Atlantic Hurricane Season of 2002

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ABSTRACT

The 2002 Atlantic hurricane season is summarized. Although the season's total of 12 named storms was above normal, many of these were weak and short-lived. Eight of the named cyclones made landfall in the United States, including Lili, the first hurricane to hit the United States in nearly 3 yr.

1. Introduction

Although the 2002 Atlantic hurricane season featured 12 tropical storms, 2 more than the long-term average, there were only 4 hurricanes, 2 fewer than the long-term average. In an average season there are two ''major'' hurricanes [i.e., maximum 1-min average winds greater than 96 kt (1 kt = 0.5144 m s^{-1}), corresponding to category 3 or higher on the Saffir–Simpson hurricane scale (Simpson 1974)], and in 2002 Isidore and Lili attained this status. An overall measure of seasonal activity is provided by the ''accumulated cyclone energy'' (ACE), which is defined as the sum of the squares of the wind speed of all named tropical cyclones every 6 h of the cyclone's existence. In 2002, because many of the named cyclones were weak and short-lived, the ACE was 65.1×10^5 kt^2, or 74% of the long-term median value of 87.5×10^5 kt^2. By this metric, the season was less active than normal.

Gustav, the first 2002 Atlantic hurricane, did not develop until 11 September, the latest date for the first hurricane since the beginning of the era of aerial reconnaissance in 1944. It is also of interest that the eight named tropical cyclones that formed during the month of September are the most on record for a calendar month. Eight named systems hit the United States—albeit several of these were weak tropical storms. Lili was the first hurricane to make a U.S. landfall since Irene in October of 1999. Table 1 lists statistics for the 2002 Atlantic tropical storms and hurricanes, and Fig. 1 is a map of their tracks. It can be seen that most of the cyclones originated at subtropical latitudes, north of 25°N. Of the 12 named systems, only 3, Dolly, Isidore, and Lili, originated from tropical waves. Two of the named systems, Gustav and Kyle, started out as subtropical cyclones.

Figure 2 show the sea surface temperature anomalies over most of the North Atlantic basin for August and September of 2002, as well as the points of formation of the tropical and subtropical cyclones during these months. The sea surface temperature anomaly fields were obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis project (Kistler et al. 2001). It can be seen that much of the Atlantic between 10° and 20°N, between Africa and the Lesser Antilles, was slightly cooler than normal, whereas west of about 50°W south of 35°N, the sea surface was slightly warmer than normal. Although the anomalies are small, none of the cyclones developed over below-normal sea surface temperatures.

The vertical shear of the horizontal wind has been recognized as an important factor for tropical cyclone genesis and intensification for several decades. Figure 3 shows the departures from the long-term (1979–98) mean of the magnitude of the 200–850-mb wind shear for August and September of 2002. These shear anomalies were computed using twice-daily analyses from the National Oceanic and Atmospheric Administration (NOAA)/National Weather Service's Global Forecast System (GFS) and long-term means from the NCEP–NCAR reanalysis project (Kistler et al. 2001). Also shown on this figure are the points of formation of the tropical and subtropical cyclones during these months. During August, vertical shear was considerably above normal over much of the Caribbean Sea, and somewhat above normal over most of the tropical North Atlantic Ocean. In September, more favorable shear anomalies developed over much of these areas. The figure also shows that most of the cyclones developed in locations where the shear was near or below normal.

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TABLE 1. Atlantic hurricane season statistics for 2002.

No.	Name	Class[a]	Dates[b]	Max 1-min wind (kt)	Min sea level pressure (mb)	U.S. damage ($ millions)	Direct deaths
1	Arthur	T	14–16 Jul	50	997		
2	Bertha	T	4–9 Aug	35	1007	Minor[c]	1
3	Cristobal	T	5–8 Aug	45	999		
4	Dolly	T	24 Aug–4 Sep	50	997		
5	Edouard	T	1–6 Sep	55	1002	Minor	
6	Fay	T	5–8 Sep	50	998	≳5	
7	Gustav	H	8–12 Sep	85	960	0.1	1
8	Hanna	T	12–15 Sep	50	1001	20	3
9	Isidore	H	14–27 Sep	110	934	330	5
10	Josephine	T	17–19 Sep	35	1009		
11	Kyle	H	20 Sep–12 Oct	75	980	5.0	
12	Lili	H	21 Sep–4 Oct	125	938	860	13

[a] T = tropical storm (wind speed 34–63 kt); H = hurricane (wind speed 64 kt or higher).
[b] Dates begin at 0000 UTC, include tropical depression stage (wind speed less than 34 kt), and exclude extratropical stage.
[c] Although some damage was reported, no specific amounts have been estimated.

It should also be noted that, based on the sea surface temperature anomalies over the equatorial east-central Pacific Ocean, a moderate El Niño prevailed during the 2002 hurricane season. According to Gray (1984), the presence of El Niño usually has a suppressing effect on Atlantic hurricane activity. The 2002 El Niño was likely a major contributor to the above-normal shear values over the Caribbean and tropical Atlantic seen in Fig. 3. There was, however, a relaxation of the shear during September. For the season as a whole, the combined influences of a slightly cooler-than-normal tropical Atlantic and an El Niño event were at least partially responsible for the below-normal activity (as measured by ACE) of 2002.

2. Summaries of individual tropical storms and hurricanes

Accounts of the individual storms and hurricanes in this section are based on the ‘‘best tracks’’ prepared by the National Hurricane Center (NHC). The best-track database is produced from a poststorm meteorological analysis of each cyclone and consists of 6-hourly representative estimates of the cyclone’s center location, maximum sustained (1-min average) surface (10 m) wind, and minimum sea level pressure. By definition, a cyclone’s life cycle includes the tropical (or subtropical) depression stage but does not include the extratropical stage.

The datasets and observing systems used by NHC for the monitoring and postanalyses of the 2002 cyclones are essentially the same as those described by Franklin et al. (2001). These include visible and infrared imagery from geostationary and polar- and near-equatorial-orbiting satellites, reports from reconnaissance aircraft of the U.S. Air Force Reserve Command (AFRC) and the NOAA Global Positioning System (GPS) dropwindsonde profiles, multichannel microwave imagery from polar-orbiting satellites, and remote surface wind measurements from the Sea Winds Scatterometer aboard the National Aeronautics and Space Administration polar-orbiting Quick Scatterometer satellite (QuikSCAT; Tsai et al. 2000). The above data sources are supplemented by conventional surface and upper-air observations from land stations, ships, and buoys, as well as weather radar observations, when available.

a. *Tropical Storm Arthur, 14–16 July*

The origin of Arthur was a weak low-level circulation first detected in the eastern Gulf of Mexico on 9 July. This system was likely associated with a decaying frontal zone that had persisted in the area for several days. The circulation and associated area of low pressure meandered for a few days, then accelerated northeastward across the southeastern United States on 13 July in response to a midlevel trough amplifying southward along the U.S. East Coast. The circulation moved along the coasts of South and North Carolina on 14 July. By 1800 UTC that day organized deep convection developed, and the system became a tropical depression centered about 40 n mi west-southwest of Cape Hatteras, North Carolina. A midlevel low cut off from the westerlies and deepened as it dropped southward over the Canadian Maritimes, and the depression responded by accelerating east-northeastward. It also strengthened and became a tropical storm on 15 July. By the time Arthur strengthened to its peak intensity of 50 kt on 16 July, it was centered about 350 n mi south of Nova Scotia, Canada, and its forward speed had increased to 35 kt. Moving around the aforementioned low, Arthur turned northward late on 16 July and became extratropical before it passed over eastern Newfoundland, Canada. Thereafter, the motion slowed and the cyclone became nearly stationary between Newfoundland and Greenland and weakened below gale strength on 19 July.

Several apparently valid ocean surface wind speeds in the 45- to 48-kt range were observed within Arthur’s circulation by QuikSCAT on 15–16 July. The Canadian data buoy 44141 observed a pressure of 997.5 mb when

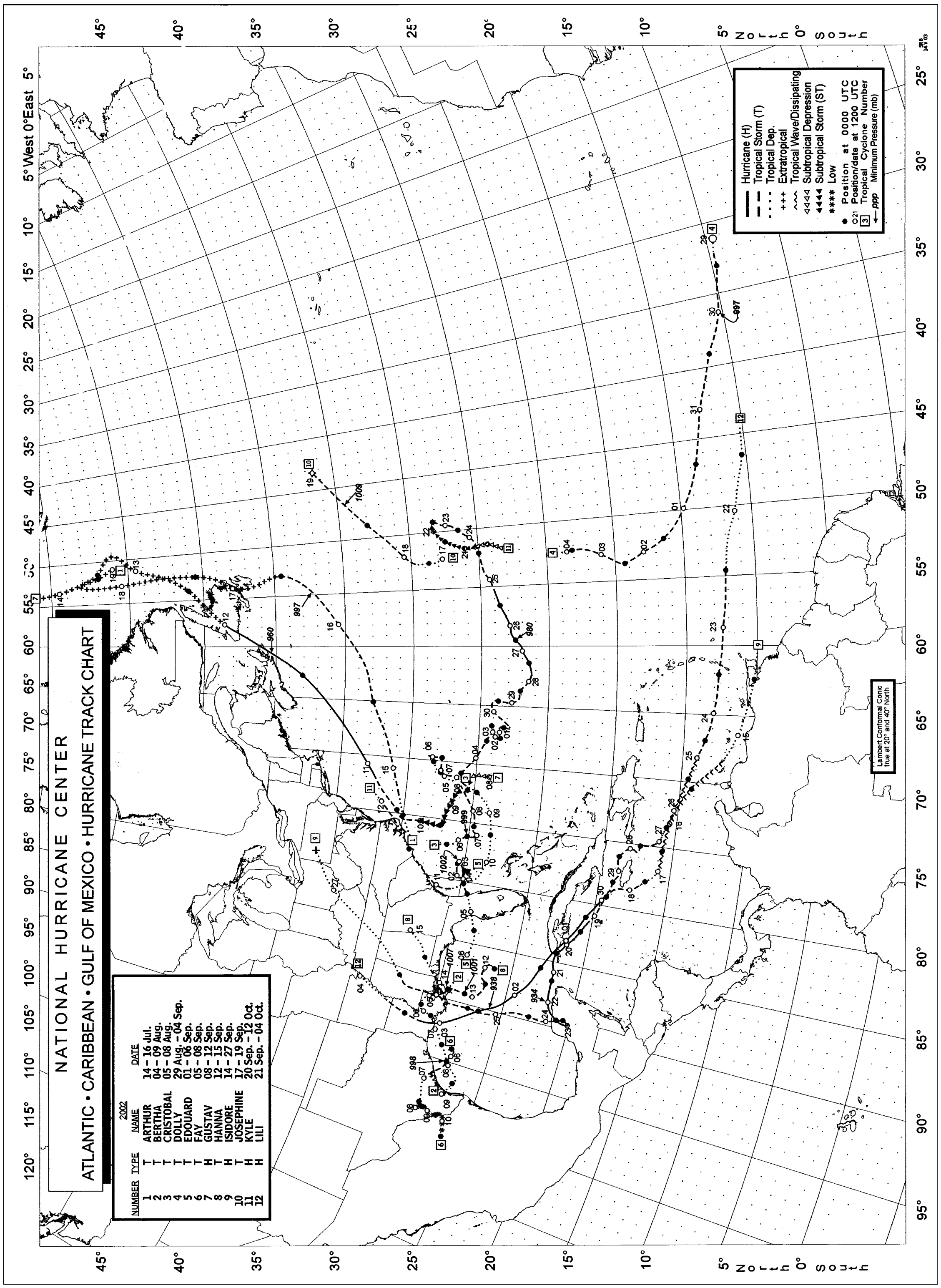


FIG. 1. Tracks of tropical storms, hurricanes, and subtropical cyclones in the Atlantic basin in 2002.

