistinct when it merged with another extratropical low about 200 n mi north of Ireland on 8 September.

2) Meteorological Statistics

The highest wind reported in Danielle was 97 kt, at 700 mb from the Hurricane Hunter reconnaissance aircraft at 1141 UTC 27 August. Additional Hurricane Hunter wind observations of 95 kt at 850 mb and 92 kt at 700 mb were taken at 1235 UTC 31 August and 1656 UTC 1 September, respectively. These data, along with satellite-based intensity estimates on 26 August, are the bases for the four intensity peaks of 90 kt in the best track. The minimum pressure estimate, 960 mb, was derived from a lowest pressure observation of 962.6 mb from the Canadian Laurentian Fan buoy, 44141, at 0900 UTC 3 September. It is also noteworthy that this buoy measured a significant wave height of 15.9 m with a maximum wave height of 26.8 m at the time of its lowest pressure. Sustained winds of 34 kt with gusts to 47 kt were observed at Bermuda at 1100 UTC 2 September.

3) Casualty and damage statistics

No reports of casualties due to Danielle have been received at the National Hurricane Center. The western part of Great Britain was lashed by Danielle as an extratropical storm on 6 September. Several people were rescued from treacherous sea conditions in the area. On the coast of Cornwall, beach areas had to be evacuated after waves became so high that they were breaking over some houses. A police all-terrain vehicle on the Isles of Scilly was swept into the sea by a rogue wave as it was being driven down a concrete pier in one of the island's main towns.

4) Warnings

A tropical storm warning was issued for Bermuda at 1500 UTC 1 September since the southern portion of

Danielle's circulation was likely to affect that island. Sustained winds of tropical storm force occurred at Bermuda about 20 h after the issuance of this warning as the center passed well to the northwest and north. No other warnings or watches were necessary for this TC.

e. Hurricane Earl, 31 August–3 September

Earl made landfall in the Florida panhandle as a category 1 hurricane. Significant storm surge flooding resulted in the ''Big Bend'' area of Florida.

1) SYNOPTIC HISTORY

Hurricane Earl formed from a strong tropical wave that emerged from the west coast of Africa on 17 August. Persistent convection accompanied the wave as it moved westward across the tropical Atlantic. A weak low-level cyclonic circulation was suggested in animation of satellite imagery, as well as in limited aircraft reconnaissance and island reports as the system passed through the Lesser Antilles on 23 August. Tropical cyclone development appears to have been inhibited by unfavorable winds aloft while the system moved through the Caribbean. These unfavorable conditions were a result of the upper-level outflow from large and powerful Hurricane Bonnie located over the southwestern North Atlantic. Nevertheless, the tropical wave continued to be easily tracked in satellite imagery as it moved into the Gulf of Mexico where cloudiness and thunderstorms increased. It is estimated that the system became a tropical depression over the southwest Gulf of Mexico midway between Merida and Tampico, Mexico, at 1200 UTC 31 August.

Based on aircraft reconnaissance, the tropical depression became Tropical Storm Earl about 500 n mi south-southwest of New Orleans, Louisiana, near 1800 UTC 31 August. The center remained difficult to locate by satellite, and, in fact, multiple centers were reported by aircraft reconnaissance for the next couple of days. Occasionally, a new center would appear to form, which made tracking extremely difficult. Although the best track shown in Fig. 1 indicates a general motion toward the north and then northeast near 10 kt while Earl was over the Gulf of Mexico, a certain amount of ''smoothing'' was necessary to account for multiple centers and any possible center reformations.

Based on aircraft reconnaissance data, Earl is estimated to have reached hurricane status at 1200 UTC 2 September while centered about 125 n mi south-southeast of New Orleans. The system never exhibited a classical hurricane appearance. Instead, satellite imagery showed the deepest convection confined primarily to the eastern semicircle and aircraft reconnaissance data indicated a very asymmetric wind field, with the strongest winds located well east and southeast of the center.

After briefly reaching category 2 status, Earl made landfall near Panama City, Florida, as a category 1 hurricane near 0600 UTC 3 September. Because the strongest winds remained well to the east and southeast of the center, the highest storm surge occurred in the Big Bend area of Florida, well away from the center. The TC weakened to below hurricane strength soon after making landfall, and became extratropical at 1800 UTC 3 September as it moved northeastward through Georgia. The deepest convection became well removed from the center by this time and the strongest winds were located over the Atlantic waters off the U.S. southeast coast. The extratropical cyclone moved off the mid-Atlantic coast near 1800 UTC 4 September, crossed over Newfoundland on 6 September, and was tracked across the North Atlantic until it was absorbed by a larger extratropical cyclone (formerly Hurricane Danielle) on 8 September.

2) METEOROLOGICAL STATISTICS

The operational aircraft reconnaissance flights into Earl were provided by the AFRC. The minimum central pressure reported by aircraft was 985 mb at 0045 UTC on 3 September. This minimum pressure was measured by dropsonde and was the lowest pressure reported during Earl's existence. The maximum winds of 104 kt from a flight level of 850 mb (near 1.5 km) were measured at 1638 UTC 2 September. These peak winds were in a limited area about 80 n mi east of the center. The Hurricane Hunters never reported an eyewall. Reconnaissance data and land-based radar presentations suggest the hurricane weakened before it moved onshore.

Satellite analyses underestimated the intensity of Earl, probably because the system never exhibited a classical TC pattern. For example, the maximum winds estimated from the Tropical Analysis and Forecast Branch (TAFB), the tropical branch of the Air Force Weather Agency (AFWA), and the Satellite Analysis Branch (SAB) were 55, 55, and 45 kt, respectively.

The WSR-88Ds at Slidell, Louisiana; Mobile, Alabama; Eglin Air Force Base, Florida; and Tallahassee, Florida, were helpful in locating the center and areas of strongest winds aloft as the cyclone moved near shore. As is often the case in landfalling hurricanes, there were no reports from land stations of sustained hurricane force winds in Earl. Table 4 lists selected U.S. surface observations. The NOAA Coastal Marine Automated Network (C-MAN) station at Cape San Blas (near Apalachicola, Florida) reported 10-min sustained winds of 48 kt between 0400 and 0500 UTC and gusts to 61 kt at 0436 UTC 3 September. The strongest winds at the time of landfall likely remained over water near the Big Bend area of Florida. Several wind reports from north Florida were relayed to the NHC through amateur radio volunteers. The highest measured wind gust was 79 kt at an elevation of 10 m from a Davis wind instrument located in the middle of St. George Island at 29.40°N, 84.53°W at 0102 UTC 3 September. The storm surge was estimated to be near 2.4 m in Franklin, Wakulla,

TABLE 4. Hurricane Earl selected surface observations, Sep 1998.

Location	Pressure (mb)	Day/time (UTC)	Sustained wind (kt)[a]	Peak gust (kt)	Day/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Louisiana								
Moisant International Airport	1003.7	02/2251	25	31	02/1658			6.10
New Orleans Lakefront Airport	1003.4	02/2258	29	32	02/1658			7.90
Venice	1000.3	02/1504	29	38	02/1820			
Slidell			21	27	02/2112			63.80
California Bay						1.6		
Industrial Canal						1.1		
Bayou Bienvenue						1.5		
Mississippi								
Pascagoula/Trent Lott Airport	1002.4	02/2232	21	29	02/2014			27.40
Gulfport			23	29	02/1846			
Bay St. Louis								107.70
Alabama								
Mobile Regional Airport	1002.7	03/0011	23	28	02/1913			62.20
Mobile Brookley Field	1002.4	03/0028	24	31	02/2120			33.50
Evergreen	1002.0	03/075518	18	24	03/0223			1.80
Mobile State Docks							0.6	
Little Dauphin Island Bay							0.8	
Bayou La Batre							0.8	
Fairhope Agricultural Station				26	02/2200			55.10
Grand Bay Agricultural Station				32	03/2033			56.90
Seemes Agricultural Station				16	01/1913			42.90
Tillmans Corner								175.30
Dothan Airport	994.2	03/0919	22	31	03/0528			136.10
Florida								
Pensacola Regional Airport	998.3	03/0100	32	49	03/0047			77.70
Pensacola NAS	997.6	02/2356	32	43	02/1800			71.40
Crestview	995.6	03/0601	35	47	03/0424			153.20
Destin	994.2	03/061030	30	41	03/0222			63.50
Hurlburt Field AFB	994.9	03/0527	31	44	03/0426			138.40
Eglin AFB	997.6	03/0655		38	03/0354			160.30
Whiting Field (Milton)	1000.0	03/0600	23	37	03/0300			56.40
Panama City Airport	987.1	03/0725	36	46	03/0612			316.50
Panama City (5 mi NE)								416.10
Marianna Municipal Airport	990.5	03/1004	32	42	03/1002			151.40
Tallahassee Regional Airport	989.5	03/1005	29	40	03/0959			137.40
Perry-Foley Airport	996.6	03/1026	24	32	03/0432			111.80
Cross City Airport	999.0	03/0700	19	26	02/2232			108.50
Apalachicola	990.5	03/0833						
Shell Point				51	03/0310			
Dept of Meteorology, The Florida State University				42	03/1020			133.40
Turkey Point			38	57	03/1000			
Brooksville	1003.7	03/0306	32	41	03/1136			76.20
New Port Richey	1004.4	03/0246	29	40	03/1103			78.0
Clearwater tide gauge			26		03/0750			
St. Petersburg/Clearwater	1005.1	03/0731	22	39	03/1550			41.10
St. Petersburg Uncommissioned ASOS	1004.1	03/0248	33	39	03/0323			
St. Petersburg			34	41	03/0322			
St. Petersburg Pier			21	33	03/0700			
Tampa Airport	1004.1	03/0252	32	39	03/1108			22.10
MacDill AFB	1008.5	03/0239	24	34	03/1330			35.80
Tampa Airport	1004.1	03/0252	32	39	03/1108			22.10
MacDill AFB	1008.5	03/0239	24	34	03/1330			35.80
Old Port Tampa			23	38	03/1330			
Sunshine Skyway			33	42	03/1730			
Winter Haven	1006.4	03/0519	28	34	03/1303			11.70
Lakeland	1006.9	03/1050	10	28	03/0500			
Sarasota Airport	1004.4	03/0252	32	41	03/1205			
Lido Key tide gauge			26		03/0750			
Punta Gorda	1007.5	03/0509	23	29	03/1316			1.50
Fort Myers	1007.5	03/0507	23	29	03/1246			10.20
Regional SW Airport	1007.1	03/0455	23	29	03/1238			0.50
Inverness								35.60
Ruskin								18.50
Escambia County						0.6–0.9[e]		

TABLE 4. (*Continued*)

Location	Pressure (mb)	Day/time (UTC)	Sustained wind (kt)[a]	Peak gust (kt)	Day/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Santa Rosa County						0.9[e]		
Okaloosa county						1.2[e]		
Franklin County						2.4[e]		
Wakulla County						2.4[e]		
Jefferson County						2.4[e]		
Taylor County						2.4[e]		
Dixie county						1.8–2.1[e]		
Levy County							1.5–2.1[e]	
Citrus County							1.2–1.5[e]	
Hernando County							0.9–1.4[e]	
Pasco County							0.9–1.4[e]	
Pinellas County							0.9–1.4[e]	
Hillsborough County							0.9–1.4[e]	
Manatee County							0.9–1.4[e]	
Sarasota County							0.6–0.9[e]	
Charlotte County							0.6–0.9[e]	
Lee County							0.6–0.9[e]	
C-MAN stations								
Grand Isle	1002.4	02/1600	31	40	02/1100	1.2		
Dauphin Island	1001.1	02/2200	38	47	02/1900			
Cape San Blas	991.0	03/0500	48[f]	61	03/0500			
Cedar Key	1001.9	03/0700	37	47	03/0900			
Venice	1007.0	03/0800	30	36	03/0500			
Keaton Beach	998.3	03/1100	41[f]	55	03/095012			
Southwest Pass	999.0	02/1500	37[f]	48	02/1410			
NOAA buoys								
42040	994.9	02/1900	41	55	02/1500			
42039	989.4	03/0100	45	63	03/0100			
42036	999.9	03/0300	35	47	03/0300			
42002	1000.6	01/2300	26	34	31/2000			
42001	998.9	02/1000	37[f]	52	01/1000			
42007	1000.5	02/2200	30	37	02/1700			

[a] National Hurricane Center standard averaging period is 1 min; ASOS and C-MAN are 2 min; buoys are 8 min.
[b] Day/time is for sustained wind when both sustained and gust are listed.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above NGVD.
[e] Estimated.
[f] 10-min average wind.

Jefferson, and Taylor Counties and approximately 2 m in Dixie County. These values tapered off to less than 1 m in Lee County. Rainfall totals of 75–150 mm were common near the path of Earl, although much higher amounts were recorded in a few areas. A storm total of 416 mm near Panama City, Florida, was the highest reported. Several tornadoes were reported in central and north Florida, Georgia, and South Carolina.

There was an extensive sampling of the Gulf of Mexico with GPS dropsondes from the NOAA jet around 0000 UTC 2 September. These data showed that a midtropospheric trough over the east-central United States extended into the central Gulf of Mexico. This atmospheric feature provided the steering current that moved Earl northeastward into the Florida panhandle.

3) CASUALTY AND DAMAGE STATISTICS

Hurricane Earl was directly responsible for three deaths. Two occurred as a result of a boat that capsized off Panama City. One death occurred as a result of a tornado near St. Helena, South Carolina.

The Property Claims Services Division of the Insurance Services Offices estimated that Earl caused insured property damage of $15 million in Florida, $1 million in Georgia, and $2 million in South Carolina. These estimates do not include storm surge damage. In addition, the National Flood Insurance Program reported $21.5 million of insured (storm surge related) losses in Florida. Using a two to one ratio of total to insured property losses gives a total U.S. damage estimate of $79 million for Earl.

4) WARNINGS

Since the NHC forecasts are based, in part, on the computer guidance, which in the case of Earl generally had a westward bias, hurricane warnings were not extended eastward over the landfall location until 1300 UTC 2 September. These warnings were not issued with

TABLE 5. Tropical Storm Frances selected surface observations, Sep 1998.