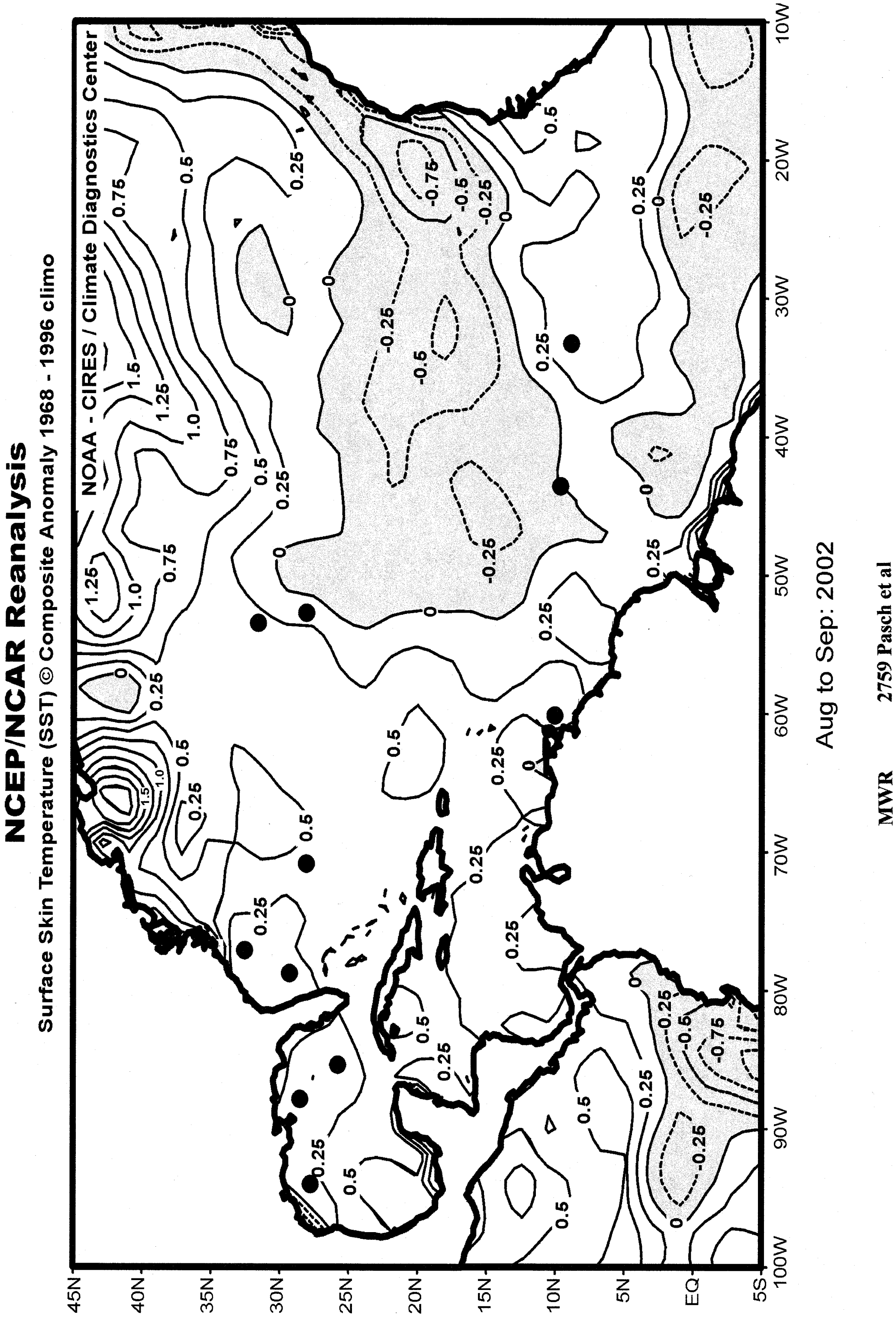


FIG. 2. Sea surface temperature anomalies (from the 1968 to 1996 mean) for Aug through Sep of 2002. Contour interval is 0.25°C. Areas of cooler-than-normal sea surface temperatures are shaded. Dots denote the points of formation of tropical and subtropical cyclones during these 2 months.

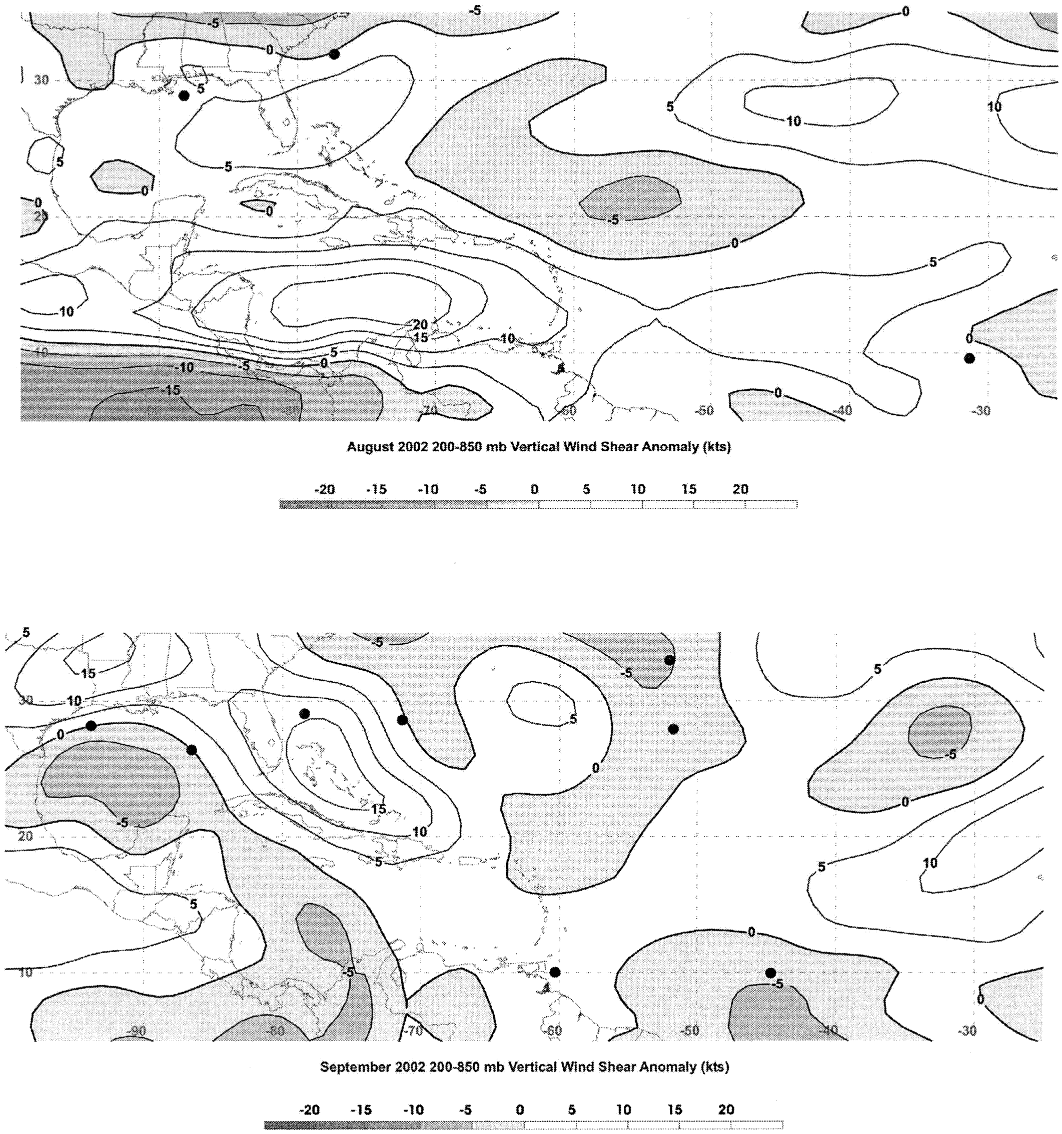


FIG. 3. Anomalies from the long-term (1979–98) mean of the magnitude of the 200–850-mb wind shear for (top) Aug and (bottom) Sep 2002. Negative anomalies (below-normal values of shear) are shaded. Dots denote the points of formation of tropical and subtropical cyclones during these 2 months.

the center of Arthur passed about 40 n mi to its south. This buoy also reported an 8-min mean wind speed of 39 kt with a gust to 52 kt when the center of Arthur passed. The ship *Weston* reported winds of 44 kt on 16 July while located about 140 n mi south-southeast of the center of Arthur.

Before Arthur became a tropical cyclone, its originating low pressure system spread heavy rains across portions of north Florida, Georgia, and South Carolina on 13 July. Later, as an extratropical cyclone, Arthur produced rainfall accumulations of up to about 25 mm over Newfoundland on 17 July. Reported wind speeds along Newfoundland's east coast included 34 kt at Bonavista on 17 July. There were no casualties or damage reported in association with Arthur.

b. Tropical Storm Bertha, 4–9 August

Bertha was a minimal tropical storm that made landfall in southeastern Louisiana.

1) SYNOPTIC HISTORY

Bertha formed from a nontropical surface low pressure trough that later spawned Tropical Storm Cristobal in the western North Atlantic Ocean. This trough extended from the north-central Gulf of Mexico across Florida and into the Atlantic on 1 August and moved little for the next two days. A poorly defined low pressure center was first noted over the north-central Gulf of Mexico on 3 August. Satellite, surface, and radar observations indicated that the low became better organized just east of the mouth of the Mississippi River on 4 August, and the system developed into a tropical depression around 1800 UTC that day. The depression strengthened as it moved west-northwestward, and an Air Force Reserve Hurricane Hunter aircraft indicated that the system became Tropical Storm Bertha near 2300 UTC 4 August. The center made landfall near Boothville, Louisiana, about 2 h later. After landfall, Bertha assumed a wobbly northwestward motion that took the center to the north of Lake Ponchartrain later on 5 August. The cyclone weakened back to a depression by 1200 UTC that day.

Bertha maintained its circulation over land while moving slowly westward and then southward on 6 August. On 7 August, it began a southwestward motion, back into the Gulf of Mexico around 0900 UTC that day. This motion continued until late on 8 August. While satellite and radar data showed periods of increased organization, surface and aircraft observations showed only slight strengthening over the northwestern Gulf. The cyclone turned west-northwestward late on 8 August, and this motion brought the center of the depression to the Texas coast east of Kingsville around 0800 UTC 9 August. Bertha weakened quickly after landfall and dissipated over southern Texas later that day.

2) Meteorological statistics

The highest surface winds measured in the storm were at NOAA buoy 42007 located at 30.1°N, 88.8°W, which reported 10-min average winds of 33 kt at 2240 UTC 4 August and 0310 UTC 5 August. The buoy reported a peak gust of 43 kt at 0441 UTC 5 August. A nearby station operated by Louisiana State University reported a 34-kt wind gust at 0000 UTC 5 August. The highest reported wind at a coastal site was a gust of 36 kt at a National Ocean Service station in Waveland, Mississippi. Storm tides reached as high as 0.9 to 1.2 m (0.3 to 0.6 m above normal tide levels) along portions of the Mississippi and southeastern Louisiana coasts. Rainfall totals associated with Bertha were mainly in the 75–150-mm range, although there were locally heavier amounts, including reports of 260 mm at Pascagoula, Mississippi, and Norwood, Louisiana. No tornadoes were reported in association with Bertha.

3) Casualty and damage statistics

Press reports indicate one death associated with Bertha—a drowning in high surf at Perdido Key State Park, Florida, on 4 August. Damage associated with Bertha was minor, although no specific figures are available. Rains associated with the tropical cyclone produced areas of stream and street flooding that affected some structures.

4) Warnings

A tropical storm warning was issued at 2330 UTC 4 August for the northern Gulf Coast from Pascagoula to the mouth of the Mississippi River including Lake Borgne and Lake Ponchartrain. This warning was issued as Bertha reached minimal tropical storm strength, 1.5 h before landfall. The warning was discontinued at 1200 UTC 5 August as Bertha weakened to a depression over land.

c. Tropical Storm Cristobal, 5–8 August

Cristobal's origin was nontropical. A low pressure trough that extended from the north-central Gulf of Mexico across the southeastern United States and into the Atlantic first spawned Tropical Storm Bertha in the Gulf of Mexico. While Bertha was forming on 4 August, a second area of low pressure was also developing within the trough near the South Carolina coast. This second low moved slowly eastward and its associated convection gradually became better organized; by 1800 UTC 5 August, when the low was about 150 n mi east-southeast of Charleston, South Carolina, it had acquired sufficient organization to be considered a tropical depression.

The depression moved slowly south-southeastward over the next day and a half. Development was limited by strong northerly wind shear and a relatively dry environment, and most of the system's convection was confined to the southern portion of the circulation. The surface circulation became elongated in the southwesterly flow in advance of a southward-moving cold front. Nevertheless, a reconnaissance aircraft late on 6 August found that the central pressure had fallen and that the depression had strengthened to a tropical storm. On 7 August, Cristobal began a slow eastward motion as it started to come under the influence of a large mid- to upper-level trough moving off the U.S. East Coast. The main convective activity shifted from the south to the southeast, and then to the east quadrant of the circulation by early on 8 August. This reorganization of the convection was accompanied by a modest increase in winds, to 45 kt, although there was apparently no concurrent decrease in central pressure.

On 8 August, with additional dry air moving into the circulation and convection becoming intermittent, Cristobal began a sudden acceleration to the east-northeast, with its forward speed increasing from about 3 to 20 kt over a 12-h interval. By 1800 UTC, Cristobal was becoming absorbed into the frontal zone, about 300 n mi southeast of Cape Hatteras, and reconnaissance aircraft reported some difficulty finding a low-level circulation. Satellite images suggest that the circulation of Cristobal had dissipated within the frontal zone by 0000 UTC 9 August.

d. Tropical Storm Dolly, 29 August–4 September

Dolly was the first Atlantic basin tropical cyclone of 2002 to form in the deep Tropics. It developed from a tropical wave that moved off the west coast of Africa on 27 August. As the wave moved westward, ship observations indicated that the wave was accompanied by a fairly distinct area of surface low pressure, and satellite images showed increasing thunderstorm activity. The system became a tropical depression at 1200 UTC 29 August about 550 n mi southwest of the westernmost Cape Verde Islands. The depression quickly became better organized, developing well-defined cyclonically curved convective bands and good outflow in all quadrants. It became a tropical storm by 1800 UTC on the same day and reached its peak intensity of 50 kt, with a minimum pressure of 997 mb, at 1200 UTC 30 August. Dolly moved toward the west and west-northwest around the periphery of a subtropical ridge for 2 days. Then, the tropical cyclone curved to the northwest and then north ahead of a midlevel trough, with a minor reduction in intensity around 0000 UTC 3 September when convection decreased. It became a nonconvective remnant low late on 4 September under the influence of strong shear, and the circulation dissipated soon thereafter. There were no reports of damage or casualties associated with Dolly.

Some of the early NHC forecasts for Dolly showed it strengthening into a hurricane. These predictions were based on an expected track at low latitudes—to the south of an area of strong upper-tropospheric westerlies. However the storm turned northward sooner than expected, which brought Dolly into a high shear environment, where it weakened.

e. Tropical Storm Edouard, 1–6 September

Edouard made landfall on the northeast coast of Florida as a minimal tropical storm.

1) SYNOPTIC HISTORY

Edouard formed from a disturbance of nontropical origin. Cloudiness and isolated showers developed several hundred miles east-southeast of Bermuda on 25 August, likely in association with a low-level disturbance that had formed along a dying frontal zone. The system moved southwestward for several days, and when the disturbance was located near the southwest end of an upper-level trough a few hundred miles north of Puerto Rico, deep convection associated with the system increased. The area of disturbed weather moved slowly westward over the next couple of days and, on 31 August, when the system was located just to the east of the northern Bahamas, it began to become better organized. By 1 September, deep convection became persistent, and surface and reconnaissance aircraft data indicate that the system became a tropical depression around 1800 UTC that day, centered about 120 n mi east of Daytona Beach, Florida.

Although the cyclone was in an environment of moderate west-northwesterly shear, it strengthened into Tropical Storm Edouard by 0600 UTC 2 September. Later that day and early the next, the environment appeared to become more hostile. Water vapor imagery suggested that dry mid- to upper-tropospheric air was overspreading the cyclone center, and radiosonde data indicated 30–40-kt winds near the storm at the 200-mb level. Despite this, Edouard was able to intensify further, and it reached its peak strength of 55 kt around 1200 UTC 3 September. However, very soon thereafter, the storm began to succumb to the influence of strong shear and dry air aloft, and a weakening trend was underway. By midday on 3 September, the associated deep convection had decreased, and the low-cloud circulation center was clearly exposed.

Soon after Edouard's genesis, steering currents weakened. From 2–3 September, the cyclone moved in a clockwise loop. Then, as a weak and narrow midtropospheric ridge developed to its north, Edouard headed erratically westward and west-southwestward toward the northeast coast of Florida. Strong shear continued to impact the system, and although occasional bursts of deep convection occurred near the center, the cyclone was barely of tropical storm strength when the center crossed the coastline in the vicinity of Ormond Beach, Florida, around 0045 UTC 5 September. Edouard weakened to a depression almost immediately after landfall and crossed north-central Florida. The depression emerged into the Gulf of Mexico near Crystal River, Florida, around 1400 UTC on 5 September. Strong northwesterly shear, associated with the upper-tropospheric outflow from developing Tropical Storm Fay located over the western Gulf, precluded any redevelopment of Edouard. On 6 September, Edouard moved westward over the northeastern Gulf, and by 1200 UTC on that day, it was an insignificant low-cloud swirl with minimal deep convection. The system dissipated shortly thereafter, as it became absorbed into the larger circulation of Tropical Storm Fay.

2) METEOROLOGICAL STATISTICS

There were no reports of sustained tropical storm force winds over land associated with Edouard. On 4 September, Patrick Air Force Base reported a peak wind gust of 34 kt at 2127 UTC, and the St. Augustine Coastal Marine Automated Network (C-MAN) station reported a peak gust of 33 kt at 1900 UTC. Rainfall estimates from the Melbourne radar indicated maxima of 100 to 125 mm near the Seminole/Orange County line, just northeast of Union Park (Orange County), Florida. Storm tides and wave action were not significant, and there were no tornadoes reported.

3) Casualty and damage statistics

There were no reports of casualties due to Edouard. Some freshwater flooding occurred in Brevard, Seminole, and Orange Counties in Florida. This was mainly roadway flooding, and damage appeared to be minor.

4) Warnings

A tropical storm warning was issued early on 2 September while Edouard was moving slowly northwestward. The looping motion delayed the threat to the coastline, however, resulting in the discontinuation of tropical storm warnings later that day. A tropical storm warning was reissued for the northeast Florida coast about 16 h prior to landfall.

f. Tropical Storm Fay, 5–11 September

Tropical Storm Fay was a short-lived cyclone that made landfall along the central Texas coast, producing widespread heavy rainfall and inland flooding.

1) Synoptic history

During the first few days of September, a mid- to upper-level trough moved southward from the United States and became stationary across the northern Gulf of Mexico. Deep convection developed along a surface low pressure trough that hugged the northern Gulf of Mexico coastal areas. Gradually, the trough drifted southward over the Gulf of Mexico, where sea surface temperatures exceeded 30°C. By 4 September, a poorly defined low-level circulation had developed over the northwest Gulf of Mexico. Observations from a reconnaissance flight around 1800 UTC 5 September showed that the circulation had become sufficiently well defined to indicate the formation of a tropical depression about 85 n mi southeast of Galveston, Texas.

The depression moved steadily south-southwestward and strengthened fairly quickly. The cyclone became Tropical Storm Fay around 0000 UTC 6 September about 110 n mi southeast of Galveston. Fay moved south-southwestward for 12 h before turning toward the west, where it reached a peak intensity of 50 kt by 1200 UTC that day about 125 n mi southeast of Galveston. Shortly thereafter, Fay moved erratically in a general west-northwestward direction and maintained its 50-kt intensity for nearly 24 h until its landfall at 0900 UTC 7 September on the southern Matagorda Peninsula, about 10 n mi east of Port O'Connor, Texas. After making landfall, the broad circulation reformed farther north, about 25 n mi northwest of Palacios, Texas. Fay then turned toward the west and accelerated to about 15 kt. By 0600 UTC 8 September, Fay degenerated into a remnant low pressure system about 30 n mi southwest of Hondo, Texas. However, the rather tenacious remnant low meandered across southern Texas and northeastern Mexico for another 3 days, producing copious rainfall before finally dissipating about 65 n mi northwest of Monterrey, Mexico.

2) Meteorological statistics

Selected surface observations from land stations and data buoys are given in Table 2. Maximum storm surge values were generally around 0.6–0.9 m along the Texas coast, and 0.5–0.8 m along the Louisiana coast west of Cameron. Rainfall across the upper Texas coast and in the Houston metropolitan area ranged from 200 to 300 mm in many areas, with some estimated totals of 500–600 mm near the town of Sweeney. Rainfall across metropolitan San Antonio ranged from 100 to 200 mm with some isolated reports in excess of 280 mm. Across the remainder of south-central Texas, rainfall exceeded 200–300 mm at several locations, with a total of 439 mm reported at Fowlerton.

There were 12 confirmed tornadoes associated with Tropical Storm Fay over southeastern and south-central Texas on 6–8 September. One of these, in Fort Bend County, was of F1 intensity; all of the others were of F0 intensity.

3) Casualty and damage statistics

No deaths were reported in association with this tropical cyclone. Fay damaged more than 800 single-family homes, 100 multifamily buildings, and nearly 100 businesses in Brazoria County. Coastal floods and beach erosion caused $3.5 million in damage to public roads, bridges, and recreational areas along the upper Texas coast, especially in Galveston County. Only minor beach erosion occurred farther south. Widespread, locally severe inland freshwater flooding occurred across the upper Texas coastal area, north of where the center of Fay passed. In Galveston County, Fay impacted at least 135 residential structures, with 23 receiving damage totaling about $500,000. In Brazoria County, more than 1500 homes and nearly 500 cars were flooded. In Matagorda County, 130 single-family homes and 32 businesses were damaged by flood waters. In addition, over $1 million in damage was done to public facilities, including roads, bridges, and public buildings. In Wharton County, nearly 200 single-family homes were damaged or destroyed by flood waters.

After Fay moved inland, its remnant low generated widespread showers and thunderstorms that, in turn, produced torrential rainfall and extensive flooding across southern Texas. Some homes and businesses across the area were damaged because of the floods. Ten homes were damaged because of floods in La Coste in Medina County, while another 20 homes were damaged in Pearsall in Frio County. Widespread minor damage also occurred to roads and bridges across Bexar, Medina, Wilson, Atascosa, Frio, Comal, and Guadeloupe Counties because of the floods. However, the remnants of Fay brought much-needed rainfall to help alleviate water shortage problems in the drought-stricken regions of west-central and south Texas.

Six of the tornadoes spawned by Fay caused damage and/or injuries. Late on 6 September, a tornado destroyed a beach house in Surfside (Brazoria County), and a second tornado damaged a home in Matagorda County near Van Vleck. Shortly after midnight on 7 September a third tornado hit west Columbia, knocking down numerous trees along Highway 36, and a fourth destroyed a mobile home, damaged three other mobile homes, and tore apart a barn in Boling (Wharton County). The fifth and most significant tornado (F1 intensity) touched down early on 7 September in Fort Bend County, where it destroyed a mobile home and injured three people. This same tornado later crossed the San Bernard River into Wharton County, where it destroyed another mobile home and heavily damaged two others. A sixth tornado also caused minor damage near Hungerford in Wharton County on 7 September.

4) WARNINGS

A tropical storm warning was issued at 2100 UTC 5 September, roughly 36 h prior to landfall.

g. Hurricane Gustav, 8–12 September

Hurricane Gustav was a category 2 hurricane of subtropical origin. It struck the Outer Banks of North Carolina as a tropical storm and made landfall over the eastern end of Nova Scotia and western Newfoundland as a category 1 hurricane.

1) SYNOPTIC HISTORY

An area of showers developed between the Bahamas and Bermuda on 6 September in association with a developing upper-level trough and a weak surface trough. The upper-level trough amplified over the next 2 days as an upstream ridge was enhanced by Tropical Storm Fay over the Gulf of Mexico. As this occurred, convection increased in both coverage and intensity, and the surface trough became better defined. A broad area of surface low pressure formed from the system, a couple hundred miles northeast of the Bahamas, late on 7 September. By 1200 UTC 8 September, the cyclone had developed a well-defined surface circulation and a broad, curved band of convection around, but over 60 n mi removed from the center. Therefore, the system became a subtropical depression at that time, about 440 n mi south-southeast of Cape Hatteras. Later that day, an Air Force Reserve Hurricane Hunter aircraft investigated the cyclone and found it had become Subtropical Storm Gustav.

Gustav moved erratically west-northwestward on 9 September as it slowly strengthened. On that day, the cyclone's central region was composed of a fairly large area of light winds with multiple embedded low-level cloud swirls, and aircraft and satellite position fixes often differed by 30 to 50 n mi. Gustav turned north early on 10 September while convection became better organized near the center. Based on the change in convective organization, and the development of a band of strong winds closer to the center, it is estimated that the cyclone transformed into a tropical storm around 1200 UTC. Maximum sustained winds reached 55 kt while the center passed between Cape Hatteras and Diamond Shoals, North Carolina, about 2100 UTC that day. Although the circulation center stayed offshore, the radius of maximum winds passed over portions of the Outer Banks. Gustav turned northeastward when it reached the Cape Hatteras area, then accelerated northeastward on 11 September in southwesterly flow caused by baroclinic cyclogenesis over the New England states and southeastern Canada. When the tropical cyclone interacted with the baroclinic system, it intensified. Gustav became the 2002 season's first hurricane just before 1200 UTC 11 September and reached a maximum intensity of 85 kt near 1800 UTC that day. It weakened slightly before making landfall over the southern part of Cape Breton, Nova Scotia, near 0430 UTC 12 September as a hurricane with 80-kt winds. The cyclone was becoming extratropical when it made a second landfall over southwestern Newfoundland near 0900 UTC. Gustav lost all tropical characteristics by 1200 UTC while it moved northeastward and decelerated across Newfoundland. The remnant extratropical low moved into the Labrador Sea, where it turned northwestward late on 13 September and dissipated on 15 September.