Location	Pressure (mb)	Day/time (UTC)	Sustained wind (kt)[a]	Peak gust (kt)	Day/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Louisiana								
Acadiana Regional Airport	1006.8	11/2300	23	30	11/1605			196.10
Cameron						1.6		
Jefferson County Airport	1002.0	11/2100	33	43	11/1312			216.40
Lake Charles Airport	1003.7	11/2100	28	35	11/1929			204.20
Lafeyette Regional Airport	1006.8	11/2100	27	35	11/0034			229.60
Patterson Memorial Airport	1008.8	11/2300						
Sabine Pass						1.3		
Salt Point	1007.1	11/2100	22	33	12/0438			289.10
Texas								
Galveston Airport			37	47	10/2219			253.50
Houston International Airport			24	31	10/2039			172.50
Houston/Hobby Airport			32	40	10/1919			233.70
Palacios Airport			29	46	10/1915			242.10
Bolivar Roads							1.8	
Eagle Point							1.6	
Jamaica Beach							2.2	
Matagorda Locks							2.4[e]	
Morgans Point							2.3	
Pier 21							1.7	
Pleasure Pier							2.2	
Sargeant Swing Bridge							2.4[e]	
Alice				33	10/2133			
Bob Hall Pier						1.2		
Corpus Christi	993.9	11/1321	31	38	10/1931			
Corpus Christi NAS	993.8	11/1100	32	42	10/1056			
Cotulla				28	11/0747			
Kingsville NAS	996.3	11/1137		32	11/1024			
Rockport	993.2	11/1321	31	39	11/1832	1.2		
Victoria			36	41	11/0602	1.5		
Brazoria County								
Alvin								274.30
Demi-John community								330.20
Freeport Dow Chemical								199.10
Manvel								252.70
West Columbia								411.50
Chambers County								
Anahuac								291.30
Beach City								209.80
Hankavmer								237.50
Oak Island								208.30
Smith Point								295.90
Wallisville								197.40
Winnie								284.50
Austin County								
Belleville								114.30
Sealy								147.10
Colorado County								
Colubus								87.90
Cordele								174.50
Fort Bend County								
East Bernard								138.70
Fulshear								182.90
Needville								182.40
Orchard								158.80
Richmond								173.70
Rosenberg								228.60
Simonton								203.20
Galveston County								
Dickinson								210.80
League City								241.30
KGBC radio station								215.10
Santa Fe								315.00
Harris County								
Barker Dam								10.40

TABLE 5. (*Continued*)

Location	Pressure (mb)	Day/time (UTC)	Sustained wind (kt)[a]	Peak gust (kt)	Day/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Baytown								167.40
Buffalo Bayou at Katy								18.00
Buffalo Bayou at West Beltway								
Hockley								358.30
Denver Harbor								374.75
Houston								269.20
Houston Spring Branch								78.70
Houston 3 mi SW downtown								330.20
La Porte								326.90
Missouri City								164.80
Seabrook								377.20
West Houston								273.10
Jackson County								
Edna								175.80
Ganado								216.90
Lake Texana								85.10
Liberty County								
Cleveland								132.80
Liberty								140.00
Matagorda County								
Bay City								275.30
Matagorda Colorado Locks								431.80
Palacios								268.50
Montgomery County								
Montgomery								47.00
Wharton County								
Danevang								179.10
Pierce								3.00
Wharton								170.90

[a] National Hurricane Center standard averaging period is 1 min; ASOS and C-MAN are 2 min; buoys are 8 min.
[b] Day/time is for sustained wind when both sustained and gust are listed.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above NGVD.
[e] Estimated.

as much lead time (17 h prior to the arrival of the center) as the NHC desires. Fortunately, appropriate preparations appear to have been completed anyway.

f. Tropical Storm Frances, 8–13 September

Frances brought very heavy rainfall to portions of eastern Texas and southern Louisiana.

1) SYNOPTIC HISTORY

Frances formed within a broad area of low pressure that first showed signs of organization of its associated convective cloudiness on 4 September. The convection was widespread over the western Caribbean and southern Gulf of Mexico, but there was no well-defined low-level circulation center. This situation persisted for several days as the system moved slowly west-northwestward. During this time a tropical wave moved into the area, and the system consolidated. By 8 September, the system developed a 1000-mb central surface pressure and considerable organized deep convection over a large area of the western Gulf of Mexico. It is estimated that a tropical depression formed by 1800 UTC on this date about 140 n mi east of Brownsville, Texas. At this stage in its development, with its large size, loosely organized convection, and lack of a distinct center, the TC was similar to the so-called monsoon depression of the western North Pacific basin.

The tropical depression drifted southward for about a day. By 1800 UTC on 10 September, wind observations from a data buoy, reconnaissance aircraft, and several oil rigs indicated that the depression had strengthened to a 35-kt tropical storm. Frances began moving north to northwestward at 10–15 kt. The center moved inland across the Texas coast just north of Corpus Christi at 0600 UTC on 11 September. By this time, Frances had strengthened to 55 kt under a large anticyclone aloft, in weak vertical shear, over SSTs near 30°C.

After moving inland, the center moved in a small cyclonic loop for 12 h between Corpus Christi and Victoria, and then moved northward across eastern Texas as a weakening tropical depression. The best track ends at 1800 UTC on 13 September, when the center was near the Texas–Oklahoma border north of Dallas, but the remnant low pressure and rainfall were tracked northward to Iowa during the next 24 h.

2) METEOROLOGICAL STATISTICS

Table 5 lists selected surface observations, including selected rainfall totals. Tropical storm force wind speeds were observed at several data buoys and oil rigs in the western Gulf of Mexico. The C-MAN station at Sabine, Texas, reported a maximum 2-min wind speed of 44 kt; this is the highest observed sustained surface wind speed. Sustained winds of tropical storm force were observed over land at Galveston and Victoria, Texas, and at Jefferson County Airport in Louisiana. Frances was a large storm; 34-kt winds extended approximately 300 n mi north and east of the center. Storm surge flooding of up to 1.8–2.4 m occurred along the middle and upper Texas coast and up to 1.5 m along the Louisiana coast. This flooding persisted for about 48 h. Freshwater flooding from rainfall was the most significant weather effect. Frances dropped copious rainfall over east Texas and southern Louisiana. The highest total reported in Texas was 411.5 mm in Brazoria County, and the highest total from Louisiana was over 289 mm. Undoubtedly, even higher amounts are likely to have accumulated in these areas. Over a dozen tornadoes were reported over southwestern and south-central Louisiana on 11–12 September. These caused one death (see next section), and extensive damage to schools in Acadia and Evangeline Parishes, and to homes in Lafayette Parish.

3) CASUALTY AND DAMAGE STATISTICS

The only known fatality directly attributable to Frances was in Lafourche Parish, Louisiana, where a man was killed when his trailer home was destroyed by a tornado spawned by the tropical storm. Six others were injured by this tornado. An indirect death occurred in the New Orleans area where a woman died in an automobile accident.

Moderate beach erosion occurred along much of the upper Texas and western Louisiana coastlines. Three Texas counties and four Louisiana parishes were declared federal disaster areas, primarily due to the rainfall flooding. These include Brazoria, Galveston, and Harris Counties and the parishes of Cameron, Jefferson, Lafourche, and Terrebonne. The Insurance Services Offices reported that a total of $110 million in insured property damage has been claimed in Texas, Louisiana, and Mississippi. The *Houston Chronicle* reported that $256 million in damage was inflicted in Galveston County. The total damage estimate for Frances is $500 million.

4) WARNINGS

Tropical storm warnings were issued along the Gulf of Mexico coast from Tampico, Mexico, northward and eastward including all of Texas and Louisiana. The warnings for the central Texas coast were issued at 2100 UTC on 9 September, some 33 h before landfall and almost 24 h prior to the time tropical storm force winds reached the coast.

g. Hurricane Georges, 15 September–1 October

Georges was the second-strongest and second-deadliest hurricane in the Atlantic basin during the 1998 season. Its 17-day journey resulted in eight landfalls, from the northeastern Caribbean to the coast of Mississippi, and 602 fatalities—mainly in the Dominican Republic and Haiti.

1) SYNOPTIC HISTORY

Georges originated from a tropical wave that crossed the west coast of Africa late on 13 September. Rawinsonde data from Dakar, Senegal, showed a 35–45-kt easterly jet between 550 and 650 mb. On 14 September, visible satellite imagery depicted a large, well-defined cloud system in association with the wave; and meteorologists at the TAFB, SAB, and AFWA began satellite-based Dvorak intensity classifications. By early on 15 September, ship reports indicated the presence of a closed surface circulation, and a tropical depression formed at 1200 UTC about 300 n mi south-southwest of the Cape Verde Islands in the far eastern Atlantic. During the next 24 h the depression became better organized as banding features developed and deep convection formed over the center. The system became a tropical storm at 1200 UTC on 16 September centered about 620 n mi west-southwest of the Cape Verde Islands. Georges moved on a persistent west-northwest course for the next 10 days, a classic Cape Verde–type track, in response to a mid- to upper-level tropospheric ridge that strengthened with height.

After it became a tropical storm, Georges continued to gradually strengthen over the next several days. Around 1800 UTC on 17 September, a banding-type eye feature appeared, indicating that Georges had reached hurricane intensity. By 19 September, an upper-level anticyclone was well established over Georges and satellite pictures suggested that the hurricane was beginning to strengthen rapidly, as indicated by colder cloud tops, increased symmetry of the deep convection, and the warming and contracting of the well-defined eye (Fig. 6).

By early afternoon on 19 September, the first AFRC reconnaissance aircraft reached the hurricane and measured maximum flight-level winds of 146 kt and a minimum central pressure of 938 mb, confirming the intensification trend noted in satellite imagery. Georges's surface winds increased to near 125 kt at 1800 UTC on 19 September, making it a category 4 hurricane. Several GPS dropsondes were deployed in the eyewall of the hurricane as it neared peak strength. Near-surface (below 60 m) wind estimates from these drops indicated maximum winds of 134–150 kt. On this basis, Georges is estimated to have reached a peak intensity of 135 kt

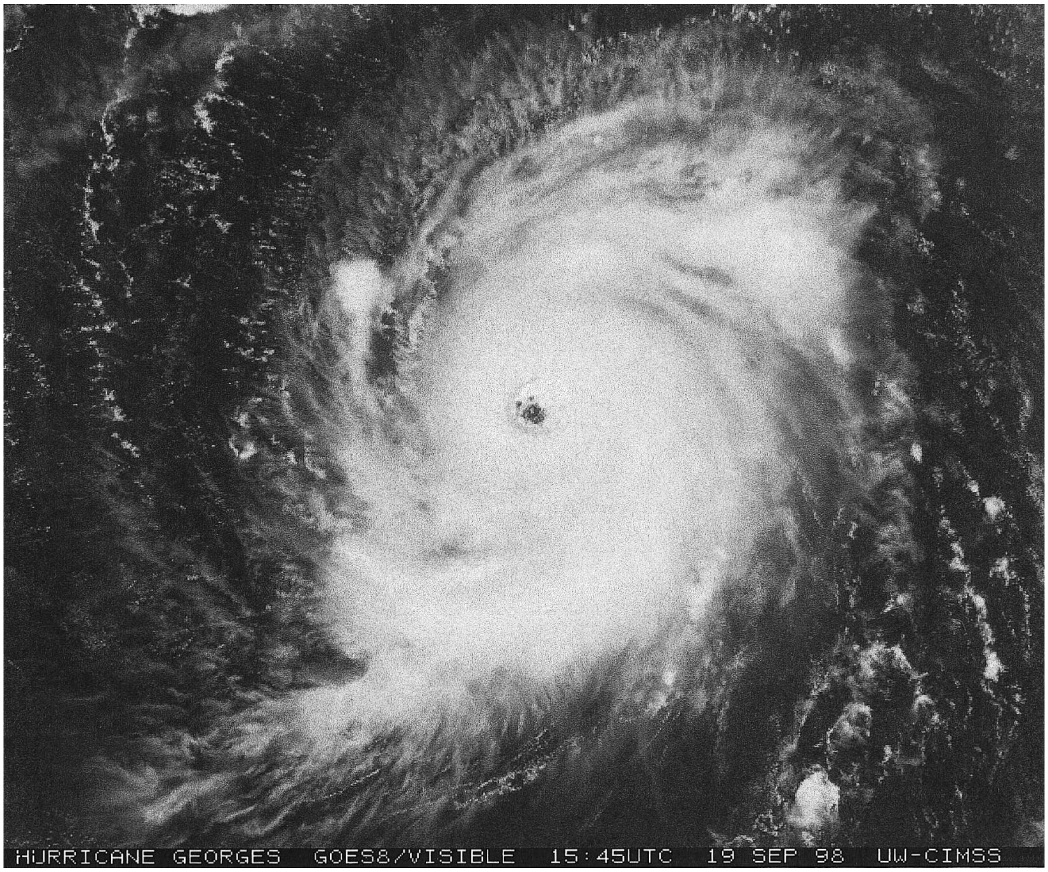

FIG. 6. Visible *GOES-8* satellite image of Hurricane Georges at 1545 UTC 19 Sep 1998, showing a well-defined eye.

at 0600 UTC on 20 September while located about 285 n mi east of Guadeloupe in the Lesser Antilles.

Shortly after 0600 UTC 20 September, the hurricane began to weaken. The eye became indiscernible in satellite pictures, and later that afternoon aerial reconnaissance could no longer find a closed eyewall. Examination of water vapor satellite imagery and satellite-derived wind analyses from the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin suggest that one factor possibly responsible for the weakening could have been upper-level northerly vertical wind shear induced by an upper-level anticyclone located over the eastern Caribbean. By the evening of 20 September, the central pressure had risen 26 mb. Georges made the first two of its eight landfalls in the Lesser Antilles (on Antigua, and then St. Kitts and Nevis) early on 21 September with maximum sustained surface winds near 100 kt.

By midmorning of 21 September, an upper-level low over Cuba moved westward away from Georges, and discouraged a northwestward turn of the hurricane away from Puerto Rico. Later in the afternoon, the shear appeared to diminish and the outflow aloft improved, but Georges never fully reintensified due in part to the circulation's interaction with land. Georges made landfall in southeast Puerto Rico with sustained surface winds near 100 kt on the evening of 21 September. The hurricane moved inland over Puerto Rico, weakened slightly, and then moved into the Mona Passage early on 22 September. Georges began to reintensity over the Mona Passage and made landfall later that morning, about 75 n mi east of Santo Domingo in the Dominican Republic, with estimated sustained surface winds of 105 kt. Figure 7 is a radar image of Georges at landfall in the Dominican Republic, and Fig. 8 is a satellite image of the hurricane around the same time.

During the next 21 h, Georges weakened as it moved slowly across the mountains of the Dominican Republic and Haiti, where it produced heavy rain, deadly flash floods, and mud slides. The system emerged into the Windward Passage on the morning of 23 September with 65-kt maximum winds. Georges changed little before making landfall about 25 n mi east of Guantanamo Bay in eastern Cuba later that afternoon. The system remained a hurricane as it moved slowly west-northwestward across the northern coast of Cuba, and it crossed the northern coast to the sea by late afternoon on 24 September. Satellite imagery showed that Georges retained fairly impressive upper-level outflow during its crossing of both Hispaniola and Cuba.