2) METEOROLOGICAL STATISTICS

The maximum winds reported in Gustav were flight-level winds of 104 kt from both Air Force Reserve (at 850 mb) and NOAA (at 700 mb) Hurricane Hunters around 1900–2000 UTC 11 September. Using the standard flight-level-to-surface reduction for eyewall conditions (Franklin et al. 2003a), the NOAA report would yield a surface wind estimate of 90–95 kt. However, neither aircraft reported an eye or eyewall, so a more conservative reduction for convective bands would yield a surface wind estimate of 85–90 kt. This is in better agreement with the 80–85-kt estimated surface wind from the Air Force aircraft and with an 83-kt surface wind measured by the Stepped Frequency Microwave Radiometer instrument on the NOAA aircraft. The minimum aircraft-reported pressure on a formal fix was 969 mb at 1701 UTC 11 September. However, a GPS dropwindsonde released later that day near the flight-level wind maximum southeast of the center reported a surface pressure of 964 mb, indicating that, as Gustav moved rapidly northeastward, the wind center was displaced to the northwest of the pressure center.

Table 3 is a selection of surface observations in Gustav. Many ships and buoys between North Carolina and

TABLE 2. Selected surface observations for Fay, 5–11 Sep 2002.

Location	Min sea level pressure		Max surface wind speed					
	Date/time (UTC)	Pressure (mb)	Date/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Buoys								
42019 (27.9°N, 95.4°W)	07/0100	999.6	06/2000	36	45			
42035 (29.3°N, 94.4°W)	07/0000	1003.9	07/0300	33	41			
C-MAN stations								
PTAT2 (27.8°N, 97.1°W)	07/0900	1004.3	08/1000	29[e]	34			
SRST2 (29.7°N, 94.1°W)	07/0000	1006.9	07/2110	29[e]	38			
Texas								
Angleton Arpt (KLBX)	06/1811	1002.4	07/0008	28	37			112.5
Angleton Courthouse								254.0
Austin/(Georgetown Arpt)								89.7
Austin/Great Hills								129.8
Austin/Lake Georgetown								96.3
Austin/Leander 5SW								125.5
Bay City								162.3
Bay City Co-op								227.3
Berram 3N (Burnet Co.)								141.7
Boerne (Kendall Co.)								148.8
Camp Verde 2W								101.6
Canyon Lake Dam								100.1
Cheapside (Gonzales Co.)								99.8
Clute (TECQ[f] site)			06/1945	42[h]	62			
Clute (TECQ[f] site)			06/2020		72			
Derby/Frio River								220.5
Devine 6SSE								206.2
Dilley (Frio Co.)								257.3
E. Matagorda (TCOON)[g]			07/0354	30	41			
Elgin (Bastrop Co.)								110.5
Falcon Dam								109.5
Folwerton Coop (FWTT2)								439.2
Freeport Army Corps of Engineers								254.0
Freeport Dow Chemical								260.9
Freeport/Hwy 36 Bridge			06/1943	41[h]				327.9
Freeport RTNS[i] (TCOON)[g]			07/0354	50				
Freeport RTNS[i] (TCOON)[g]			07/0512	45	65			
Galveston Arpt (KGLS)	06/1307	1004.4	06/1923	33	40			103.9
Galveston Causeway/I-45			06/2009	32[h]	49			126.0
Goliad 1SE Coop (GLIT2)								229.4
Harlingen								83.3
Houston IAP (KIAH)	06/2314	1006.4	06/2221	23	26			85.6

TABLE 2. (*Continued*)

Location	Min sea level pressure		Max surface wind speed					
	Date/time (UTC)	Pressure (mb)	Date/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Karnes City 2N								175.8
Kelly AFB (KSKF)								275.8
La Grange/Colorado River								98.3
Lane City								210.8
Laredo Arpt (KLRD)								96.5
Luling 12NE								87.9
Jamaica Beach Coop	06/1345	1004.4	06/2037	33	44			146.3
McAllen								83.3
Mercedes								98.0
New Braunfels 3ENE								81.8
Galveston North Jetty (TCOON)[g]	07/0600	1004.0	07/0600		41			
Galveston South Jetty (TCOON)[g]	07/0000	1003.4	06/1718	34				
Galveston North Jetty (TCOON)[g]			06/2245		44			
Palacios Arpt (KPSX)	06/1959	999.7	06/1959	38	50			
Pearsall 9E (Frio Co.)								304.8
Pearsall (Frio Co.)								252.0
Galveston Pleasure Pier (NOS)[j]	07/0100	1003.5	06/2248	39	45			
Port Aransas						0.61		
Port O'Connor (TCOON)[g]			07/0200		35			
Raymondville								153.2
Refugio 2NW (GOIT2)								185.4
Refugio 3SW (REFT2)								157.5
Rio Grande City								153.2
Round Rock								95.8
Sabinal (Uvalde Co.)								172.5
San Antonio Arpt (KSAT)								112.8
San Antonio/Five Palms								281.7
San Antonio/Loop 410								169.4
San Antonio/New Dawn								299.7
San Saba								89.2
Seguin 8S								165.9
Taylor Ranch/San Saba								83.8
Tow 10ESE (Llano Co.)								158.2
Yorktown								98.8
West Galveston Bay (TCOON)[f]	07/0700	1001.3	07/0518	42	55			
Zapata								102.4

[a] Date/time is for sustained wind when both sustained and gust are listed.
[b] Except as noted, sustained wind averaging periods for C-MAN and land-based ASOS reports are 2 min; buoy averaging periods are 8 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above National Geodetic Vertical Datum (1929 mean sea level).
[e] 10-min average.
[f] Texas Commission on Environmental Quality
[g] Texas Coastal Oceanic Observing Network, Texas A&M University, Corpus Christi, TX.
[h] 5-min average.
[i] Real-Time Navigation System.
[j] National Ocean Service.

TABLE 3. Selected surface observations for Gustav, 8–12 Sep 2002.

Location	Min sea level pressure		Max surface wind speed			Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
	Date/time (UTC)	Pressure (mb)	Date/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)			
North Carolina								
Alligator River Bridge			10/2100		56			
Beaufort (KMRH)[f]	10/1900	999.7	10/2033	32	39			49.5
Cape Hatteras Coast Guard			10/2130		68			
Cape Hatteras Fishing Pier	10/2112	985.3	10/2112	37	55			
Cedar Island			10/2130		48			
Duck (NOS)	10/2324	995.0	10/2248	44	55			
Elizabeth City (KECG)	10/2145	999.0	10/2054	26	38			15.5
Frisco (KSHE)	10/1700	987.5	11/0100	25	36			119.9
Manteo (KMQI)[f]	10/2100	993.5	10/2300	35	47			57.7
Nags Head			10/2000		53			
Ocracoke			10/2030		64			124.5
Nova Scotia								
Ashdale								104.9
Hallifax								94.0
Hart Island (CWRN)	12/0345	961.4						
Liverpool								102.1
Lyon's Brook								108.0
Middleboro								100.1
Sable Island (CWSA)[f]	12/0300	969.2	12/0414	48	66			
St. Paul's Island (CWEF)[f]	12/0500	961.6	12/0742		66			
Prince Edward Island								
Charlottetown			12/0245	35	52	1.2–1.5		70.1
Buoys and C-MAN								
Buoy 41001	11/0600	997.5	11/0310	36[e]	46			
Buoy 41002	10/0500	996.7	10/1500	29	35			
Buoy 44004	11/1300	977.5	10/1420	44[e]	62			
Buoy 44008	11/1700	983.1	11/1600	29	35			
Buoy 44011	11/1900	972.4	11/2000	44	61			
Buoy 44014	11/0400	991.3	11/0500	35	44			
Buoy 44137	12/0000	983.6	12/0500	47				
Buoy 44139	12/0500	982.8	12/0600	41				
Buoy 44142	11/2300	964.3	12/0000	44	60			
Buoy 44145[f]	12/0900	994.8	13/0000	52				
Buoy 44251	12/1000	984.7	13/0000	37				
Buoy 44255	12/0800	968.1	13/0700	37				
Cape Lookout (CKLN7)	10/1700	996.9	10/2010	31[e]	40			
Diamond Shoals (DSLN7)	10/2000	984.8	10/1400	52	61			
Duck (DUCN7)	11/0000	997.7	10/2250	46[e]	57			
Frying Pan Shoals (FPSN7)	10/1000	1002.1	10/0100	44	52			

[a] Date/time is for sustained wind when both sustained and gust are listed.
[b] Except as noted, sustained wind averaging periods for C-MAN and land-based ASOS reports are 2 min; buoy averaging periods are 8 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above National Geodetic Vertical Datum (1929 mean sea level).
[e] 10-min average.
[f] Incomplete record.

Nova Scotia were affected by this cyclone. The most notable observations were from the ship *Tellus,* which reported 88- and 90-kt winds at 1500 and 1600 UTC 11 September, respectively. While these winds are consistent with the estimated strength of Gustav at the time, the ship was far enough from the center that the speeds appear somewhat suspect. The oil rig WCY533 near Sable Island, Nova Scotia, reported 74-kt winds and a 965.0-mb pressure at 0300 UTC 12 September. Other noteworthy ship and buoy reports include a 55-kt wind reported by the *Columbus Canterbury* near the North Carolina coast at 1900 UTC 10 September and a 964.3-mb pressure from Canadian buoy 44142 at 2300 UTC 11 September.

Gustav brought tropical storm force winds to portions of the North Carolina coast and eastern Nova Scotia. In North Carolina, the C-MAN station at Diamond Shoals reported 52-kt sustained winds with a gust to 61 kt at 1400 UTC 10 September and a 984.8-mb pressure at 2000 UTC. The Cape Hatteras Coast Guard station reported a gust of 68 kt at 2130 UTC. In Nova Scotia, Sable Island reported 48-kt sustained winds with a gust to 66 kt at 0414 UTC 12 September, while Hart Island reported a pressure of 961.4 mb at 0345 UTC. Tropical storm–force winds were also reported on Prince Edward Island as the wind field of Gustav expanded during extratropical transition.

Storm surge flooding of 1.5 to 1.8 m above normal tide levels occurred along the inland side of the Outer Banks in Hyde and Dare Counties, North Carolina. This occurred during a period of strong northwesterly winds following the passage of the center of Gustav. Storm tides of 0.9–1.2 m above normal were reported in Cedar Island and along the Neuse River. Tides were 0.3–0.6 m above normal elsewhere along the coasts of North Carolina and southeastern Virginia. A 1.2–1.5-m storm surge occurred at Charlottetown, Prince Edward Island. Above-normal tides were also reported along the coasts of northern and eastern Nova Scotia and eastern New Brunswick.

Storm total rainfalls were 50–125 mm over portions of the Outer Banks, Nova Scotia, and Prince Edward Island. This included a 124-mm total at Ocracoke, North Carolina, and a 108-mm total at Lyon's Brook, Nova Scotia. One tornado occurred during Gustav near Ocracoke. It was a waterspout that moved onshore.

3) Casualty and damage statistics

Gustav directly caused one death; a swimmer at Myrtle Beach, South Carolina, suffered injuries from high surf and died 2 days later. Forty people had to be rescued from storm surge in the Cape Hatteras area during the height of the storm. Damage from Gustav was minor. Damage to property and vehicles in North Carolina is estimated at about $100,000. In Canada, the worst damage occurred on Prince Edward Island, where trees were toppled and local flooding occurred. In Nova Scotia, some docks were damaged and trees blown down.

4) Warnings

A tropical storm watch was issued for portions of the North Carolina coast at 2100 UTC 8 September, while a tropical storm warning was issued for much of the watch area at 0300 UTC 9 September, 48 and 42 h, respectively, before the closest approach of the center to the Cape Hatteras area. The Canadian Hurricane Center in Halifax, Nova Scotia, issued warnings for wind, rain, and storm surge for large portions of New Brunswick, Nova Scotia, Newfoundland, and Prince Edward Island.

h. Tropical Storm Hanna, 12–15 September

Hanna was a poorly organized tropical storm that nevertheless produced rip currents responsible for three deaths off the beaches of the Florida panhandle.

1) Synoptic history

Hanna formed in the Gulf of Mexico from a complex interaction of a tropical wave, an upper-level low, and a surface trough. In the days preceding genesis, a broad surface trough in the wake of Hurricane Gustav stretched from the western Atlantic across South Florida and into the central Gulf of Mexico. During this time a westward-moving tropical wave approached the Yucatan Peninsula, and, when the wave reached the Gulf of Mexico on 10 September, a weak 1008-mb low formed on the western end of the surface trough. Initially, there was minimal convection associated with the combination of these two features; however, on 11 September an upper-level short-wave trough over the southern United States cut off over the central Gulf of Mexico, and convection began to develop to the east of both the upper-level low and the tropical wave/surface low. The convection became sufficiently organized for the system to warrant a Dvorak (1984) satellite classification at 1800 UTC that day, and over the next 6 h convection developed closer to the surface low. Shortly before 0000 UTC 12 September, a reconnaissance aircraft found a well-defined low-level circulation center, and with that the ninth depression of the season had formed about 250 n mi south of Pensacola, Florida.

The cyclone initially had some nontropical characteristics, including a westward tilt with height associated with the upper low. Despite strong southwesterly shear and a poorly organized convective structure, the depression became a tropical storm at 0600 UTC 12 September, about 225 n mi south of Pensacola. For the first 24 h after genesis, the low-level circulation center rotated counterclockwise around the middle- and upper-level centers, first moving northeastward, but turning to the southwest by late on 12 September. Moving slowly the following day, Hanna turned to the west and then to the north ahead of an approaching midlevel trough. Hanna strengthened and reached its peak intensity of 50 kt with a central pressure of 1001 mb at 0000 UTC 14 September, about 60 n mi south of the mouth of the Mississippi River. In response to the approaching trough, Hanna accelerated northward early on 14 September, and its exposed low-level circulation center began to become deformed and elongated. With nearly all the significant weather well to its east, Hanna's center of circulation passed over the extreme southeastern tip of Louisiana near 0800 UTC. Hanna then turned to the north-northeast and made its second landfall near the Alabama–Mississippi border near 1500 UTC. Maximum winds at both landfalls were near 50 kt. Hanna moved northeastward across southern Alabama and weakened rapidly, dissipating by 1800 UTC 15 September. The remnants of the tropical cyclone then produced heavy rains as they moved rapidly across Georgia and the Carolinas.

2) Meteorological statistics

Selected surface observations from land stations and data buoys are given in Table 4. At 0600 UTC 12 September, buoy 42003 (at 25.9°N, 86.0°W, about 50 n mi south-southeast of the center) reported an 8-min mean wind of 32 kt. This observation is the basis for the assignment of tropical storm status at this time. Hanna's peak intensity is estimated to be 50 kt, based on surface-adjusted flight-level winds of 46 kt at 2346 UTC 13 September and 47 kt at 1303 UTC 14 September, as well as a 47-kt 2-min wind from the Pensacola Automated Surface Observing System (ASOS) station at 1352 UTC 14 September. A wind gust to 59 kt was reported at Pensacola Beach. The only ship to report tropical storm force winds was the *Nobel Star*, which reported winds of 37 kt and a pressure of 1006.0 mb at 0300 UTC 13 September, when it was about 45 n mi west-southwest of the center. A weak tornado that blew down some trees was reported in south Mobile County, Alabama. Gulfport Harbor reported a storm tide of 1.55 m, and there were other reports in the 0.9–1.5-m range (Table 4). Minor river flooding occurred along Spring Creek near Iron City, Georgia, where the river crested at 4.66 m, 0.4 m above flood stage.

Hanna and its remnants produced heavy rains across much of the southeastern states. These rains were largely confined to the eastern semicircle of the storm, with numerous reports of storm-total accumulations of between 125 and 250 mm. The highest reported storm total, 395 mm, was from Donalsonville, Georgia.

Hanna produced an F0 intensity tornado near Theodore (Mobile County), Alabama, on 14 September. Hanna's remnants produced an F0 tornado in Burke County, Georgia, on 15 September.

3) Casualty and damage statistics

Three deaths are attributed to rip currents generated by Hanna. A man drowned in rough surf near Pensacola Beach on the afternoon of 14 September. Two other men drowned, one at Seagrove Beach (Walton County) on 14 September, and another at Panama City Beach on 15 September.

Minor beach erosion was reported from Dauphin Island, Alabama, to Navarre Beach, Florida, as well as in the Florida counties of Walton, Bay, and Gulf. Some storm tide flooding was reported on Dauphin Island and in Mobile County. Roughly 250 homes and 50 businesses were damaged from freshwater flooding in Donalsonville, Georgia. Data from the Georgia Farm Services Agency indicate that agricultural damage, primarily to the cotton and peanut crops, amounted to nearly $19 million. There were several other apparently minor flooding events. Well after Hanna had made landfall and weakened to a tropical depression, there was a report of a roof being blown off a house in Donalsonville. Total damage is estimated at $20 million.

4) Warnings

A tropical storm watch was issued at 1500 UTC 12 September, 41 h prior to the first landfall of Hanna in extreme southeastern Louisiana. A tropical storm warning was issued at 0900 UTC 13 September, 23 h prior to landfall. Tropical storm conditions were confined to the area under warning.

i. Hurricane Isidore, 14–27 September

Hurricane Isidore was a slow-moving tropical cyclone that hit western Cuba as a category 1 hurricane and the northern Yucatan Peninsula as a category 3 hurricane. It made landfall on the Louisiana coast as a strong tropical storm.

1) Synoptic history

A tropical wave moved off the coast of Africa on 9 September accompanied by a large area of thunderstorms. The convective activity decreased significantly while the system moved toward the west-southwest during the following few days, but the wave maintained a good low-cloud signature with cyclonic rotation. When the wave approached 50°W, the shower activity began to increase, and an upper-level anticyclone became evident over the system. By 1800 UTC 14 September, as the wave approached Trinidad and the northern coast of Venezuela, there was enough convection and rotation to classify the system as a tropical depression. The depression moved west-northwestward, and development was halted by its interaction with land. By 1800 UTC 15 September, the system had degenerated into a tropical wave in the eastern Caribbean Sea. However, as the

TABLE 4. Selected surface observations for Tropical Storm Hanna, 12–15 Sep 2002.

Location	Min sea level pressure		Max surface wind speed			Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
	Date/time (UTC)	Pressure (mb)	Date/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)			
Buoys								
42003			13/0750	37				
42007	14/1300	1003.5	14/1010	35	43			
42039			13/1700		34			
42040	14/0900	1005.0	14/0720	33	41			
CMAN stations								
Dauphin Island (DPIA1)	14/1400	1005	14/1230	41[e]	50		1.13	
Cape San Blas (CSBF1)	12/2300	1010.0	14/2040	33[e]	43			
Alabama								
Belle Fontaine								146.1
Coden (Co-op)								191.8
Fairhope								53.9
Florida								
Chipley (Co-op)								245.6
Crestview (Walker Elementary)								128.0
Destin (DTS)								118.1
Destin Middle School								137.4
Eglin AFB (VPS)			14/1857	32	41			70.4
Eglin A-5 (Santa Rosa Island)	14/2038	1009.5	14/1556	35	48			87.6
Hurlburt Field (HRT)			14/1655	37	54			96.0
Mariana								182.9
Milligan								104.4
Niceville (Co-op)								93.0
Pensacola (PNS)	14/1353	1007	14/1352	47	57		1.04	77.5
Pensacola Beach			14/1430	43	59			
Pensacola NAS (NPA)			14/1437	41	48			
Tallahassee								160.5
Walton County							1.22	
Georgia								
Blakely								194.3
Donalsonville Co-op)								395.2
Leesburg (Co-op)								129.8
Newton (Co-op)								177.8
Louisiana								
Bayou Dupre							1.31	
Industrial Canal							1.11	
Mississippi								
Gulfport Harbor							1.55	
Pascagoula (PQL)	14/1354	1005.8						
Waveland							1.46	

[a] Date/time is for sustained wind when both sustained and gust are listed.
[b] Except as noted, sustained wind averaging periods for C-MAN and land-based ASOS reports are 2 min; buoy averaging periods are 8 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above National Geodetic Vertical Datum (1929 mean sea level).
[e] 10-min average.

wave entered the western Caribbean Sea, it redeveloped a closed circulation by 1200 UTC 17 September and regained tropical depression status about 120 n mi south of Kingston, Jamaica.

The depression became Tropical Storm Isidore around 0600 UTC 18 September. Steering currents became weak, and the tropical cyclone moved very slowly toward the northwest, passing just west of Jamaica. Isidore then moved very slowly toward the west-northwest and, shortly after crossing the Cayman Islands, it became a hurricane. The hurricane's winds reached 90 kt around 0600 UTC 20 September as it neared the southwestern coast of the Isle of Youth, Cuba. Although the minimum pressure continued to fall, Isidore's winds decreased somewhat just prior to landfall near Cabo Frances in western Cuba at 2100 UTC 20 September with maximum winds of 75 kt. For more than 12 h, Isidore relentlessly pounded western Cuba. Then the hurricane moved westward and southwestward toward the Yucatan Peninsula and restrengthened. Isidore reached its maximum intensity of 110 kt by 1800 UTC 21 September and maintained this intensity until landfall near Puerto Telchac on the north coast of the Yucatan, Mexico, the following day.

Isidore meandered for 24–36 h over northern Yucatan and weakened to a minimal tropical storm. It then moved northward over the Gulf of Mexico where the circulation expanded, but the cyclone never redeveloped an inner core of strong winds. Isidore made landfall with winds of 55 kt and a minimum pressure of 984 mb just west of Grand Isle, Louisiana, at 0600 UTC 26 September. Once it moved inland, Isidore weakened to a tropical depression and produced torrential rains while moving north-northeastward across the southeastern United States. It became an extratropical storm over southwestern Pennsylvania around 1800 UTC 27 September and was then absorbed into a frontal zone.

2) Meteorological statistics

Isidore's estimated peak intensity of 110 kt represents a compromise between reconnaissance winds adjusted to the surface and satellite estimates. It is interesting to note that this hurricane's minimum central pressure, 934 mb, typically would correspond to a higher maximum wind speed. This illustrates the limitations of using pressure as an indicator of tropical cyclone intensity.

Isidore moved very close to Cayman Brac, which reported sustained winds of 42 kt with gusts to 61 kt at 0325 UTC 19 September. During the time Isidore was near the Isle of Youth, the eye contracted to 8 n mi, and based on data from a GPS dropwindsonde in the eyewall, surface winds were near 90 kt. Surface observations, along with aircraft and dropwindsonde data, suggest that Isidore's intensity was 75 kt when it crossed western Cuba. The minimum pressure measured in Cuba was 970 mb at Isabel Rubio, and that station experienced wind gusts to 74 kt. Several locations in the area reported the calm of the eye. There was a significant storm surge along the south coast of Cuba in Playa Cajio, south of Habana and in Ensenada de Cortes, Pinar del Rio. When Isidore was already in the Gulf of Mexico, rainbands over Cuba produced a wind gust of 86 kt in association with an isolated tornado in the town of Candelaria at 1600 UTC 23 September.

The maximum winds reported in Yucatan were gusts to 70 kt at Merida around 2350 UTC 22 September as the western eyewall moved through the area. That station reported a minimum pressure of 969.9 mb at 0000 UTC 23 September. Figures 4 and 5 are satellite and radar images, respectively, of Hurricane Isidore making landfall on the northern coast of the Yucatan Peninsula.

Later, when Isidore was heading for Louisiana, the storm's winds reached an estimated 55 kt based on data from the ship *Deepwater Pathfinder*, which reported sustained winds of 56 kt with gusts to 71 kt and 6-m waves at 1743 UTC 27 September. The Belle Chase Naval Air Station in Louisiana experienced northeast winds of 50 kt with gusts to 60 kt at 0155 UTC 26 September. This is the highest wind reported by any land station as Isidore made landfall on the Louisiana coast. The highest observed storm surge along the U.S. coast was 2.5 m at Rigoletes, Louisiana, and at Gulfport Harbor, Mississippi. Highest rainfall totals ranged from near 200 mm in the greater New Orleans area to over 300 mm at Semmes (near Mobile), Alabama. There were nine tornadoes reported in the United States: three occurred in extreme southern Alabama on 25–26 September, all of F0 intensity, and six were observed in the Florida panhandle on 25 September, two of F1 intensity and four of F0 intensity. Selected surface observations in Isidore from land stations and data buoys are given in Table 5.

3) Casualty and damage statistics

Press reports indicate that there were two deaths attributable indirectly to Isidore in Merida, Mexico. One was an electrocution by a downed power line, and the other was in a weather-related car crash. Five direct deaths occurred in the United States. On 22 September, a man drowned in a rip current near Port Fourchon, Louisiana, and another drowned in the surf at Manatee County Beach, Florida; both of these deaths occurred while Isidore was near the north coast of the Yucatan Peninsula. A man drowned in a vehicle parked near a casino in Mississippi when the storm surge inundated the parking lot. Another man died when a tree fell across his car in eastern Mississippi, and a man drowned after driving his vehicle into 3 m of water in Clarksville, Tennessee. An indirect death occurred in Mississippi when a man suffering from cardiac arrest could not be reached by rescuers because of flood waters.