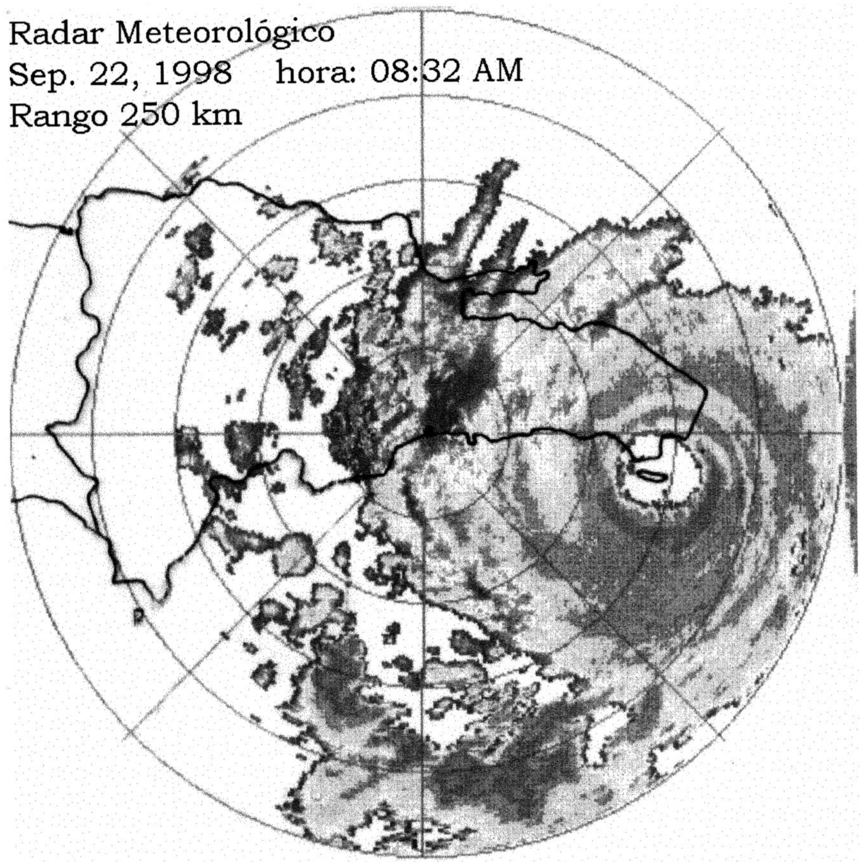

FIG. 7. Radar image, from the Meteorological Service of the Dominican Republic in Santo Domingo, of Hurricane Georges near landfall in the Dominican Republic at 1332 UTC 22 Sep 1998.

Once back over water, the hurricane began to reintensify. Early on 25 September, a band of deep convection developed east of the center, which expanded throughout the morning. Georges made landfall during midmorning of 25 September in Key West, Florida, with a minimum central pressure of 981 mb and maximum winds of 90 kt. After moving away from Key West, Georges turned more to the northwest, then north-northwest, and gradually slowed down on 26 and 27 September. This occurred in response to the midtropospheric anticyclone north of the hurricane shifting eastward into the southeastern United States. The hurricane made landfall near Biloxi, Mississippi, on the morning of 28 September with estimated maximum sustained 1-min winds of 90 kt and a minimum central pressure of 964 mb. After landfall, the system meandered over southern Mississippi and was downgraded to a tropical storm on the afternoon of 28 September.

Moving in a cyclonic loop over southern Mississippi, Georges became quasi-stationary for the next 6–12 h. The tropical storm began moving in a generally northeast to east direction early on 29 September and was downgraded to a tropical depression by midmorning while located about 30 n mi north-northeast of Mobile, Alabama. Georges continued to move eastward at 5–10 kt on 29 and 30 September. By the early morning of 1 October, the system dissipated near the northeast Florida–southeast Georgia coast, although a very weak remnant low did emerge over the western Atlantic during the day. This remnant circulation merged with a frontal zone by late on 1 October.

2) METEOROLOGICAL STATISTICS

(i) Wind and pressure data

The bulk of the aerial reconnaissance flights into Georges were done by the AFRC Hurricane Hunters. The Hurricane Hunters flew 17 missions, and made 81 center fixes while NOAA aircraft performed 6 missions contributing 24 center fixes. The highest wind speed reported was 152 kt (at 700 mb) at 0112 UTC 20 September by the NOAA aircraft. The lowest central pressure reported was 937 mb at 0613 UTC 20 September by the Hurricane Hunters with a corresponding maximum flight-level wind of 144 kt. During this period, subjective Dvorak intensity estimates from the TAFB, SAB, and AFWA were T6.5 (127 kt/935 mb) and ob-

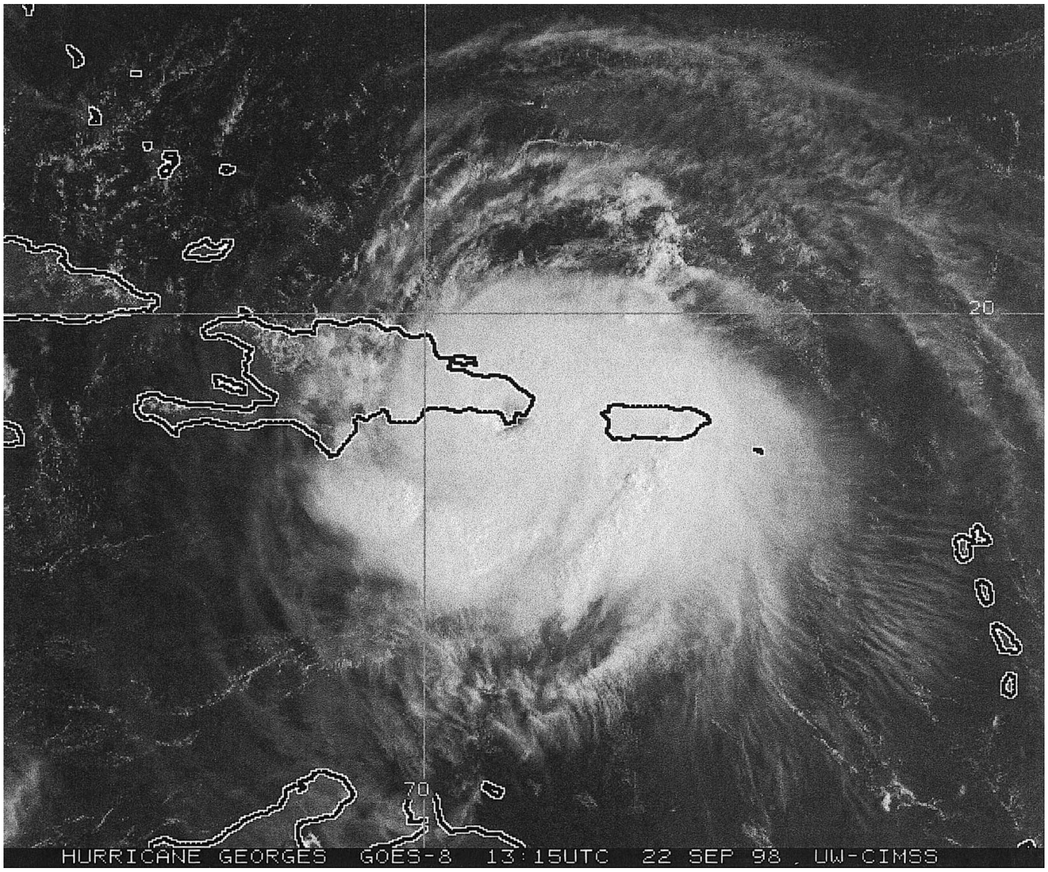

FIG. 8. Visible *GOES-8* satellite image of Hurricane Georges at 1315 UTC 22 Sep 1998, near the time of landfall in the Dominican Republic.

jective-based Dvorak estimates ranged between T6.5 and T7.0 (140 kt/921 mb).

Georges's track brought it within range of WSR-88Ds at San Juan, Puerto Rico; Key West, Florida; New Orleans, Louisiana; and Mobile, Alabama. At 2213 UTC 21 September, the WSR-88D in San Juan measured winds near 100 kt 30–60 m above the antenna as the center was making landfall in Puerto Rico. A dual-doppler radar (Doppler-on-Wheels, DOW) was operating during Georges's landfall in Biloxi, Mississippi (J. Wurman 1998, personal communication). Around 0855 UTC 28 September, the radar showed a maximum 2–5-s wind gust of 107 kt.

Several land-based locations in the Caribbean recorded sustained hurricane force winds during Georges passage including Hamilton Airport and Virgin Islands Territorial Emergency Management Agency (VITEMA) at Herman Hill in St. Croix, Cyril E. King Airport in St. Thomas, and all the official reporting sites in Puerto Rico. The highest sustained wind and gust reported at an official site were 78 and 93 kt, respectively, at Roosevelt Roads Naval Station at 2302 UTC 21 September. These, as well as other selected surface observations for Georges, are listed in Table 6a. The highest unofficial wind report received in the Caribbean was a wind gust of 153 kt (at an elevation of about 213 m) from the island of Saba of the Netherlands Antilles at 1044 UTC 21 September. The corresponding minimum pressure recorded at the site was 971.9 mb. As is often the case in the Caribbean, many unofficial weather reports are relayed to the NHC via amateur radio operators. These observations are invaluable in helping to determine conditions in locations with no official weather reporting equipment. One of the most important observations reported was in Fajardo, Puerto Rico, where the Civil Defense office measured a sustained wind of 96 kt with gusts to 113 kt at 2130 UTC 21 September. Operationally, this report was the basis of making Georges a category 3 hurricane at landfall in Puerto Rico. The AFRC Hurricane Hunter reconnaissance reported a maximum flight-level wind of 117 kt and a minimum central pressure of 962 mb near the time of landfall in the southeastern Dominican Republic. Surface reports received from the Instituto de Meteorologica in Cuba indicate that the maximum 1-min surface wind observed was 71 kt at Punta Lucrecia, Holguin, while the highest gust of 80 kt was measured at Sagua La Grande, Villa Clara. The minimum central pressure recorded over Cuba was 988 mb in Cayo Coco. All of these reports occurred as

TABLE 6a. Hurricane Georges selected surface observations, Sep 1998.

Location	Pressure (mb)	Day/time (UTC)	Sustained wind (kt)[a]	Peak gust (kt)	Day/time (UTC)[b]	Storm surge (m)[c]	Storm surge (m)[d]	Total rain (mm)
U.S. Virgin Islands								
St. Croix								
Hamilton Airport	976.0	21/1702	64	79	21/1842			172.50
VITEMA/Hermon Hill			71	81	21/1815			
Maria Hill[i]	972.2		78	98	21/1534			
Jolly Hill								188.20
Estate/COOP Observer								66.80
Annaly/COOP Observer								134.60
East Hill/COOP Observer								157.50
St. Thomas								
Cyril E. King Airport	991.0	21/1943	66	81	21/2031			126.70
Bonne Resolution Gut (drainage way)								152.90
National Park								144.80
Wintberg/COOP Observer								57.40
St. John								86.60
USGR Rain Gauge								86.60
Coral Bay/COOP Observer								61.00
Catherineburg/COOP Observer								192.00
Puerto Rico								
Luis Marin Airport	979.7	21/2311	69	81	21/2318			133.60
Roosevelt Roads NS	971.4	21/2145	76	93	21/2250			116.10
Ponce			65	85	22/0330			
Quebradillas[i]	978.4	22/0300	78	85	22/0244			
Naranjito (Barrio Alto)[i]				109	22/0040			
Rincon[i]	983.1	22/0430	87	113	22/0445			
Mayaguez Bo Guanajibo	976.9	22/0345						
Cupey Rio/COOP Observer	974.5	21/2245						238.50
Isabela KP4MYO[i]			89	143	22/0610			
Yabucoa[i] (Courtesy Sun Oil)			65	83	21/2140			
Trujillo Alto								211.60
USGS Rain Gauges								
Caguas								728.20
Lago El Guineo/Villalba								625.30
Rio Saliente at Coabey								617.20
Rio Portuguez at Tibes								468.90
Quebrada Salvatierra								430.00
Rio Grande de Arecibo								428.50
Lago Garzas/Adjuntas								342.60
River Espiritu Santo								331.20
NWS COOP Observer								
Jayuya								720.30
Orocovis (Cacao)								599.90
Coamo								571.50
Mayaguez City								541.00
Cayey								532.60
Maricao								476.30
Juana Diaz (Guayabal)								440.70
Ponce								351.30
San Lorenz								329.90
Yauco								244.30
Trujillo Alto								211.60
USGS Storm Surge Fajardo								
Cuba								
Punta Lucrecia			71					
Sagua La Grande				80				
Cayo Coco	988.0							
Guantanamo Bay			60		20/0245			228.10
Limonar								620.00
Bermeja								516.10
Santiago de Cuba								470.90
Nueva								316.00
Ciego de Avila								200.90
Florida								
Leesburg	1013.3	25/1953	19	31	25/2218			30.20
Sanford	1013.6	25/2055	20	30	25/1834			46.00

TABLE 6a. (*Continued*)

Location	Pressure (mb)	Day/time (UTC)	Sustained wind (kt)[a]	Peak gust (kt)	Day/time (UTC)[b]	Storm surge (m)[c]	Storm surge (m)[d]	Total rain (mm)
Patrick AFB	1013.5	25/1955	15	23	25/1943			
Titusville	1011.9	25/1550	20	40	25/1550			42.90
Miami International Airport			33	44	25/1056			23.90
Tamiami Airport			33	57	24/2318			
NWSFO MIA/TPC								44.70
Homestead								88.90
Tavernier								213.60
Duck Key			70	84	25/XXXX[g]			
Marathon Airport				58	25/1100			
Marathon/Monroe EOC				96	25/XXXX[g]			
Vaca Key						1.2–1.5		
Grassy Key						1.2–1.5		
Cudjoe Key						1.5–1.8		
Ramrod Key						1.5–1.8		
Big Pine Key						1.5–1.8		
Summerland Key						1.5–1.8		
Key West	982.5[f]		48[f]	76[f]	25/1353			
New Port Richey	1011.4	25/1953	20	36	25/2153			43.40
St. Petersburg/Clearwater	1010.7	25/1953	24	34	25/2117			16.50
St. Petersburg	1010.1	25/1953	23	35	25/2331			
Tampa Airport	1010.6	25/2056	20	30	25/2116			31.20
McDill AFB	1010.8	25/1955	20	37	25/2100			26.40
Old Port Tampa			11	33	25/2150			
Sunshine Skyway			29	33	25/2150			
Winter Haven	1012.2	25/1953	19	31	25/2146			22.60
Sarasota/Bradenton Airport	1009.0	25/1853	29	36	25/1926			54.40
Punta Gorda	1009.5	25/2053	30	42	25/1816			10.70
Fort Myers	1008.2	25/1753	31	38	25/1732			17.80
Regional SW Airport	1007.7	25/1653	24	37	25/1703			
Naples			31	48	25/1855			
Inverness								11.70
Ruskin								36.30
Arcadia/Horse Creek								76.70
Levy County							0.6–1.2[e]	
Citrus County							0.3–0.9[e]	
Hennando County							0.6–0.9[e]	
Pasco County							0.3[e]	
Pinellas County							0.6–0.9[e]	
Hillsborough County							0.6–0.9[e]	
Manatee County							0.9[e]	
Sarasota County							0.9–1.2[e]	
Charlotte County							1.2–1.5[e]	
Lee County							0.6–0.9[e]	
Tallahassee Airport	1003.3	30/0752	24	29	29/2224			163.10
Weather Station, The Florida State University				39	26/2129			
Apalachicola			28	33	29/1311			
Panama City Airport			24	37	29/0605			
Munson (NE of Milton)								976.90
Bay Minette								753.40
Andalusia								683.30
Milton (COOP)								636.50
Milton School								371.30
Milton/Whiting Field	992.5	n/a	38	50	28/0240			467.60
Destin	999.4	29/2353	33	49	28/0156			157.70
Hurlburt AFB	1000.0	29/2200	44	69	29/0216			433.80
Crestview	999.6	29/2253	28	43	28/2005			507.50
Eglin AFB	994.0	29/2300	42	79	28/0642			615.70
Pensacola Airport	998.7	29/0953	44	58	28/0321			400.80
Pensacola NAS	997.9	29/0956	40	61	27/2200			326.10
Pensacola Emergency Management Office				61	28/0235			
Pensacola (TV station)								681.50
Shell Point Sailboard Club				39	29/2045			
St. Teresa Beach				49	29/2225			
Pensacola Beach						2.3		

TABLE 6a. (*Continued*)

Location	Pressure (mb)	Day/time (UTC)	Sustained wind (kt)[a]	Peak gust (kt)	Day/time (UTC)[b]	Storm surge (m)[c]	Storm surge (m)[d]	Total rain (mm)
Choctawhatchee Bay						1.6		
Destin Harbor						1.6		
Panama City Beach						1.6		
Alabama								
Mobile Regional	989.9	28/0921	44	55	28/0924			381.50
Mobile Brookley Field	989.9	28/0853	47	54	27/2240			
Evergreen	999.6	29/0241	31[e]	39[e]	29/0353			194.80
Fairhope Agricultural Station				56	28/0709			370.10
Fairhope (COOP)								401.80
Grand Bay Agricultural Station				52	28/1811			
Semmes Agricultural Station				43	28/1836			453.10
Alabama Port								347.00
Atmore Nursery (COOP)								384.80
Bay Minette (COOP)								753.40
Brewton								375.90
Brewton Agricultural Center								415.00
Brewton (COOP)								468.40
Leakesville (COOP)								290.60
Niceville								496.10
Alberta (COOP)								251.50
Georgiana (COOP)								486.40
Jackson (COOP)								324.10
Thomasville (COOP)								259.10
Whatley (COOP)								384.80
Mobile, downtown								333.50
Greenville (COOP)								461.00
Andalusia (TV station)								683.30
Gulf Breeze								682.50
Jay								462.00
Spanish Port								504.40
Camden (COOP)								273.60
Gulf Shores						2.7[j]		
Bayou La Batre						2.7[j]		
Downtown Mobile						2.6[j]		
Fort Morgan–Gulf						2.6[j]		
Mobile Bay—Belle						2.5[j]		
Weeks Bay						2.0[j]		
Fort Morgan—Bay						1.8[j]		
Ono Island						1.6[j]		
Dauphin Island—Bay						1.6[j]		
Mississippi								
Gulfport Airport			42	63	28/0931[f]			
Keesler AFB	964.9	28/1055	65		28/0855			233.20
Pascagoula/Trent Lott Airport			36	47	27/2306[f]			
Gulfport Harbor Harrison County Civil Defense			53	69	28/1015	2.5		
Gulfport–1 mi N of Beach (Courtesy MS Power & Light)				102[h]	n/a			
Gulfport/Harrison County Civil Defense	967.2	28/1015						
Pascagoula COOP Observer								423.70
Ocean Springs								398.30
Vancleave								376.20
Wiggins								336.60
Lyman								250.20
Pass Christian Harbor						1.9		223.30
Pascagoula—Bayou Chico						2.9[j]		
Biloxi—Black Bay						2.7[j]		
Gulfport						2.3[j]		
Pass Christian						2.0[j]		
Bay St. Louis						1.8[j]		
Louisiana								
New Orleans International Airport	996.6	28/1052	35	46	28/1137[f]			
New Orleans Lakefront Airport	994.5	28/0953	39	48	28/0911[f]			
Slidell			31	42	28/0401[f]			22.10
Lake Pontchartrain								
East Lake–Rigolets			37	54	28/0910	1.8		
Mid Lake–Pontchartrain			42	59[j]	28/1020	1.4		

TABLE 6a. (*Continued*)

Location	Pressure (mb)	Day/time (UTC)	Sustained wind (kt)[a]	Peak gust (kt)	Day/time (UTC)[b]	Storm surge (m)[c]	Storm surge (m)[d]	Total rain (mm)
West Lake–Frenier			33[j]	45	28/0110	1.4		
North Lake–Mandeville			21	42	28/0840			
New Orleans Audubon Park								22.40
Slidell COOP Observer								37.60
Covington COOP Observer								28.20
Bogalusa COOP Observer								75.70
West End Marina						1.6		
Industrial Canal						2.2		
North End Causeway						1.3		
Lake Borgne								
Bayou Bienvenu						2.3		
Bayou Dupre						2.0		
Plaquemines Parish—East								
NE Gardene Bay (13 mi ESE of Pointe A La Hache)						2.7[f]		

[a] National Hurricane Center standard averaging period is 1 min; ASOS and C-MAN are 2 min; buoys are 8 min.
[b] Day/time is for sustained wind when both sustained and gust are listed.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above NGVD.
[e] Estimated.
[f] Power failed shortly after this observation; a more extreme value may have occurred.
[g] Time unknown.
[h] Maximum gusts recorded (time unknown) higher gusts may have occurred; anemometer height 9.1 meters AGL.
[i] Unofficial observer data.
[j] U.S. Army Corps of Engineers Data (Mobile District).
[k] Preliminary estimate.

TABLE 6b. Hurricane Georges selected National Buoy Data Center (NBDC) observations, Sep 1998.

Location	Pressure (mb)	Day/time (UTC)	Sustained wind (kt)[a]	Peak gust (kt)	Day/time (UTC)[b]	Significant wave height (m)
C-MAN stations						
Lake Worth, FL	1010.0	25/1100	30	35	25/1400	
Fowey Rocks, FL	1006.3	25/1000	45	52	25/1000	
Molasses Reef, FL	1003.1	25/0800	46	53	25/1400	
Long Key, FL	1000.0	25/1000	47	58	25/1400	
Sombrero Key, FL	994.5	25/1300	81	92	25/1500	
Sand Key, FL	990.5[c]	25/1300	56	71	25/1400	
Dry Tortugas, FL	976.3	25/2000	59	68	26/0000	
Venice, FL	1011.6	30/0900	24	27	30/1800	
Keaton Beach, FL	1005.4	30/0900	30	37	29/2300	
Cedar Key, FL	1007.2	30/1000	29	34	30/0500	
Cape San Blas, FL	1003.2	30/0800	38	43	29/1900	
Dauphin Island, AL	987.0	28/0800	59	71	28/0600	
Grand Isle, LA	997.3	28/0100	40	50	27/2000	
Southwest Pass, LA	989.1	27/2200	54	63	27/2200	
NOAA buoys						
42003 (25.9°N/89.9°W)	983.2	26/1800	51	66	26/2000	7.2
42039 (28.8°N/86.0°W)	1002.6	27/0700	43	56	27/0300	6.9 (26/2000)
42036 (28.5°N/84.5°W)	1009.2	27/0100	34	48	26/1800	5.3 (26/1600)
42040 (29.2°N/88.3°W)	963.4	27/2300	54	68	27/1900	10.9 (27/1900)
42007 (30.1°N/88.8°W)	983.5[c]	28/0400	44[c]	54[c]	27/2100	4.9[c] (27/1500)
NDBC buoy						
41522 (14.3°N/58.7°W)			35		20/1852	

[a] National Hurricane Center standard averaging period is 1 min; ASOS and C-MAN are 2 min; buoys are 8 min.
[b] Day/time is for sustained wind when both sustained and gust are listed.
[c] Buoy failed shortly after this observation; a lower pressure and a higher wind and wave height may have occurred.

Georges moved out of Cuba and into the Florida Straits where it began to restrengthen.

The maximum 2-min average wind recorded at Key West, Florida, was 48 kt at 1353 UTC 25 September with the peak gust of 76 kt; the minimum central pressure reported was 982.5 mb. It should be noted that higher winds and a lower pressure value likely occurred after an equipment/power failure at this site around 1500 UTC. The highest gust recorded in the Florida Keys was 96 kt at the Monroe County Emergency Operations Center in Marathon. The Sombrero Key C-MAN buoy recorded a maximum sustained wind of 82 kt with a peak gust to 92 kt at 1500 UTC 25 September. Moreover, this buoy recorded hurricane force winds for a 3-h period (1300–1600 UTC). This, along with other National Data Buoy Center (NDBC) observations, can be found in Table 6b.

Georges made its final landfall near Biloxi, Mississippi, around 1130 UTC on 28 September with maximum sustained surface winds of 90 kt and a minimum central pressure of 964 mb. The AFRC aircraft reported a 960-mb pressure at 0503 UTC. The lowest pressure measured by a land station was 964.9 mb at 1055 UTC 28 September at Keesler Air Force Base (KBIX) in Biloxi; Harrison County Civil Defense in Gulfport, Mississippi, recorded 967.2 mb at 1015 UTC. The NOAA ship *Oregon II* measured a minimum central pressure of 970 mb at 0830 UTC 28 September while in port in Pascagoula, Mississippi. On 28 September, KBIX reported sustained hurricane force winds (65 kt) at 0855 UTC. At 0755 UTC, KBIX reported wind gusts of 109 kt, and 149 kt at 0855 UTC 28 September. The latter value is questionable because 1) near-simultaneous DOW maximum wind measurements were 107 kt; 2) the anemometer at KBIX is a hot-wire anemometer, known to have serious errors in heavy rain, for example, the erroneous 205-kt wind gust in Typhoon Paka (Hagemeyer 1998); and 3) AFRC dropsonde data from the same time period measured a peak wind of 101 kt at 920 mb. A Texas Instrument WR25 anemometer, operated by Mississippi Power and Light 1 mi north of the beach in Biloxi, measured a wind gust of 102 kt. Reconnaissance data from the AFRC aircraft suggest that the boundary layer and inner core of Georges never fully recovered from its passage across Hispaniola and Cuba. Despite an apparently healthy cloud and outflow pattern, and a gradual drop in minimum central pressure of 13 mb (from 975 to 962 mb) over a 36-h period, from early on 26 September to the evening of 27 September the eye never became reestablished to its former stature. Most of the aircraft reports from 26 to 28 September indicated a partially formed eyewall, open to the west or southwest. Also, eyewall GPS dropsonde data near landfall in Mississippi suggest that the winds at the surface were 20%–30% below those at flight level (3 km). This contrasts with eyewall observations taken when Georges was near peak intensity just east of the Leeward Islands where surface winds were generally *equal to* or *greater than* those at the 3-km level.

(ii) Storm surge data

The storm surge plus breaking wave effects was about 3 m near Fajardo, Puerto Rico. On the U.S. mainland, high water mark surveys were conducted in the Florida Keys and along the northern Gulf of Mexico shoreline from Mississippi to Apalachicola, Florida. The goal of the survey was to measure both still water marks in buildings and debris lines. Generally, still water marks in buildings represent the storm surge while debris lines represent the storm surge and breaking wave effects combined. In almost all cases the measured debris line height outside a structure is higher than the measured still water mark inside the structure. In the Florida Keys the range of the still water marks was 0.9–2.3 m while the debris line heights were 1.1–3.3 m. Most of these measurements were taken on the Atlantic-facing shoreline. Along the Gulf coast the range of the still water marks was 2.1–3.7 m in Mississippi, 1.5–3.3 m in Alabama, and 1.1–1.4 m in the Florida panhandle. Similarly, the debris line heights ranged from 1.7 to 3.8 m in Mississippi, 1.5 to 3.8 m in Alabama, and 1.4 to 5.6 m in the Florida panhandle. The high debris line heights in Florida reflect the very deep water that lies just offshore that allows large waves to break very close to the shoreline and ‘‘run up’’ the beach.

(iii) Rainfall data

Georges was a prodigious rain producer. In the U.S. Virgin Islands, rainfall totals were generally between 76 and 203 mm. In Puerto Rico, the maximum official 2-day United States Geologic Survey (USGS) rain gauge measurement was 625 mm in Lago El Guineo near Villalba, while the maximum Cooperative Observer (COOP) 2-day total reported was 720 mm in Jayuya. No surface-based rainfall estimates are available from the Dominican Republic or Haiti. Satellite-derived estimates suggest that as much as 1000 mm of rain may have fallen over portions of the Dominican Republic and Haiti during the 24-h period ending at 1200 UTC on 23 September. Over Cuba, the Instituto de Meteorologica reported a maximum storm total of 620 mm in Limonar.

Rainfall in the Florida Keys was considerably less than in Cuba or Hispaniola. Key West recorded 213 mm. In contrast, storm totals along the Gulf coast were higher, because of the hurricane’s marked deceleration. The maximum rainfall total from an official observation site was 616 mm at Eglin AFB in the Florida panhandle while the highest storm total was 753 mm from a COOP in Bay Minette, Alabama. Rainfall totals generally ranged from 250 to 500 mm over most of southern Mississippi and Alabama, and the Florida panhandle. As a result of the heavy rains, widespread river flooding occurred in southern Mississippi from 30 September through 2 October flooding homes and forcing evacuations. The Tchoutacabouffa River at D'lberbville, Mississippi, set a record crest of 5.8 m at 0200 UTC 30 September.

(iv) Tornadoes

Most of the reported tornado activity associated with Georges occurred in Florida and Alabama. Twenty-eight tornadoes are estimated to have touched down, mostly in northwest Florida. No deaths were directly attributable to these tornadoes. Two tornadoes were also reported in Puerto Rico.

3) Casualty and damage statistics

The 602 direct deaths attributed to Georges make it the 19th-deadliest TC in the Atlantic basin during the twentieth century. Most of the deaths occurred in the Dominican Republic and Haiti, due mainly to flash flooding and subsequent mud slides in high terrain regions. The lone direct death in the United States, a freshwater drowning, occurred in Mobile, Alabama.