Damage from Isidore in Jamaica was mainly related to torrential rains. In western Cuba and the Yucatan Peninsula, there was severe damage, primarily to the

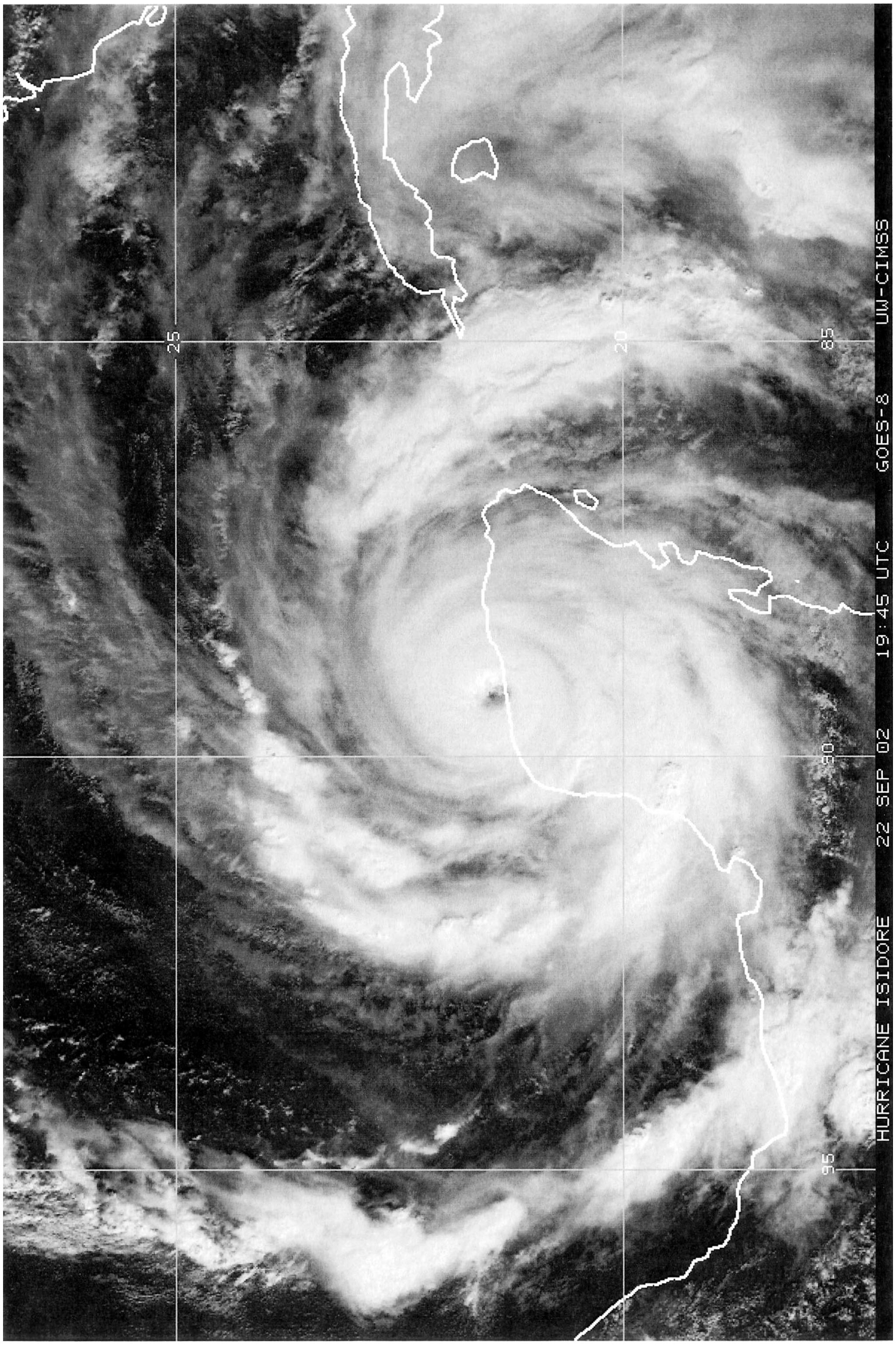


FIG. 4. Visible satellite image of Hurricane Isidore at 1945 UTC 22 Sep 2002.

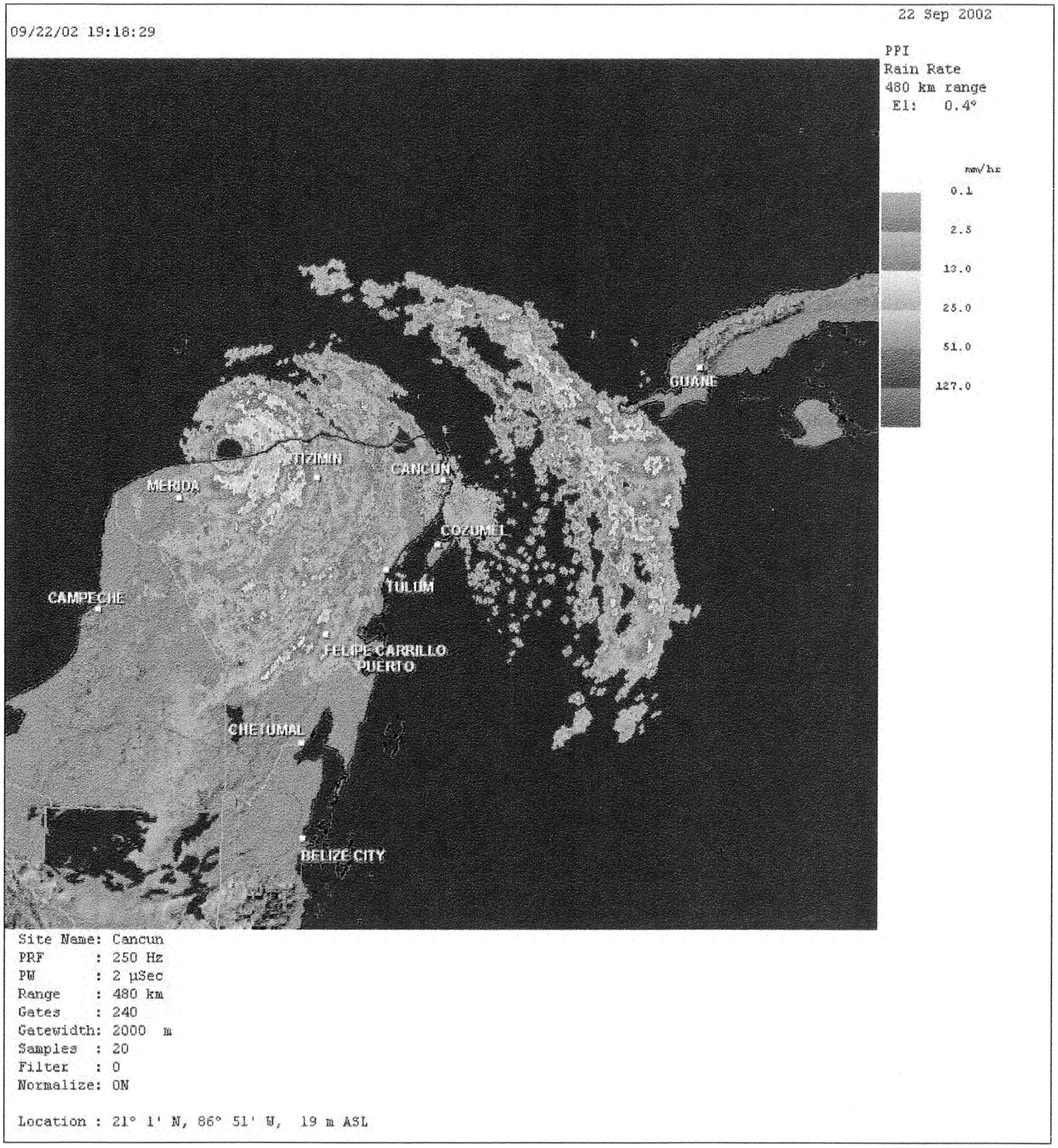


FIG. 5. Image of Hurricane Isidore from Cancun, Mexico, radar at 1918 UTC 22 Sep 2002.

agriculture and cattle industries. According to the weather services of Cuba and Mexico, numerous houses and power lines were damaged by wind. In the United States, the American Insurance Services Group reported that insured losses due to Isidore totaled $165 million. Using a two-to-one ratio of overall to insured damage gives a total damage estimate of $330 million. Most of the damage occurred in Louisiana.

4) WARNINGS

Since Isidore threatened to affect several land areas, a large number of watches and warnings were issued by the NHC or coordinated with various Caribbean countries. A hurricane warning was issued for western Cuba about 45 h prior to landfall. A hurricane warning was issued for the northern coast of the Yucatan Peninsula about 36 h prior to landfall. Along the northern Gulf of Mexico coast, a tropical storm warning was issued about 39 h prior to landfall.

j. Tropical Storm Josephine, 17–19 September

Josephine was of nontropical origin, forming from a weak low pressure system along a dissipating, nearly stationary frontal zone about 750 n mi east of Bermuda on 16 September. Over the next day as the low moved slowly westward, a small area of deep convection formed near the low-level circulation center. Thus, the system's cloud pattern changed from one that resembled a nontropical cyclone to that of a tropical cyclone. It is estimated that the system became a tropical depression around 1200 UTC 17 September while centered about 620 n mi east of Bermuda. The tropical cyclone moved slowly north-northwestward to northward for about 24 h. Deep convection associated with the system was intermittent, and at times the low-level center became exposed. However, the cyclone strengthened slightly and is estimated to have reached tropical storm intensity by 0600 UTC 18 September, based on a report of 37-kt winds from the ship *Cool Express* as well as QuikSCAT and Special Sensor Microwave Imager (SSM/I) winds near 35 kt around that time. Josephine then accelerated northeastward in the flow ahead of a deep-layer midlatitude trough. The system lost its tropical characteristics around 1200 UTC 19 September, at which time a report from the ship *Albatros* indicated that the cyclone had strengthened. That vessel reported winds near 50 kt about 75 n mi southeast of the center. Soon thereafter, the storm merged with a larger extratropical low and frontal system.

There were no reports of damage or casualties associated with Josephine.

k. Hurricane Kyle, 20 September–12 October

Hurricane Kyle lasted for 22 days, making it the third longest-lived tropical cyclone in the Atlantic basin, surpassed for longevity only by Ginger of 1971 and Inga of 1969. It was a category 1 hurricane for a few days and eventually made landfall along the southeastern United States coast as a weak tropical storm before moving back out to sea.

1) SYNOPTIC HISTORY

Kyle formed from a nontropical low pressure system in the central North Atlantic Ocean. A cold front moved across Bermuda on 13 September and stalled to the southeast of the island by 15 September. The stationary front gradually weakened and became an elongated area of low pressure by 18 September. A sharp midlevel short-wave trough moved off the southeast coast of the United States and likely acted to trigger development of a stationary surface low pressure center by 1200 UTC 19 September about 750 n mi east-southeast of Bermuda. Thunderstorms gradually developed into narrow bands a few hundred miles away from the well-defined low-level circulation center. Surface winds gradually increased to 25 kt early on 20 September, and the overall satellite cloud pattern became much better organized. By 1800 UTC that day, it is estimated that a subtropical depression developed from the system, centered about 715 n mi east-southeast of Bermuda. Later that day, the depression made a clockwise loop. The cyclone strengthened into Subtropical Storm Kyle at 0600 UTC 21 September, while centered about 680 n mi east of Bermuda. Deep convection developed near the center, and Kyle gradually acquired warm-core tropical characteristics. It is estimated that Kyle became a tropical storm at 1800 UTC 22 September about 760 n mi east of Bermuda. Embedded in weak steering currents, Kyle drifted erratically toward the southwest for about a week and steadily intensified. The cyclone became a hurricane at 1200 UTC 25 September about 550 n mi east-southeast of Bermuda. A peak intensity of 75 kt is estimated to have occurred at 1200 UTC 26 September about 425 n mi east-southeast of Bermuda. Kyle maintained this intensity for the next 24 h before gradually weakening under the influence of moderate northwesterly to northerly vertical shear.

After Kyle weakened below tropical storm strength at 1800 UTC 30 September, the cyclone made a slow counterclockwise loop about 300 n mi west of Bermuda from 5 to 8 October. Afterward, Kyle moved westward and then northwestward before making landfall along the South Carolina coast late on 11 October. During this period, fluctuations in intensity occurred and Kyle strengthened back into a tropical storm on 1, 6, and 11 October.

After making its first landfall near McClellanville, South Carolina, at around 1700 UTC 11 October, Tropical Storm Kyle moved northeastward and skirted the remaining upper coastline of South Carolina. Its center moved inland again a few hours later near Long Beach, North Carolina, around 2200 UTC. Kyle weakened to a tropical depression by 0000 UTC 12 October near Surf City, North Carolina, and then strengthened back into a tropical storm over Pamlico Sound 6 h later. It exited the eastern portion of the state near Nags Head at around 0800 UTC. A little later that day, the cyclone merged with a cold front when it was located about 280 n mi south-southwest of Nantucket, Massachusetts.