Insured property damage estimates supplied by the Insurance Services Office yielded a total of $2.955 billion in the United States including Puerto Rico and the U.S. Virgin Islands. These estimates exclude storm surge damage. Based on the insured losses, the total estimated damage from Georges is $5.9 billion, $2.31 billion of which occurred in the continental United States. In Puerto Rico, there was extensive damage to homes throughout the island. More than 72 000 homes were damaged, of which about 28 000 were completely destroyed. During the hurricane, over 26 000 people were in shelters. In the Dominican Republic some 185 000 persons were left homeless by Georges, and 100 000 remained in shelters for several weeks due to a lack of electricity and water service. In Haiti, government officials stated that over 165 000 had been left homeless by the hurricane. Agriculture in Puerto Rico was hit hard by Georges: 95% of the plantain and banana crop was destroyed, along with 75% of the coffee crop. Despite Georges's weakened state when it moved across Cuba, it had a substantial impact. A total of about 60 000 homes were reported damaged, of which nearly 3500 were completely destroyed. As in Puerto Rico, agriculture was hard hit with major losses at banana plantations in eastern Cuba.

The damage to dwellings in the United States was not so extensive as in the Caribbean. In the Florida Keys, 1536 homes were damaged, of which 173 were completely destroyed. Many of these were mobile homes. Some roof and structural damage was also reported along the coast of Mississippi. In the first 60 days or so after Georges's final landfall in Mississippi, the American Red Cross spent $104 million on relief services in the United States Virgin Islands, Puerto Rico, Alabama, Louisiana, Mississippi, the Florida Keys, and the Florida panhandle. This makes Georges the most expensive disaster aid effort in the organization's 117-year history.

4) Warnings

Since Georges was well forecast, the lead times on the hurricane warnings were more than sufficient for the completion of typical protective actions. Nearly 897 000 residents evacuated in south and west-central Florida, including about 100 000 people in Dade County. About 35 000 persons left the Florida Keys in response to the mandatory evacuation order issued by the Monroe County Emergency Management Center. It should be noted however that about 40% of the Keys' residents did not evacuate, in spite of the threat of a direct hit by a major hurricane.

h. Tropical Storm Hermine, 17–20 September

Hermine was barely of tropical storm strength when it made landfall on the coast of Louisiana.

1) Synoptic history

Hermine developed from a tropical wave that crossed Dakar, Senegal, on 5 September and moved westward across the Atlantic. The wave had no significant deep convection until it reached the Windward Islands. There, cloudiness and showers increased and there was a large 24-h pressure change on 12 September. The wave continued westward close to the coast of South America and then moved northwestward through the northwest Caribbean Sea, to the Yucatan Channel, where a low pressure system developed. The system began to interact with an upper-level low in the Gulf of Mexico and another tropical wave that reached the area. During this period, a large and well-defined monsoon-type flow prevailed over Central America, the northwestern Caribbean Sea, and the Gulf of Mexico. It was not until 1200 UTC 17 September that the system acquired enough organization to be classified as a tropical depression.

The depression made a cyclonic loop over the central Gulf of Mexico as it interacted with the upper-level low located in the Bay of Campeche. The depression gradually became organized, despite the unfavorable upper-level wind shear that prevailed in the area, and reached tropical storm status at 1200 UTC 19 September. Hermine moved on a general northward track and made landfall as a weakening 35-kt tropical storm near Cocodrie, Louisiana, at 0500 UTC 20 September.

2) Meteorological statistics

Hermine's landfall resulted in rainfall of generally less than 25 mm, and there were no reports of tropical storm force winds.

3) Casualty and damage statistics

There were no reports of casualties due to Hermine, and damage was minor.

4) Warnings

Due to the unusually large uncertainties in the forecast track of Hermine while the cyclone was looping in the central Gulf of Mexico, it was necessary to issue tropical storm watches and warnings for a large portion of the Gulf coast, from the upper Texas coast to the Florida panhandle.

i. Hurricane Ivan, 19–27 September

Hurricane Ivan was the first in a trio of hurricanes to form and persist over the eastern Atlantic Ocean during the latter part of September. The wave from which Ivan developed was easily identified by a concentration of thunderstorms over western Africa near the Greenwich Meridian on 14 September. Although deep convection diminished when the wave neared the coast, cloudiness and sounding data showed the system's passage into the Atlantic on 16 September.

Strong convection associated with the wave redeveloped to the south of the Cape Verde Islands on 17 September. Position estimates from satellite analyses began that day. The cloudiness near the apex of the wave became more concentrated on 18 September. Late that day, Dvorak T-numbers first reached 2.0 from the TAFB and 1.5 from the SAB. Slow development followed and it is estimated that the system became a tropical depression near 0000 UTC on 19 September, about 175 n mi to the southwest of the Cape Verde Islands.

The TC was influenced by mid- to upper-level cyclonic flow centered to its northwest, over the central Atlantic. At first, that pattern consisted of a trough elongated southward from 30°N. During Ivan's development, however, water vapor imagery showed the trough become a closed circulation that partially enveloped the TC. A second trough later affected Ivan as well. These features influenced the details of Ivan's track, which was generally northwestward at 10–15 kt from 20 to 25 September. The troughs also produced vertical shear that slowed Ivan's development. Ivan became a tropical storm late on 20 September, and during the following 48 h wind speeds increased to around 55 kt, as estimated from the appearance of what could have been an eye on satellite pictures for about an hour.

Ivan's hurricane stage occurred rather far to the north. At 1400 UTC on 23 September, the eye reappeared and was more prominent than earlier, indicating that Ivan was becoming a hurricane as it neared 30°N. After again disappearing, the eye became its most distinct with a diameter of about 20 n mi. Ivan is estimated to have reached its peak intensity of about 80 kt on the morning of 26 September, when it was centered about 300 n mi to the west of the Azores Islands. At that time, the influence of the upper troughs on Ivan was decreasing and the track of the hurricane was increasingly controlled by the westerlies just to the north. Late on 26 September, the eye disappeared. The inner convective structure deteriorated rapidly as Ivan passed eastward over cooler waters north of the Azores Islands on 27 September. Ivan then became a weakening extratropical storm, and then gale, which moved northeastward.

j. Hurricane Jeanne, 21 September–1 October

Jeanne formed from a tropical wave that was slow to emerge from western Africa. The associated disturbed weather lingered near the African coast from 19 through 20 September, and gradually became better organized. An initial Dvorak classification was made by the TAFB at 1800 UTC 19 September, locating a center about 120 n mi offshore of the coast of Guinea. Only a slight increase in organization and little motion was noted during the following 24 h. By 0600 UTC 21 September, deep convection had increased and it is estimated that the system had become a tropical depression, while centered about 140 n mi southwest of the coast of Guinea–Bissau. According to NHC records beginning in 1886, only Tropical Storm Christine of 1973 formed farther east in the Atlantic basin than Jeanne. However, it should be noted that prior to the satellite surveillance era (which began in the 1960s) some storms may have gone undetected in this region.

The cyclone moved generally west-northwestward, gradually strengthening into a tropical storm later on 21 September. Jeanne was situated in an environment of slight east to southeasterly shear, which is typical for systems in the eastern tropical Atlantic. Early on 22 September, Jeanne began to intensify at a faster pace, and by 1800 UTC that day it became a hurricane about 120 n mi southwest of the Cape Verde Islands. This was the closest point of approach to those islands. For the next couple of days, Jeanne continued moving toward the west-northwest, strengthening to its estimated peak intensity of 90 kt while located about 580 n mi west of the westernmost Cape Verde Islands. The forward speed slowed and the hurricane turned toward the northwest, and then north, during 25–27 September. On 25–26 September Jeanne weakened, mainly due to increased southwesterly vertical shear. These events were likely caused by an amplifying mid- to upper-tropospheric trough located about 10° to the west. This trough assured that Jeanne would remain in the eastern Atlantic for its life cycle.

Under the continued influence of the trough, Jeanne accelerated toward the north-northeast on 28 September. The hurricane reintensified somewhat, to near 80 kt, while located about 550 n mi west-southwest of the Azores. As the system turned toward the northeast and east-northeast on 29 September, its forward speed slowed and it weakened to a tropical storm. Jeanne continued toward the east-northeast while gradually weakening. Around 0000 UTC 1 October, the cyclone reached the Azores but had degenerated to a depression with few tropical characteristics. The extratropical low moved eastward from the Azores, generating an area of gale force winds before reaching the coast of Portugal just north of Lisbon around 0000 UTC 4 October. Jeanne's extratropical remnants became unidentifiable over Spain later that day.

Jeanne's peak intensity of 90 kt on 24 September is based on satellite estimates. A French drifting buoy, identifier 41599, reported winds of 55 kt at 60°, 48 kt at 60°, and 75 kt at 110° near 23.3°N, 40.6°W at 1000, 1100, and 1900 UTC, respectively, on 26 September. Although this buoy's data could be considered questionable, the 75-kt wind was used for the best track intensity, since it was reported very near the center of the hurricane where, simultaneously, a burst of deep convection occurred. The island of Horta in the Azores reported wind gusts to 35 kt around 1800 UTC 30 September.

k. Hurricane Karl, 23–28 September

Karl developed from a small nontropical surface low pressure area that appeared off the coast of the Carolinas on 21 September. Deep convection became better organized as the low moved eastward, and a tropical depression formed from the disturbance near 1200 UTC 23 September about 50 n mi west-northwest of Bermuda. Convective banding increased and the system became Tropical Storm Karl that evening. Embedded in the flow on the southwest side of a broad deep-layer trough over the northwest Atlantic, the TC began moving east-southeastward about this time.

Satellite imagery showed the gradual development of a more symmetrical cloud pattern with the center embedded among the coldest convective tops. Karl became a hurricane near 1200 UTC 25 September about 550 n mi east-southeast of Bermuda. At this time, Hurricane Georges was over the Straits of Florida, Hurricane Ivan was over the North Atlantic about 500 n mi west-southwest of the Azores, and Hurricane Jeanne was over the tropical Atlantic about midway between Africa and the Lesser Antilles. According to records at the NHC, the last time four hurricanes were present in the Atlantic at the same time was on 22 August 1893. Records also note that on 11 September 1961, three hurricanes and possibly a fourth existed.

Karl moved northeastward around the southeastern side of the large deep-layer trough. A well-defined eye developed, and it is estimated that Karl first reached a maximum intensity of 90 kt at 0000 UTC 27 September while centered about 875 n mi east-northeast of Bermuda. The eye remained distinct for at least 6 h, after which time the hurricane started to weaken primarily due to increasing upper-level shear. The hurricane accelerated toward the northeast and weakened to a tropical storm by 0000 UTC 28 September over 23°C water 175 n mi west-northwest of the westernmost Azores. Karl continued moving over increasingly cooler waters and became extratropical later on 28 September as the circulation center became well removed from any deep convection. The extratropical cyclone was tracked to south of Ireland by late on 29 September.

l. Hurricane Lisa, 5–9 October

Lisa originated from a tropical wave that moved westward from Africa into the eastern tropical Atlantic Ocean on 29 September. The associated cloudiness was fairly well organized and centered at about 10°N. By the next day, it was an almost indistinguishable part of the intertropical convergence zone (ITCZ) which was active across the entire tropical Atlantic. By 3 October, the system became better defined as its convection increased and the ITCZ cloudiness dissipated to its east and west. On 4 October, midway between Africa and the Lesser Antilles, there were signs of a low-level circulation and it is estimated that a tropical depression formed at 0000 UTC on 5 October.

The depression strengthened into Tropical Storm Lisa on 5 October, although it was in an environment of strong vertical shear, as evidenced by the low-level center's appearance to the west of the deep convection. This shear was caused by an upper-level low located northwest of the storm. The presence of this low also weakened the ridge to the north, causing the storm to turn northward. During the next 2 days, a strong baroclinic trough in the westerlies evolved into a deep low in the central North Atlantic. This resulted in an acceleration toward the northeast. The forward speed exceeded 50 kt by the afternoon of 9 October. The vertical shear relaxed over the storm and it gradually strengthened. Lisa turned northward on 9 October, steered by the deep low to its west and a 1032-mb high to its east. This strong east–west pressure gradient also resulted in increasing the surface winds well to the east of the center. Lisa briefly strengthened to a 65-kt hurricane on 9 October before merging with an extratropical frontal system in the far North Atlantic. On 10 October, it was no longer possible to identify a well-defined circulation in satellite imagery.

A NOAA drifting buoy (16.6°N, 46.9°W) in the central tropical Atlantic observed 35-kt winds at 0850 UTC on 5 October and 36-kt winds at 2138 UTC. These observations were essential in determining that Lisa had become a tropical storm, as satellite-based intensity estimates were well below storm strength at these times. The estimate that Lisa acquired 65-kt hurricane force winds on 9 October was based on satellite intensity estimates and on a report of 61 kt from the ship *ZCBD9* at 46.9°N, 33.3°W (approximately 240 n mi east of the center) at 1800 UTC. By that time the system was rapidly becoming extratropical, and it is not certain that the strongest winds were near the center.

m. Hurricane Mitch, 22 October–5 November

Mitch was responsible for over 9000 deaths, predominately from rain-induced flooding in Honduras and Nicaragua, making it one of the deadliest Atlantic TCs in history. The 905-mb minimum central pressure and estimated maximum sustained wind speed of 155 kt over the western Caribbean make Mitch the strongest October hurricane observed since records began in 1886. Mitch moved across the Yucatan Peninsula and southern Florida as a tropical storm.

1) SYNOPTIC HISTORY

Mitch developed from a tropical wave that moved across the southern portion of west Africa on 8–9 October. Rawinsonde data from Abidjan, Ivory Coast (980 n mi southeast of Dakar), suggest that the wave passed through the region around 8 October. The system crossed the west coast of Africa, south of 15°N, on 10 October. Over the next 7 days, west-southwesterly upper-level winds prevented significant development as the wave progressed across the tropical Atlantic.

After the system moved through the eastern Caribbean Sea on 18 and 19 October, satellite pictures on 20 October showed an organizing cloud pattern over the south-central Caribbean. Shower and thunderstorm activity continued to become better organized over the southwest Caribbean Sea early on 21 October. That afternoon, an AFRC reconnaissance aircraft investigated the disturbance, and found winds of 39 kt at the 300-m flight level and a central pressure of 1001 mb. Thus, the system became a tropical depression at 0000 UTC 22 October, about 360 n mi south of Kingston, Jamaica. The depression strengthened to a tropical storm later that day, as it moved in a cyclonic loop about 225 n mi east-southeast of San Andres Island. By 23 October, intensification was disrupted by westerly vertical wind shear associated with an upper-level low north-northwest of the TC. Later on 23 October, the upper low weakened, the shear diminished, and Mitch began to strengthen while moving slowly northward.

Mitch became a hurricane at 0600 UTC 24 October centered about 255 n mi south-southwest of Kingston. Later that day, as it turned toward the west, Mitch began a period of rapid intensification. During the 24-h period beginning on the afternoon of 24 October, its central pressure dropped 52 mb, to 924 mb. A symmetric, well-established upper-tropospheric outflow pattern was evident in satellite imagery, and the hurricane continued to strengthen. On the afternoon of 26 October, the central pressure reached a minimum of 905 mb, while the cyclone was centered about 50 n mi southeast of Swan Island. This pressure is the fourth lowest ever measured in an Atlantic hurricane, tied with Hurricane Camille in 1969. This is also the lowest pressure ever observed in an October hurricane in the Atlantic basin. Prior to Mitch, the strongest measured hurricane in the northwest Caribbean was Hurricane Hattie in 1961, with a central pressure of 924 mb. At its peak on 26 October, Mitch's maximum sustained 1-min surface winds were estimated to be 155 kt, category 5 intensity. Figure 9 is a satellite image of Mitch near peak strength.