2) METEOROLOGICAL STATISTICS

Selected surface observations from land stations and data buoys are given in Table 6. The estimate of 35-kt winds at landfalls along the South Carolina and North Carolina coasts were based on reconnaissance flight-level data and offshore buoy reports of 10-min average wind speeds of 35 kt with gusts to 40 kt. However, tropical storm–force winds were confined to offshore

TABLE 5. Selected surface observations for Isidore, 14–27 Sep 2002.

Location	Min sea level pressure		Max surface wind speed			Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
	Date/time (UTC)	Pressure (mb)	Date/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)			
Buoys								
42002			25/2000	34	42			
42003	25/2100	1000.2	26/0000	38	48			
42039	26/0800	998.0	26/0800	38	45			
42040	26/0900	989.5	26/0030	39[e]	51			
42041	26/0500	988.6	26/0700	34	40			
42007	26/1200	987.1	26/0310	46[e]	58			
C-MAN stations								
CSBF1	26/1300	1001.1	26/0800	40	50			
BURL1	26/0900	984.7	25/2300	46	59			
DPIA1	26/0900	989.5	26/1000	42	52			
GDIL1	26/0900	986.6	26/0440	37[e]	62			
United States								
Alabama								
Dauphin Island	26/1300	989.5						
Mobile State Docks							1.80	
Middle Bay Light House							1.86	
Brookley Field	26/1343	992.0	26/1129	40	50			
Bay Minette								279.4
Mobile	26/1410	991.0	26/1226	42	50			221.0
Semmes	26/1345	991.0						302.3
Louisiana								
Belle Chasse Naval Air	26/1053	985.1	26/0155	50	60	2.28		
New Orleans	26/1207	985.1	26/0525	35	42			
New Orleans Int. Arpt	26/1147	985.8	26/0757	40	47			190.5
Bootheville	26/0953	985.8	26/0440		37			134.6
East Lake Pontchartrain			26/0510		36			
Slidell	26/1226	985.1						111.8
Rigoletes						2.53		
Sea Rim State Park			25/2144		35			
Mississippi								
Gulfport	26/1359	987.1	26/0725		43	2.52		139.7
Pascagoula	26/1316	989.9	26/1310		35			121.9
Kessler	26/1200	987.1	26/0155		41			
Point Cadet								

TABLE 5. (*Continued*)

Location	Min sea level pressure		Max surface wind speed					
	Date/time (UTC)	Pressure (mb)	Date/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)	Storm surge (m)[c]	Storm tide (m)[d]	Total rain (mm)
Florida								
Pensacola	26/1153	995.0	26/0258		44		1.59	231.1
Pensacola Naval Air (NPA)			26/1256		43			170.2
Destin			26/1221	35	45			154.9
Eglin Air Force (VPS)			26/1340		46			
Hurlburt Field (HRT)			26/0839		49			
Pensacola Beach			26/0130		55			
Perdido Key			26/0330		47			
Pensacola Escambia			26/0830		49			
Fort Walton Beach			26/0807		44			
Apalachicola (ASOS)			26/1258		38			
Panama City (ASOS)			26/0653		35			
Jamaica								
Kingston	18/0900	1007.5	18/1045		41			
Cotton Tree Gully								690.9
Mount Nelson								480.1
Cedar Valley								480.1
Cayman Islands								
Cayman Brac	19/0325	1001.0	19/0325	42	61			
Cuba								
Isla de la Juventud								
78324 Punta del Este	20/1000	1000.6	20/1310	71			624.8	
78321 La Fe	20/1500	999.9	20/1045	54	72			497.8
78309 Cuba-Francia	20/1100	999.5	20/1235	43	71			353.1
78221 Nueva Gerona	20/1100	1004.2	20/1200	45	67			454.7
Pinar del Rio								
78310 Cabo San Antonio	21/0600	991.4		37	57			370.8
78315 Pinar del Rio	21/2100	990.9	20/2150	63			353.1	
78317 Paso Real	21/2220	995.7	21/1745	50			355.6	
78313 Isabel Rubio	21/2140	970.0	22/0030		74		553.6	
78312 Santa Lucia	21/0000	992.6						160.0
78316 La Palma	21/0000	993.6	22/0130		53			
78318 Bahia Honda	21/0000	1001.9	22/1540				152.4	
78314 San Juan	21/2140	990.4	21/0045	37	58			447.0
78311 La Bajada								566.4
Mexico								
Yucatan								
Merida	23/0000	969.9	22/2350	70				147.3

[a] Date/time is for sustained wind when both sustained and gust are listed.
[b] Except as noted, sustained wind averaging periods for C-MAN and land-based ASOS reports are 2 min; buoy averaging periods are 8 min. Non-U.S. wind reports are 10 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above National Geodetic Vertical Datum (1929 mean sea level).
[e] 10-min average.

TABLE 6. Selected surface observations for Kyle, 20 Sep–12 Oct 2002.

Location	Min sea level pressure		Max surface wind speed			Storm surge	Storm tide	Total rain
	Date/time (UTC)	Pressure (mb)	Date/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)	(m)[c]	(m)[d]	(mm)
Buoys								
41004 (32.5°N, 79.1°W)			11/1400		34			
41536 (21.8°N, 67.7°W)	29/0600	1014.5	29/0600	51				
41652 (28.7°N, 65.8°W)	30/0320	1007.7	30/0320	45				
C-MAN stations								
FBIS1 (32.7°N, 79.9°W)			11/0307		34			
FPSN7 (33.5°N, 77.6°W)	11/2100	1012.0	11/2100	35[e]	40			
DSLN7 (35.2°N, 75.3°W)			11/2210	41[e]	51			
ALSN6 (40.5°N, 73.8°W)			12/1300	36				
Georgia								
Hunter Field (KSVN)								135.8
Savannah (RAWS)								83.8
North Carolina								
Bald Head Island			11/2130		43	0.15		
Carolina Beach			11/2145		42	0.15		
Greenville (PGVN7)								142.2
Holden Beach			11/2100		37	0.15		
Oak Island			11/2100		38			
Williamson								134.6
Williamson 2E								120.1
South Carolina								
Charleston (KCHS)	11/1540	1011.1	11/1434	20	25			124.7
Charleston City Office			11/1400		34			41.9
Edisto Beach								161.2
Georgetown Coast Guard	11/1800	1009.1	11/1720		43			46.2
Walterboro								76.20
Witherbee (RAWS)								148.5

[a] Date/time is for sustained wind when both sustained and gust are listed.
[b] Except as noted, sustained wind averaging periods for C-MAN and land-based ASOS reports are 2 min; buoy averaging periods are 8 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above National Geodetic Vertical Datum (1929 mean sea level).
[e] 10-min average.

waters in the eastern semicircle, and there were no reports of sustained tropical storm–force winds along or inland of the United States coast. Storm surge values were generally around 0.3 m from Florida to North Carolina, with a few isolated occurrences of near 0.6 m at Fort Pulaski, Georgia, and at Charleston Harbor, South Carolina. Rainfall totals were generally less than 50 mm, with a few isolated amounts of 125–150 mm reported. At least four tornadoes were reported across eastern South Carolina and southeastern North Carolina during Kyle's passage. Two of these, in Georgetown, South Carolina, and Beaufort County, North Carolina, were estimated to be of F2 intensity. The other two tornadoes appeared to be of F0 intensity.

3) CASUALTY AND DAMAGE STATISTICS

Kyle caused no significant structural damage, and only minor beach erosion was reported along the North Carolina and South Carolina coastlines. Minor urban flooding occurred. The Georgetown, South Carolina, tornado destroyed five manufactured homes, two houses, and a car. Twenty-eight additional structures sustained major damage. Eight people sustained minor injuries. In North Carolina, a damaging F1–F2 tornado touched down near Pantego, in Beaufort County. The tornado flipped one mobile home, blew the roof off of a house, and destroyed seven hog houses. No injuries were reported with any of the North Carolina tornadoes.

Insured losses associated with Kyle were reported to be approximately $2.5 million: the total damage is estimated at $5.0 million. No deaths were reported in association with Kyle.

4) WARNINGS

A tropical storm warning was issued about 14 h prior to Kyle's first landfall on the South Carolina coast, and about 19 h prior to the second landfall on the North Carolina coast.

l. Hurricane Lili, 21 September–4 October

Hurricane Lili crossed western Cuba as a category 2 hurricane and made landfall on the Louisiana coast as a category 1 hurricane. Lili also affected the Windward Islands as a tropical storm, the northeastern Cayman Islands as a category 1 hurricane, and caused serious flooding in Jamaica. Nine deaths are attributed to Lili. Lili reached category 4 intensity over the Gulf of Mexico.

1) SYNOPTIC HISTORY

Lili originated from a tropical wave that moved over the tropical Atlantic Ocean from the west coast of Africa on 16 September. On 20 September, the wave developed a low-level cloud circulation center midway between Africa and the Lesser Antilles. Convective clouds became sufficiently well organized on 21 September to qualify the system as a tropical depression, while centered about 900 n mi east of the Windward Islands.

The tropical cyclone moved just north of due westward at over 20 kt, crossing the Windward Islands as a developing tropical storm on 23 September. Lili's winds briefly reached 60 kt the next day, but the storm degenerated to an open wave on 25–26 September in the east-central Caribbean Sea as its organization was disrupted by vertical wind shear. Lili redeveloped a low-level closed circulation on 27 September. A day later, its forward speed decreased to about 5 kt, and the system began a slow northward jog around the north coast of Jamaica, while dumping large amounts of rain on that island over a 4-day period. Resuming a west-northwestward track, Lili became a hurricane on 30 September while passing over Little Cayman and Cayman Brac Islands. Lili continued to strengthen, and its maximum winds were near 90 kt when the center moved over the southwestern tip of the Isle of Youth on the morning of 1 October, and over western mainland Cuba a few hours later.

After departing Cuba, Lili strengthened over the Gulf of Mexico. On 2 October, while the hurricane approached the central Gulf, it intensified rapidly to an estimated maximum wind speed of 125 kt, category 4 intensity, by 0000 UTC 3 October. Then, while still over water, Lili weakened even more rapidly than it had strengthened. Accelerating to about 15 kt, Lili turned northward and made landfall on the Louisiana coast on 3 October with an estimated intensity of 80 kt. Thus, during the 13 h prior to landfall, the hurricane's winds decreased by about 45 kt. After moving inland, Lili was absorbed by an extratropical low on 4 October while moving northeastward near the Tennessee–Arkansas border.

2) METEOROLOGICAL STATISTICS

Selected surface observations from land stations and data buoys are given in Table 7. Sustained wind speeds were near 45–50 kt as Lili moved quickly across the Windward Islands. A sustained wind speed of 47 kt with a gust to 68 kt was observed at Martinique early on 24 September.

The forward motion slowed to 5 kt as Lili moved between Haiti, Jamaica, and eastern Cuba. This slow motion contributed to the copious rainfall over Jamaica from 27 to 30 September, where over 600 mm was recorded (Table 7).

The highest wind report from Cuba was a 10-min average of 87 kt with a gust to 98 kt from Francia on the Isle of Youth, and this is the basis for a best-track wind speed of 90 kt over Cuba. The highest reconnaissance-measured flight-level wind speed during this time was 87 kt. Over 150 mm of rainfall was recorded at

TABLE 7. Selected surface observations for Lili, 21 Sep–4 Oct 2002.