After passing over Swan Island on the 27 October, Mitch began to gradually weaken while moving slowly westward. It then turned southwestward and southward toward the Bay Islands off the coast of Honduras. By around 0000 UTC on 28 October, even though the central pressure had risen to 933 mb, and maximum flight-level (700 mb) winds were near 130 kt, GPS dropsondes indicated that surface winds were about 140 kt, that is still category 5 intensity. Even though Mitch passed very near the island of Guanaja as a category 5 hurricane, it is unlikely that winds of that strength were experienced on the island. Mitch slowly weakened as its circulation interacted with the landmass of Honduras. From midday on 27 October to early on 29 October, the central pressure rose 59 mb. The hurricane meandered near the north coast of Honduras from late on 27 October through 28 October before landfall about 70 n mi east of La Ceiba during the morning of 29 October, with estimated surface winds of 70 kt and a minimum central pressure of 987 mb.

After landfall, Mitch moved slowly southward, then southwestward and westward, over Honduras, weakening to a tropical storm by 0600 UTC 30 October, and to a tropical depression by 1800 UTC 31 October. The overall motion was slow, less than 4 kt, for a week. This resulted in a tremendous amount of rainfall, as high as 900 mm or more, primarily over Honduras and Nicaragua (Table 7). A large east–west mountain range, with peaks approaching 3 km, covers this part of Central America. Thus, upslope rainfall enhancement likely contributed to the large totals. The heavy rainfall produced flash floods and mud slides that killed thousands of people. Some heavy rains also occurred in other portions of Central America. Although Mitch's surface circulation center dissipated near the Guatemala–Mexico border on 1 November, the remnant circulation aloft continued to produce locally heavy rainfall over portions of Central America and eastern Mexico for the next couple of days.

By the afternoon of 2 November, TAFB and SAB meteorologists began to follow a cloudsystem center, the remnants of Mitch, in satellite imagery over the Bay of Campeche. Shower and thunderstorm activity began to increase later on 2 November. On 3 November, a low-level circulation became evident in the eastern Bay of Campeche. Later that day, an AFRC aircraft found 45-kt winds at 500 m and a minimum central pressure of 997 mb, indicating the redevelopment of Tropical Storm Mitch about 130 n mi southwest of Merida, Mexico. Mitch moved northeastward and weakened to a depression early on 4 October after it made landfall over the northwestern Yucatan Peninsula. The center reemerged over the south-central Gulf of Mexico by midmorning

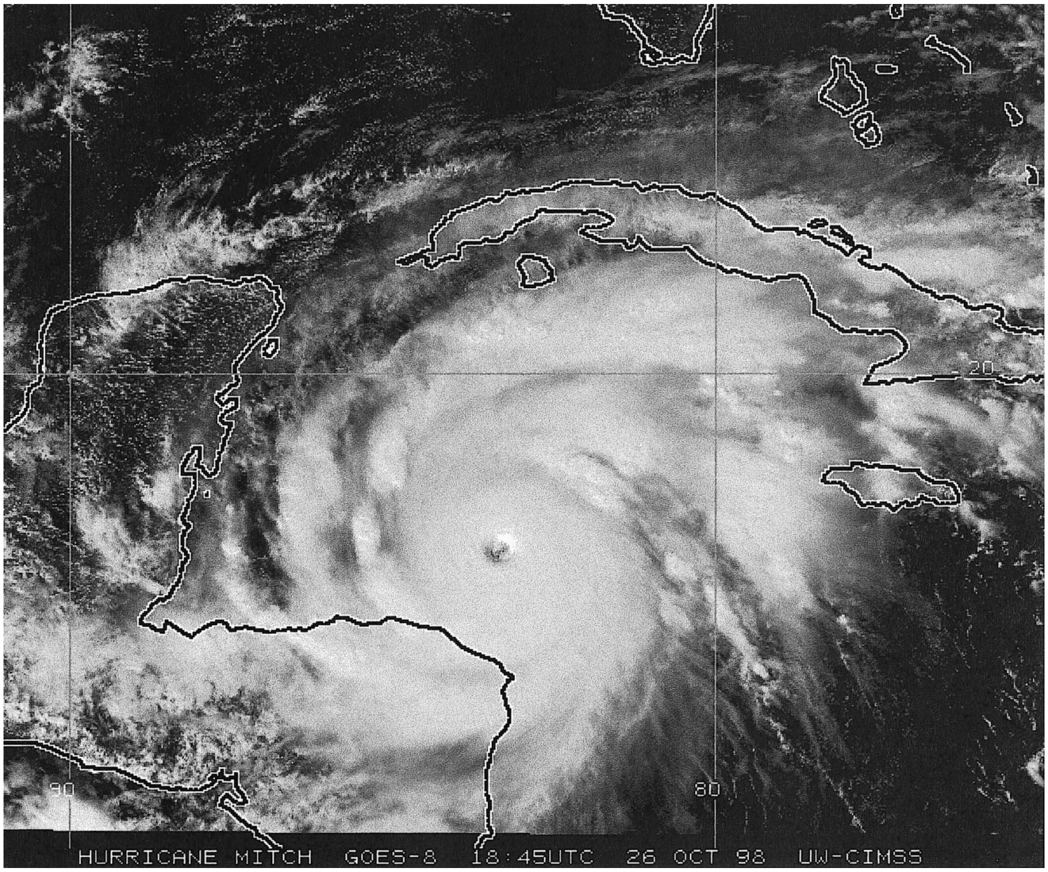

FIG. 9. Visible *GOES-8* satellite image of Hurricane Mitch near its peak intensity of 155 kt.

TABLE 7a. Hurricane Mitch selected Honduras rainfall totals, 25–31 Oct 1998.

Location	Total rain (mm)
Choluteca	911.6
Le Ceiba	876.8
Balfate	671.3
Tela	565.4
Yoro	520.4
Orica	454.4
Santa Lucia	385.6
Sabana Grande	369.1
Lepaguare	335.0
Amapala	314.5
Colonia 21 De Octubre	301.0
Santa Barbara	300.0
Unah (Tegucigalpa)	294.1
Moroceli	270.5
Roatan	270.5
La Mesa	268.0*
Catacamas	257.3
Gracias	255.3

* No data available 30–31 Oct; a higher amount could have occurred.

on 4 October, and Mitch regained tropical storm strength. The storm began to accelerate northeastward as it became involved with a frontal zone moving through the eastern Gulf of Mexico. Mitch made landfall on the morning of 5 November in southwest Florida near Naples, with estimated maximum sustained winds of 55 kt. Mitch continued to move rapidly northeastward and by midafternoon of 5 October, moved offshore of southeastern Florida and became extratropical. The extratropical cyclone accelerated northeastward across the North Atlantic Ocean from 6 October through 9 October.

2) METEOROLOGICAL STATISTICS

The AFRC Hurricane Hunters flew 19 missions, and made 41 center fixes while NOAA aircraft performed 2 missions and 9 center fixes. The highest 700-mb flight-level wind report was 168 kt at 1900 UTC 26 October by the AFRC. This wind speed was observed 14 n mi northeast of the center near the time of a 905-mb GPS dropsonde-measured pressure. A dropsonde in the northeast eyewall showed winds to near 160 kt at 900 mb, but lower speeds below that altitude. There was a 14-m wind speed of 130 kt measured by a dropsonde at 2244 UTC 27 October. The highest satellite-based

TABLE 7b. Hurricane Mitch selected surface observations, Oct 1998.

Location	Pressure (mb)	Day/time (UTC)	Sustained wind (kt)[a]	Peak gust (kt)	Day/time (UTC)[b]	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Florida								
Key West Airport	995.7	05/0853	35	48	05/0653			53.60
Boca Chica NAS	996.6	05/0855	25	38	05/0855			
Marathon Airport	997.2	05/1053	18	30	05/1104			
Homestead								79.20
Homestead AFB	995.9	05/1158	20	35	05/1229			
Tamiami Airport	995.1	05/1153	20	33	05/1153			90.90
Miami International Airport	994.1	05/1356	20	38	05/1042			149.40
Opa Locka Airport	993.9	05/1353	28	38	05/1153			
Hollywood								83.60
Fort Lauderdale								168.10
Fort Lauderdale Beach								98.60
Fort Lauderdale Airport	993.8	05/1353	29	36	05/1120			
Fort Lauderdale Executive Airport	993.8	05/1353	25	34	05/1830			
Pompano Beach Airport	993.7	05/1353	28	39	05/0408			
West Palm Beach								170.20
West Palm Beach	994.7	05/1153	25	34	05/1658			
Naples								36.10
Naples Airport	991.2	05/1115	18	27	05/1246			
Miami Beach			26	40	05/1248			80.00
Flamingo			33	39	05/0948			
Virginia Key	995.0	05/1352	26	37	05/1252			
Lower Keys							0.6–1.2[e]	
Collier County	993.9						<0.3[e]	
Miami-Dade County	993.8						<0.3[e]	
Broward County							0.3–0.6[e]	
Vero Beach Airport	996.6	05/1321	25	42	05/13219			105.20
Vero Beach FAA tower								138.40
Cape Canaveral	1000.7	05/1358	22	39	05/1705	0.9[e]		
Patrick AFB	999.0	05/1355	27	37	05/1735			
Melbourne	998.3	05/1350	20	30	05/1150			115.30
Melbourne National Weather Service Office (NWS)								125.70
Titusville	1002.0	05/1358	25	35	05/1758			
Fort Pierce Airport	994.6	05/1255	20	29	05/1400			136.10
Orlando International Airport	1001.5	05/1253	23	29	05/1714			40.10
Stuart	995.3	05/1230						
Jupiter/Tequesta	1003.2							177.80
Port Myaca	997.9							164.60
Stuart	995.2							154.90
Fort Pierce	996.2							135.40
Okeechobee	998.9							105.90
St. Petersburg (KPIE)	1001.8	05/0953	20	25	05/0953			31.00
St. Petersburg (KSPG)	1000.9	05/1053	21	27	05/0945			
St. Petersburg Pier			30	35	05/1300			
Tampa Airport	1001.5	05/1056	14	23	05/1156			11.90
MacDill AFB	1001.5	05/1059	12	22	05/1331			34.00
Tampa Old Port			24	29	05/1254			
Ruskin								49.30
Sunshine Skyway			29	34	05/1054			
Winter Haven	1001.2	05/1054	16	23	05/1153			21.34
Lakeland	1001.4	05/1054	13	20	05/1152			49.30
Sarasota Airport	1000.0	05/1050	15	25	05/1350			44.50
Arcadia								120.90
Punta Gorda	997.3	05/0944	25	33	05/0944			98.60
Fort Myers	994.6	05/1017	21	31	05/1238			153.70
Fort Myers Regional S.W. Airport	993.6	05/1018	27	33	05/1018			
C-MAN stations								
Fowey Rocks, FL	995.9	05/1400	52	63	05/1300			
Molasses Reef, FL	997.1	05/1200	41	45	05/1100			
Long Key, FL	996.9	05/1100	32	39	05/0900			
Sombrero Key, FL	997.2	05/1100	41	46	05/0800			
Sand Key, FL	995.9	05/0700	39	43	05/0700			
Dry Tortugas, FL	993.4	05/0500	41	47	05/0500			
Lake Worth, FL	994.1	05/1300	36	42	05/1200			
NOAA buoys								
42003 (25.9°N/85.9°W)	1001.4	05/0500	37	44	04/2350	4.5		
41010 (25.9°N/78.5°W)	995.4	05/2000	37	45	05/1800	4.2		

intensity estimate, obtained by both objective and subjective methods, was 155 kt on 26 and 27 October. Table 7a lists rainfall observations from Honduras, with a maximum of 911.6 mm from Choluteca. Even higher values may have gone unobserved. Table 7b lists selected surface observations from Florida, where the highest observed sustained wind speed was 52 kt, at an elevation of 44 m, from the Fowey Rock C-MAN station just offshore of Miami. Mitch spawned five tornadoes in south Florida: two in the Florida Keys, one each in Broward, Palm Beach, and Collier Counties. The most significant of these (F2 intensity) occurred in the upper Florida Keys, Islamorada to North Key Largo.

3) Casualty and damage statistics

The estimated death toll from Mitch is 9086. The U.S. Agency for International Development reported the following death totals: Honduras, 5677; Nicaragua, 2863; Guatemala, 258; El Salvador, 239; Mexico, 9; and 7 in Costa Rica. The death toll also includes 31 fatalities when the schooner *Fantome* sank near Guanaja (Carrier 2001). In addition, another 9191 persons were listed as missing. The exact death toll will probably never be known. However, Mitch was one of the deadliest Atlantic TCs in history, ranking below only the 1780 ''Great Hurricane'' in the Lesser Antilles (Rappaport and Fernandez-Partagas 1995), and comparable to the Galveston hurricane of 1900, and Hurricane Fifi of 1974 (which also struck Honduras). Mitch also claimed two lives in Monroe County, Florida. Both deaths were drowning-related incidents resulting from a fishing boat capsizing. Sixty-five persons were injured by the tornadoes in Florida.

In Honduras, there was an estimated 50% loss to crops. At least 70 000 houses were damaged, and more than 92 bridges were damaged or destroyed. There was severe damage to the infrastructure of Honduras; entire communities were isolated from outside assistance. To a lesser extent, damage was similar in Nicaragua, where a large mud slide inundated 10 communities situated at the base of La Casitas Volcano. Guatemala and El Salvador also suffered from flash floods that destroyed thousands of homes, and extensively damaged bridges and roads. The Florida tornadoes damaged or destroyed 645 homes. Insured property damage supplied by the Florida Insurance Council puts the insured damage estimate for Florida at $20 million. These estimates exclude storm surge damage. The total estimated U.S. damage from Mitch is $40 million.

4) Warnings/forecast critique

Hurricane warnings were issued for Jamaica, Honduras, Guatemala, Belize, and the Caribbean coast of the Yucatan Peninsula, Mexico. A tropical storm warning was issued for the Cayman Islands, the Gulf of Mexico coast of the Yucatan Peninsula, Cuba, and south Florida and the Florida Keys. As the effects of Mitch on Nicaragua were confined to freshwater flooding, there were no hurricane warnings there.

Official track forecasts, consistent with normally reliable guidance models, called for a slow mostly northwestward motion when Mitch was in the northwestern Caribbean. In fact, Mitch moved westward and then southward; the forecast turn toward the northwest did not take place until well after the hurricane had moved inland. In retrospect, the slow southward, then southwestward, motion that began early on 27 October, was likely due to a weak midlevel anticyclone over the western Gulf of Mexico. However, the absence of radiosonde data from Mexico and Central America appears to have hindered prediction models from resolving this feature. Also, the intensity of Mitch was underpredicted by as much as 75–80 kt in the NHC forecasts at 72 h. This underscores the difficulty in forecasting rapid strengthening with the current state of the science.

n. Hurricane Nicole, 24 November–1 December

Nicole developed from a nearly stationary and strong frontal low that persisted for several days over the northeast Atlantic, a few hundred miles south of the Canary Islands. Satellite imagery suggested that the frontal low acquired tropical characteristics when a tightly wrapped convective band developed around the center of circulation. The system reached tropical storm status around 0600 UTC 24 November. Later on, a ship (call sign PFSJ) confirmed that the system had acquired tropical characteristics, with a report of 36-kt winds at 1200 UTC 24 November just to the north of the center of the tropical storm. The TC was located near the center of a larger upper-level low where the vertical wind shear was relatively weak. This is typical for late-season developments in the subtropics. Nicole continued to become organized later on 24 November; an intermittent eye was observed in satellite images. Maximum winds increased to 60 kt as indicated by reports from the same ship.

Nicole moved toward the west-southwest for the next few days south of a strong midlevel high pressure ridge.

←

[a] National Hurricane Center standard averaging period is 1 min; ASOS and C-MAN are 2 min; buoys are 8 min.
[b] Day/time is for sustained wind when both sustained and gust are listed.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above NGVD.
[e] Estimated.

TABLE 8. Comparison of 1998 Atlantic official and CLIPER average track forecast errors (rounded to the nearest n mi) for a homogeneous sample (excluding extratropical and tropical depression stages) with 1988–97 10-yr average. A forecast error is defined as the great circle distance between a forecast and a postanalysis best-track position for the same time. Cases include all subtropical storms, tropical storms, and hurricanes. Also shown is the range of the track forecast errors (n mi) for each forecast period.

	Forecast period (h)					
	0	12	24	36	48	72
1998 averages						
Official	13	46	84	116	144	203
CLIPER	13	55	113	171	224	302
No. of cases	317	314	283	257	230	188
1988–97 averages						
Official	13	47	88	127	166	248
CLIPER	13	56	112	173	233	345
No. of cases	1855	1841	1638	1456	1288	1008
1998 average departures (%) from 1988–97						
Official	0	−2	−5	−9	−13	−18
CLIPER	0	−2	+1	−1	−4	−12
1998 error range	0–109	0–180	6–501	8–606	18–816	8–1079

An upper-level trough moved rapidly eastward over the system, producing a strong wind shear. The shear removed most of the convection associated with the TC, which weakened to a tropical depression on 26 November. In fact, the system became so weak that it practically dissipated. However, the ridge that followed the upper-level trough became superimposed over the system, decreasing the shear. Deep convection regenerated, and, unexpectedly, the system reacquired tropical storm strength by 27 November. Nicole's regeneration is yet another illustration of the uncertainties in intensity forecasting, particularly at higher latitudes where extratropical influences play a role. The rejuvenated TC moved on a west-northwest track. Thereafter, it turned toward the northeast ahead of another strong approaching cold front. Nicole intensified further and reached hurricane status with peak winds of 75 kt and a minimum pressure of 979 mb at 0000 UTC 1 December. These estimates were based on satellite images that revealed the formation of an eye, resulting in objective T numbers near 4.5. In addition, data from the Defense Military Satellite Program 85-GHz microwave sensor showed an almost complete eyewall. During that period, Nicole was moving over sea surface temperatures about 2°–3°C warmer than normal, and these anomalously warm waters probably contributed to the intensification of the system. Nicole moved rapidly northward and north-northwestward around the periphery of a large deep-layer cyclonic circulation and became extratropical by 1800 UTC 1 December.

3. Forecast verification

The NHC verifies their forecasts of tropical and subtropical storms and hurricanes by comparing the ''official forecast'' positions and intensities to the ''best track'' data for each cyclone. For all TCs that are identified operationally in the Atlantic basin, the NHC issues 6-hourly official forecasts of the center position and maximum 1-min average wind speed. These official forecasts are valid 12, 24, 36, 48, and 72 h from the initial time.

Table 8 is a listing of the average track forecast errors for the tropical storms and hurricanes of 1998 for the official forecasts and for the climatology and persistence model (CLIPER; Neumann 1972). Also shown in this table are the 1988–97 average official and CLIPER track forecast errors, and the departures of the 1998 average official and CLIPER track forecast errors from the 1988–97 averages. Official track forecast errors for 1998 were slightly lower than the recent 10-yr averages at 12–72 h. A comparison with the corresponding CLIPER errors shows that, except at 0 and 12 h, the official forecasts for 1998 were slightly more improved from the 10-yr average than was CLIPER. This is of interest, since the CLIPER model is often used as a measure of forecast difficulty. Thus, the 1998 tracks were just slightly easier than average to forecast, and the official track forecasts for 1998 were, on average, quite good in comparison to other years.

Table 9 contains a listing of the average intensity (maximum one-min average wind speed) forecast errors for the 1998 tropical storms and hurricanes, and for the 1990–97 time period. Two measures of intensity forecast errors are used: the average error or bias, that is, the average forecast minus observed maximum 1-min wind speed, and the average absolute error, that is, the average absolute value of the forecast minus observed maximum 1-min wind speed. Also listed in this table are the corresponding intensity forecast errors for the Statistical Hurricane Intensity Forecast Model (SHIFOR; Jarvinen and Neumann 1979). There is a slight negative bias in the average official intensity forecasts through 36 h, but the average official errors are quite small at 48 and 72 h, indicating little bias for these later forecast time periods. For the corresponding average SHIFOR intensity forecast errors, there is a substantial negative bias at 48 and 72 h. A small average error, or bias, in intensity forecasts may be misleading since it could be the result of averaging under- and overpredictions of the maximum wind speed. So, the average absolute intensity forecast errors are a helpful measure of forecast skill. For 1998, the average absolute official intensity forecast errors ranged from 7.5 kt at 12 h to 21.2 kt at 72 h. Moreover, for 12–72 h, these average absolute errors are lower than the corresponding average SHIFOR errors. Since an improvement over SHIFOR is an indication of skill, we conclude that the 1998 average official intensity forecasts had some skill out to 72 h. It is also of interest to compare the 1998 average absolute intensity forecast errors to those for a longer-term period, 1990–97. One can see that the official errors were higher than the recent 8-yr average but that the SHIFOR errors were even higher. Therefore, since SHIFOR provides a measure of intensity forecast difficulty, 1998 featured storms whose intensity changes were harder to predict than usual. In summary, the 1998 official intensity forecast errors were slightly larger than average because of higher than normal forecast difficulty, but these forecasts exhibited skill from 1–3 days.

4. Weaker tropical systems

In this section, we will briefly discuss the tropical depressions and tropical waves that occurred during the 1998 season. The tracking of tropical waves goes back at least as far as the work of Dunn (1940). These waves play a crucial role as precursors to TC formation over the Atlantic and eastern Pacific Oceans. In fact, an average of 10% of the tropical waves develop into named TCs each year (Table 10). Normally, the strongest hurricanes originate from tropical waves. Moreover, tropical waves are one of the principal modulators of rainfall in the Caribbean basin (Riehl 1954). References to publications about tropical wave structure and properties are included in Pasch et al. (1998). A summary of how tropical waves are tracked operationally at the TPC/NHC can be found in Avila et al. (2000). Here, the statistics of depressions and waves, which began in 1967, are updated; hereafter, the compilation will be included in the Atlantic hurricane season annual summary article.

a. Tropical depressions

There were 14 tropical depression in 1998, a number that is below the 1967–97 average of 19. As pointed out by Pasch and Avila (1994), notably fewer depressions per year were counted after the early 1980s, so this average is likely not representative. Because all of the tropical depressions reached tropical storm status, their histories have been included in section 2.

b. Tropical waves during 1998

Figure 10 summarizes the tropical wave activity during 1998 and highlights the TCs that formed from the

TABLE 9. Homogeneous comparison of official and SHIFOR maximum 1-min wind speed forecast errors (rounded to the nearest 0.1 kt) for subtropical storms, tropical storms, and hurricanes in the Atlantic basin for 1998 with 1990–97 8-yr average. Error = forecast − observed.

	Forecast period (h)					
	0	12	24	36	48	72
Average official error for 1998	−1.7	−1.2	−1.5	−1.1	0.1	0.5
Average SHIFOR error for 1998	−1.7	−1.2	−2.3	−3.6	−5.1	−5.2
Average absolute official error for 1998	3.6	7.5	11.4	14.6	17.4	21.2
Average absolute SHIFOR error for 1998	3.6	9.5	13.5	17.0	20.1	24.2
No. of cases for 1998	317	314	282	257	230	188
Average 1990–97 official error	−1.8	−1.2	−1.5	−2.1	−2.9	−3.2
Average 1990–97 SHIFOR error	−1.8	−1.2	−1.8	−2.7	−3.7	−5.8
Average 1990–97 absolute official error	3.6	6.6	10.2	13.0	15.6	19.1
Average 1990–97 absolute SHIFOR error	3.6	8.3	11.7	14.1	16.4	18.8
No. of cases for 1990–97	1466	1453	1290	1147	1010	790
Average 1998 absolute official departure from 1990–97 average absolute official	0%	+14%	+12%	+12%	+12%	+11%
Average 1998 absolute SHIFOR departure from 1990–97 average absolute SHIFOR	0%	+14%	+15%	+21%	+23%	+29%
Official 1998 error range	−30 to +15	−30 to +30	−40 to +40	−50 to +40	−60 to +45	−75 to +65

TABLE 10. Atlantic tropical system statistics for 1967–98.

Year	Waves	Total TD	Total TS	Total H	From waves TD	From waves TS	From waves H	Wave-generated TS / Total TS
1967	61	29	8	6	14	5	5	0.63
1968	57	19	7	4	8	4	2	0.57
1969	58	28	18	12	16	10	8	0.56
1970	54	26	10	5	16	7	3	0.70
1971	56	23	13	6	12	6	2	0.56
1972	57	24	4	3	6	1	1	0.25
1973	56	24	7	4	10	4	2	0.57
1974	52	25	7	4	12	5	4	0.71
1975	61	28	8	6	14	5	5	0.63
1976	68	23	8	6	10	5	5	0.63
1977	69	19	6	5	7	3	2	0.50
1978	63	31	11	5	18	6	4	0.55
1979	52	27	8	5	20	8	5	1.00
1980	49	19	11	9	14	8	6	0.73
1981	62	22	11	7	17	6	6	0.55
1982	61	9	5	2	6	3	2	0.60
1983	57	6	4	3	3	1	1	0.25
1984	59	20	12	5	8	5	1	0.42
1985	53	14	11	7	9	8	5	0.73
1986	49	10	6	4	6	3	2	0.50
1987	57	14	7	3	11	5	2	0.71
1988	62	19	12	5	16	9	4	0.75
1989	63	15	11	7	14	11	7	1.00
1990	76	16	14	8	12	10	5	0.71
1991	73	12	8	4	7	3	0	0.38
1992	69	9	6	4	4	2	1	0.33
1993	70	10	8	4	9	8	4	1.00
1994	70	12	7	3	9	5	2	0.71
1995	63	21	19	11	19	17	11	0.89
1996	62	13	13	9	12	12	9	0.92
1997	63	8	7	3	3	2	1	0.28
Average	61	19	9	5	11	6	3	0.62
1998	60	14	14	10	12	10	8	0.86

TD = Tropical depression; TS = Tropical storm; H = Hurricane.

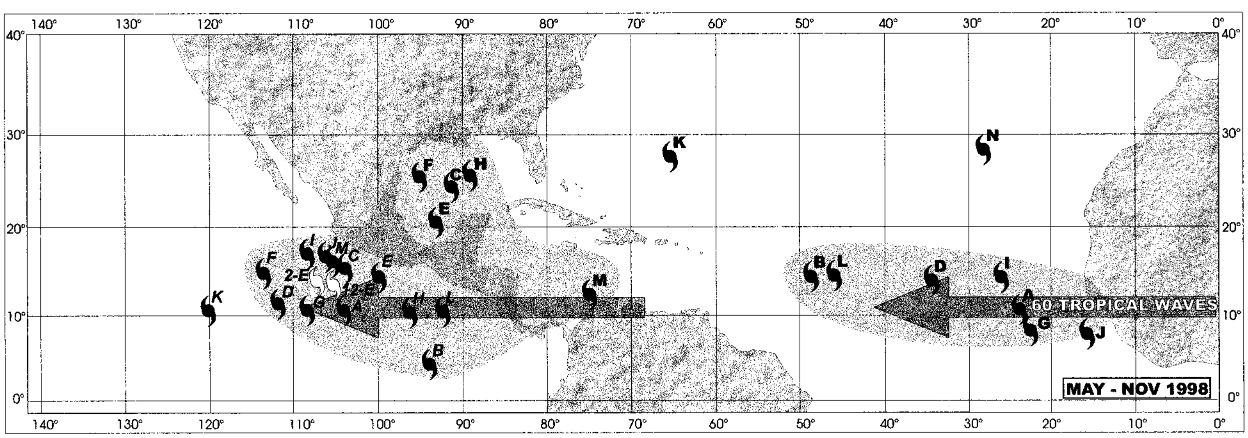

FIG. 10. Total number of waves that maintained their identities while traveling the Atlantic, Caribbean, Gulf of Mexico, and the eastern Pacific during 1998. The figure highlights the (shaded) envelope in which tropical cyclones developed, as shown by the lettered symbols (named cyclones) or numbered symbols (tropical depressions). Symbols outside the envelope are the approximate locations of tropical cyclone formation from disturbances other than tropical waves.

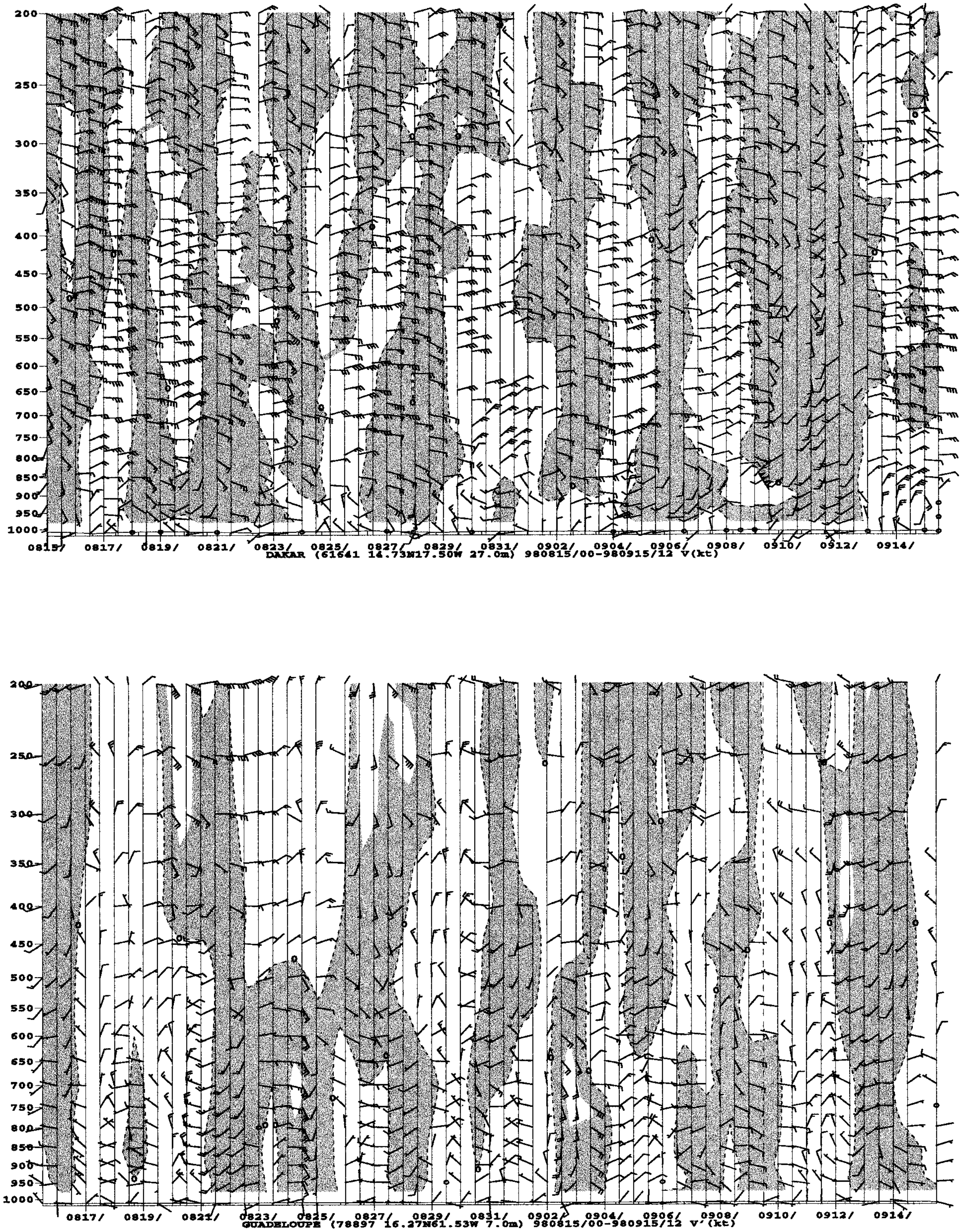

FIG. 11. Vertical time section of the wind at (a) Dakar, Senegal, and (b) Guadeloupe from 15 Aug to 15 Sep. Winds are plotted every 12 h according to convention with each half barb and full barb denoting 5 and 10 kt, respectively, and the solid flag denoting 50 kt. The mean (average for the period) wind was removed from the Guadeloupe section. Shaded areas correspond to a positive (southerly) perturbation wind component.

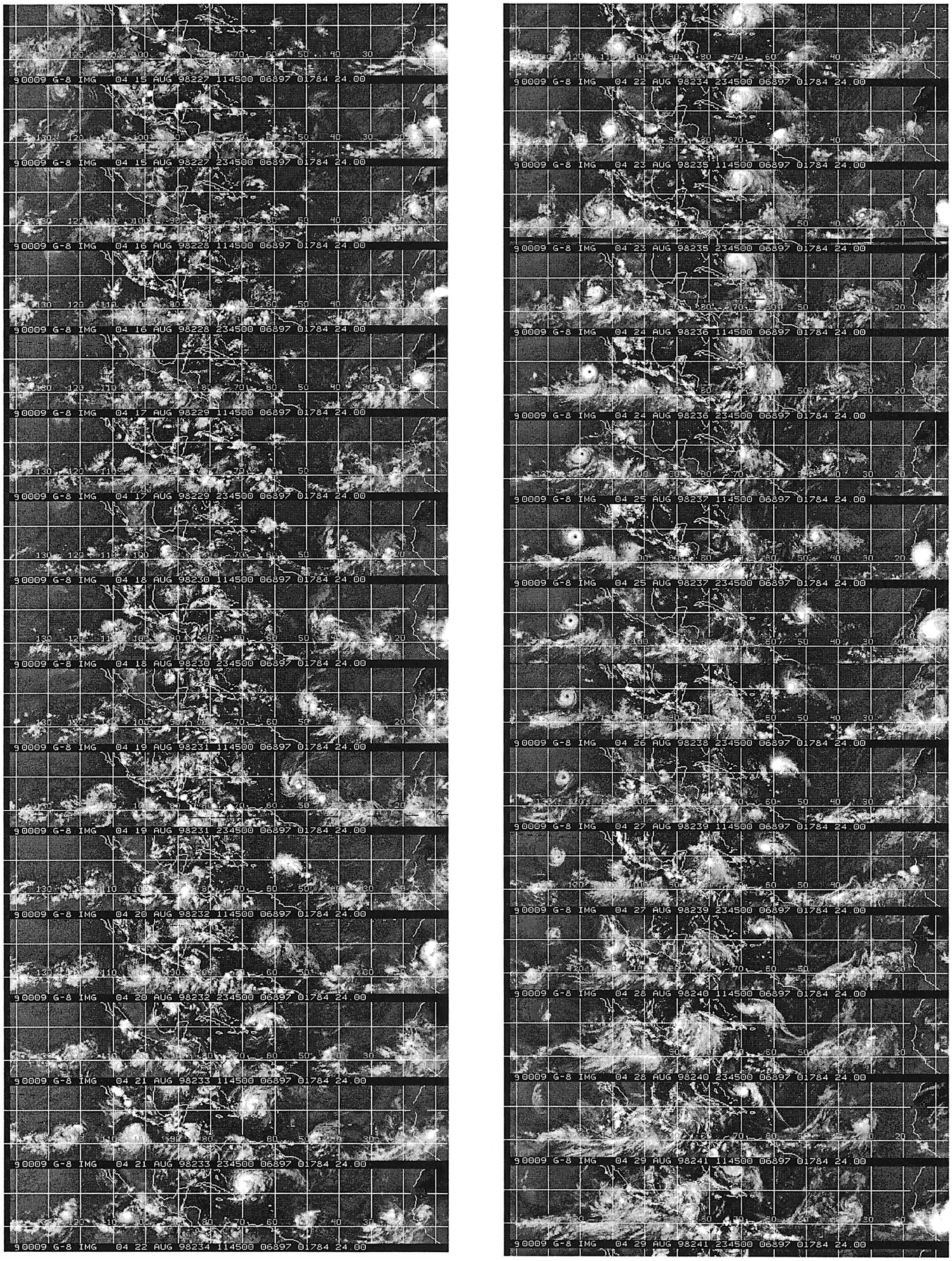

FIG. 12. Longitude vs time (Hovmöller) diagram of *GOES-8* infrared images taken twice a day at 2345 and 1145 UTC from (a) 15 to 29 Aug, and (b) 30 Aug to 12 Sep 1998. The latitude belt is roughly 5°–25°N. Latitude–longitude lines are at 10° intervals.

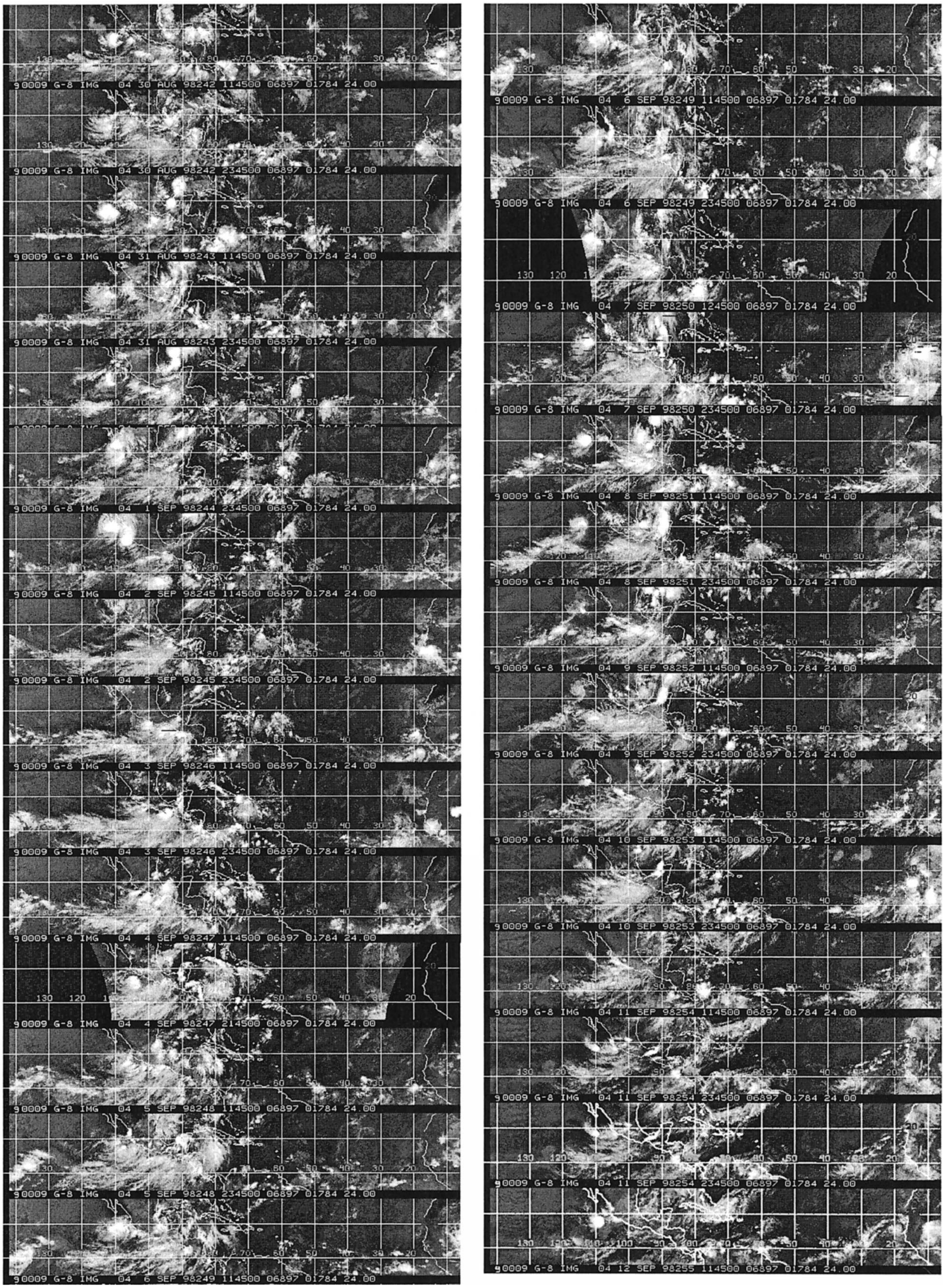

FIG. 12. (*Continued*)

waves. For the period of May to November, 60 tropical waves crossed Dakar and moved westward over the tropical Atlantic, the Caribbean Sea, and Central America. Most of them appeared to continue into the eastern North Pacific. There was approximately one wave crossing at Dakar every 3.5 days. The long-term average number of waves observed for the same period is 61. Note that, except for Hurricanes Karl and Nicole in the Atlantic and Tropical Storm Kay in the eastern North Pacific, the rest of the TCs developed in the ''envelope'' region of genesis attributed to tropical waves.

Figure 11 displays vertical time sections of the wind for Dakar and Guadeloupe from 15 August to 15 September 1998. Figure 12 shows sequences of twice per day satellite images for nearly the same period. This sample represents the climatologically most active period when tropical waves are usually the strongest and most convectively active.

From the early portion of the season, the tropical waves were clearly identified as they crossed Dakar and, in general, were accompanied by a strong midtropospheric easterly jet. In fact, a strong wave crossed Dakar on 17 June with a 50-kt easterly wind speed maximum at 600 mb. The midlevel easterly jet is considered of great importance in relation to the structure of the tropical waves. Burpee (1972) has shown that the meridional variations of the horizontal wind at the midtropospheric levels are related to wave amplification. Experience has shown that years with either a relatively weak midtropospheric jet or (as is more often the case) with a southward shift of the jet in the Atlantic normally coincide with inactive hurricane seasons.

Tropical waves were very well defined through July and in fact, one of these waves produced Tropical Storm Alex late that month. This earlier than normal TC genesis from waves suggested that the large-scale environment was already becoming favorable for waves to initiate TC formation. The waves continued to be quite strong, and the environment mostly favorable, during August and September. Figure 11 shows distinct tropical waves crossing Dakar between 15 August and 15 September. Note the deep and sharp cyclonic wind shift below 400 mb associated with the waves as they crossed Dakar. These waves were embedded within a deep easterly flow that extended to at least 200 mb throughout the period.

Because in general, waves become more difficult to track as they propagate westward across the Atlantic, the mean wind for the period was removed from the Guadeloupe time section. This way, one can then depict more clearly the passage of the waves by focusing on the sign change of the perturbed meridional component of the wind. The Guadeloupe section reveals the well-defined mid- to lower-tropospheric cyclonic perturbations associated with several waves crossing that site. In contrast with near Dakar, there was a change in the upper-level winds at Guadeloupe from easterlies, during the last 2 weeks of August, to westerlies during the following 15 days. Consequently, waves moving through the area during the first half of September encountered an environment dominated by upper-level westerlies.

Satellite imagery Hovmöller diagrams constructed operationally from May to November reveal the westward-propagating cloudiness associated with the waves during the period. The waves became distinct and convectively active over the tropical Atlantic during the second half of August (Fig. 12). Although waves were well defined in the wind field during early September, their convective activity was rather suppressed between the Antilles and Africa. This period was dominated by upper-level westerlies, alluded to above, and coincided with a relatively inactive 2-week period of no TC activity in the tropical Atlantic. During this period, most of the convection was concentrated in the western Caribbean and the Gulf of Mexico, where TC activity also was concentrated.

c. Comparison with other years

Table 10 summarizes the tropical system statistics from 1967 to 98. The ratio, *R*, between the number of tropical storms forming from tropical waves to the total number of tropical storms is used to describe the overall character of the hurricane season (Avila and Clark 1989). Low values of *R* indicate that many tropical storms originated from nontropical ''seedling'' disturbances such as upper-tropospheric cold lows or perturbations along frontal zones. High values of *R* indicate that storms mostly develop from tropical waves in the tropical Atlantic, generally south of 20°N. With a few exceptions, years with high values of *R* are years of strong hurricanes. The 1967–97 average contribution from tropical waves to the total number of storms is 0.62. In 1998, *R* was 0.86. Thus 1998 had many intense hurricanes in the deep Tropics.

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