Location	Min sea level pressure: Date/time (UTC)	Min sea level pressure: Pressure (mb)	Max surface wind speed: Date/time (UTC)[a]	Max surface wind speed: Sustained (kt)[b]	Max surface wind speed: Gust (kt)	Storm surge (m)[c]	Sorm tide (m)[d]	Total rain (mm)
Buoys								
42001			02/2010	98	130			
42003	02/0800	1009.0	02/0720	36	49			
42007			03/1140	36	47			
42041	03/0300	984.0	03/0220	56	70			
C-MAN stations								
BURL1			03/1020	52	70			
DRYF1	01/0810	1010.8	01/1714		46			
DPIA1	03/1559	1010.5	03/1559	31	35			
GDIL1			03/0640	36	69			
Louisiana								
Acadiana Regional Arpt	03/1514	984.4	03/1514	52	79			
Alexandria Int. Arpt	03/2141	980.4	02/2054	33	52			105.1
Baton Rouge	03/2353	997.0	03/1717		41			
Belle Chase			03/0855		44			
Boothville	03/0957	1005.4	03/1732	34	43			182.6
Burns Point/Salt Point							3.0–3.7	
Buras								213.4
Cajun Field, Lafayette			03/1636	41	66			
Castille Pass, near Morgan City							3.23	
Cocodrie, Terrebonne Parish							3.03	
Cote Blanch Island (Texas Tech)			03/1406	52	79			
Crewboat Channel, near Calumet							3.75	
CSI-03 (29.44°N, 92.06°W)				63				
Cypremort Point					88			
Dean Lee (Alexandria)			03/1810	43	58			
Delcambre, Route 14	03/1514	977.7	03/1508	54	84		0.61	
Frenier Causeway			03/0910	34	46			
Grand Isle							1.36	
Iberia (Jeanerertte)			03/1416	46	59			
Intracoastal City					104		1.83	
Jennings					77			99.3
Kaplan (Texas Tech tower)	03/1524	965.7	03/1438	64	86			
Lafayette Regional Arpt	03/1623	983.1	03/1559	47	63			115.3
Lake Bourne Bayou Dupre							2.0	
Lake Charles Regional Arpt	03/1641	993.9	03/1604	31	41			62.7
Lake Pontchartrain LUMCON[e]	03/2012	1001.9	03/1034	51	60			
Lake Pontchartrain Mid Causeway			03/1020	50	60			
Lake Pontchartrain RIGL1							1.84	
LUMCON[e] Headquarters	03/1024	997.7	03/1231	43	54		2.20	
Mandeville Causeway			03/1640	36	48			
New Iberia (29.9°N, 91.76°W)			03/1542	54	72			

TABLE 7. (*Continued*)

Location	Min sea level pressure		Max surface wind speed					
	Date/time (UTC)	Pressure (mb)	Date/time (UTC)[a]	Sustained (kt)[b]	Gust (kt)	Storm surge (m)[c]	Sorm tide (m)[d]	Total rain (mm)
New Orleans Int. Arpt	03/1159	1004.1	03/1617	34	44			
New Orleans Lakefront Arpt	03/0943	1003.4	03/1002	39	47			
Perry								217.7
Rice (Crowly)	03/1543	963.9	03/1528	47	61			
Terrebone Bay LUMCON[e]	03/1029	995.8	03/0553	50	59			
Vermilion Bay/Bayou Fearman							3.57	
Other States								
Beaumont, TX, Regional Arpt	03/1911	1001.4	03/1548	27	32		1.65	
Burkeville, TX								23.9
Picayune, MS								105.2
Connerly Bayou, AR								110.2
Chicago-Midway, IL								26.4
Bloomington, IN								21.6
Padukah/Barkley, KY								23.1
Cincinnati-Luken, OH								15.0
Pensacola, FL								26.4
Fairhope, AL								30.5
Jamaica								
Cedar Valley in St. Thomas								587.0
Craighead in Manchester								514.6
Knock Patrick in Manchester								550.2
Shewsbury in Westmoreland								605.0
Sunny Hill in St. Thomas								560.3
Cuba								
Francia	01/1100	991.2	01/1120	87	98			
Isabel Rubio	01/1550	971.4	01/1625	43	63			
Matias, Santiago de Cuba								158.0
Pilon, Granma								157.5
Pinar del Rio	01/1500	990.0	01/1450	59	76			
Punta del Esta	01/0905	989.7	01/1030	77	93			
San Juan y Martinez	01/1550	981.4		72	88			
Other Islands								
Morne des Cadets, Martinique			24/0300	47	68			
Pt. Salines, Grenada	24/0700	1006	24/0800	40				
Grantley Adams, Barbados			23/1700	41	65			
Hewanorra, St. Lucia			23/2100	35	47			

[a] Date/time is for sustained wind when both sustained and gust are listed.
[b] Except as noted, sustained wind averaging periods for C-MAN and land-based ASOS reports are 2 min; buoy averaging periods are 8 min. Non-U.S. wind reports are 10 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] Storm tide is water height above National Geodetic Vertical Datum (1929 mean sea level).
[e] Louisiana Universities Marine Consortium.

locations in the Granma and Santiago de Cuba Provinces of eastern Cuba.

Lili's peak intensity is estimated at 125 kt at 0000 UTC on 3 October, while the hurricane was centered in the north-central Gulf of Mexico. This is based on a reconnaissance-measured 700-mb flight-level wind speed of 142 kt. The aircraft also measured a minimum central pressure of 938 mb. The flight-level wind speed corresponds to a surface wind of 128 kt using a 90% eyewall adjustment factor. Data from several GPS dropwindsondes indicated sustained surface wind speeds of 115–123 kt near this time. Lili's eastern eyewall passed over NOAA data buoy 42001 at 2000 UTC on 2 October. This buoy reported a 10-min wind speed of 98 kt with a gust to 130 kt, which are the highest sustained and gust wind speeds ever recorded by a National Data Buoy Center buoy. Figure 6 is a satellite picture of Lili as it was approaching peak intensity.

Lili made landfall in a sparsely populated area along the south-central coast of Louisiana near Intracoastal City. The highest sustained wind observed over land in the United States was 64 kt (Table 7), from a Texas Tech University mobile anemometer tower near Kaplan, about 15 n mi north-northwest of Intracoastal City, Louisiana. The highest recorded wind gust was 104 kt at Intracoastal City. The highest aircraft flight-level wind speed near the time of landfall was 88 kt at 700 mb. The highest surface wind speed estimate obtained from GPS dropwindsondes during the last few hours before landfall was 73 kt. A Shared Mobile Atmospheric Research and Teaching (SMART) radar measured 101 kt just above the surface south of New Iberia. The lowest surface pressure observed was 963.9 mb at the Louisiana Agriclimate Information System at Crowley. Based on the above data, the maximum wind speed at landfall is estimated at 80 kt.

Lili's eyewall collapsed and its wind speed decreased substantially during the 13 h before landfall. As the hurricane neared the coast, its radius of maximum wind speed increased. Reconnaissance flight-level winds near the coast just south of Morgan City suggest that the highest winds were about 50 n mi east of the center, so that wind speeds near the coast south of Morgan City could have been as high as or higher than wind speeds near Intracoastal City, where the center crossed the coast.

Rainfall across south-central and southeastern Louisiana ranged from 100 to just over 200 mm, with the highest amount of 217.7 mm at Perry, just north of Intracoastal City. Over 100 mm was measured in northern Louisiana and southern Mississippi, and rainfall amounts of over 50 mm spread into Arkansas. Portions of Florida and Alabama had over 25 mm of rain. A tide gauge at Crewboat Channel near Calumet, Louisiana, measured a storm tide water height of 3.8 m, and another at Vermillion Bay measured 3.6 m. The water height at Burn's Point, south of Morgan City, was estimated at 3.0–3.7 m above normal, based on the observed water level inside a house. Water levels were already 0.6–1.2 m above normal prior to Lili's arrival. Lili spawned at least 26 tornadoes, 17 in Louisiana, and 9 in Mississippi. Most were short-lived and damage was in the F0 to F1 range.

3) Casualty and damage statistics

Lili went through the Windward Islands as a tropical storm. Landslides killed four people in St. Vincent, including an infant. There was damage to 400 homes in Barbados, and half the banana crop of St. Lucia was destroyed. Jamaica was hard hit by heavy rain from Lili. Four persons, including a three-year-old child, died when flood waters swept them away. Flood waters also swept away livestock and crops and caused extensive damage to homes, bridges, roadways, and other infrastructure. Flooding in Jamaica, as well as in western Cuba and Louisiana, was compounded by earlier heavy rains from Hurricane Isidore. Lili also pelted Haiti's south coast with wind and rain, and four people drowned in that country.

There were news reports of high winds uprooting trees, knocking out electricity, and damaging roofs in Cayman Brac. The hurricane cut a swath of destruction across western Cuba, damaging buildings and farmland and disrupting communications. Some 360 000 people were reported to have been evacuated from their homes. There was one death in the Pinar del Rio province directly attributable to Lili.

Although Lili weakened considerably before making landfall on the central Louisiana coast, it caused significant wind and flood damage in that area. Strong winds toppled trees onto houses and into roadways, stripped shingles from roofs, and blew out windows. The wind and driving rain flattened sugar cane fields throughout southern Louisiana. A combination of storm surge and rain caused levees to fail in Montegut and Franklin, Louisiana. Lili also temporarily curtailed oil production in the Gulf of Mexico. The U.S. insured property damage total obtained from the American Insurance Services Group is $430 million: $415 million for Louisiana and $15 million for Mississippi. The total U.S. damage is estimated at $860 million.

One fatality occurred as an indirect result of Lili in Crowley, Louisiana, where an elderly woman died from carbon monoxide poisoning from a generator. Another indirect fatality occurred in Vermilion Parish where a 79-year-old Erath man died when he fell from a ladder cleaning up storm debris.

4) Warnings

There was about 20 and 23 h of lead time from the issuance of hurricane warnings and landfall on the Isle of Youth, Cuba, and the western Cuban mainland, respectively. Hurricane warnings were issued for coastal Louisiana about 28 h prior to landfall.

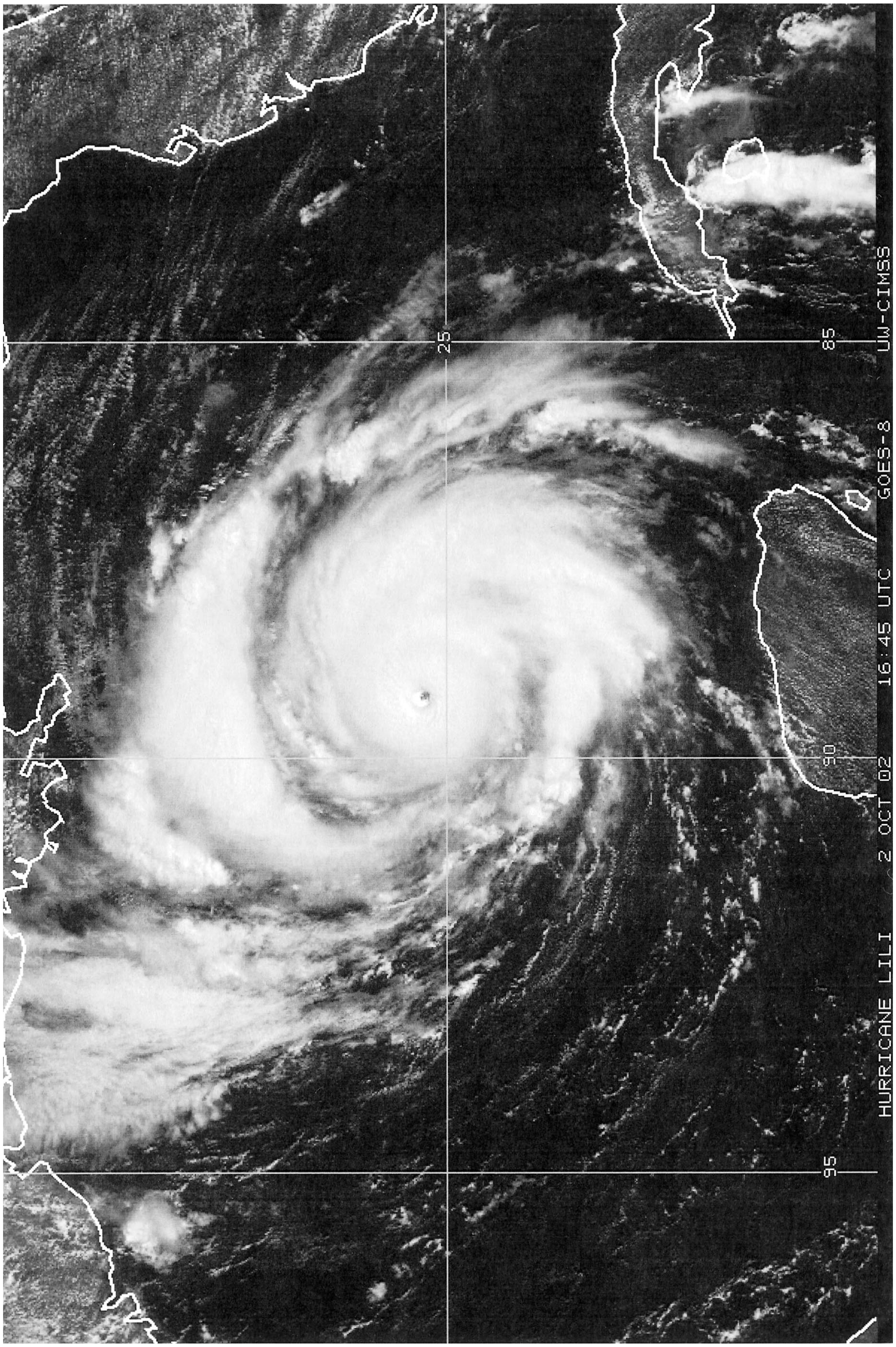


FIG. 6. Visible satellite image of Hurricane Lili at 1645 UTC 2 Oct 2002.

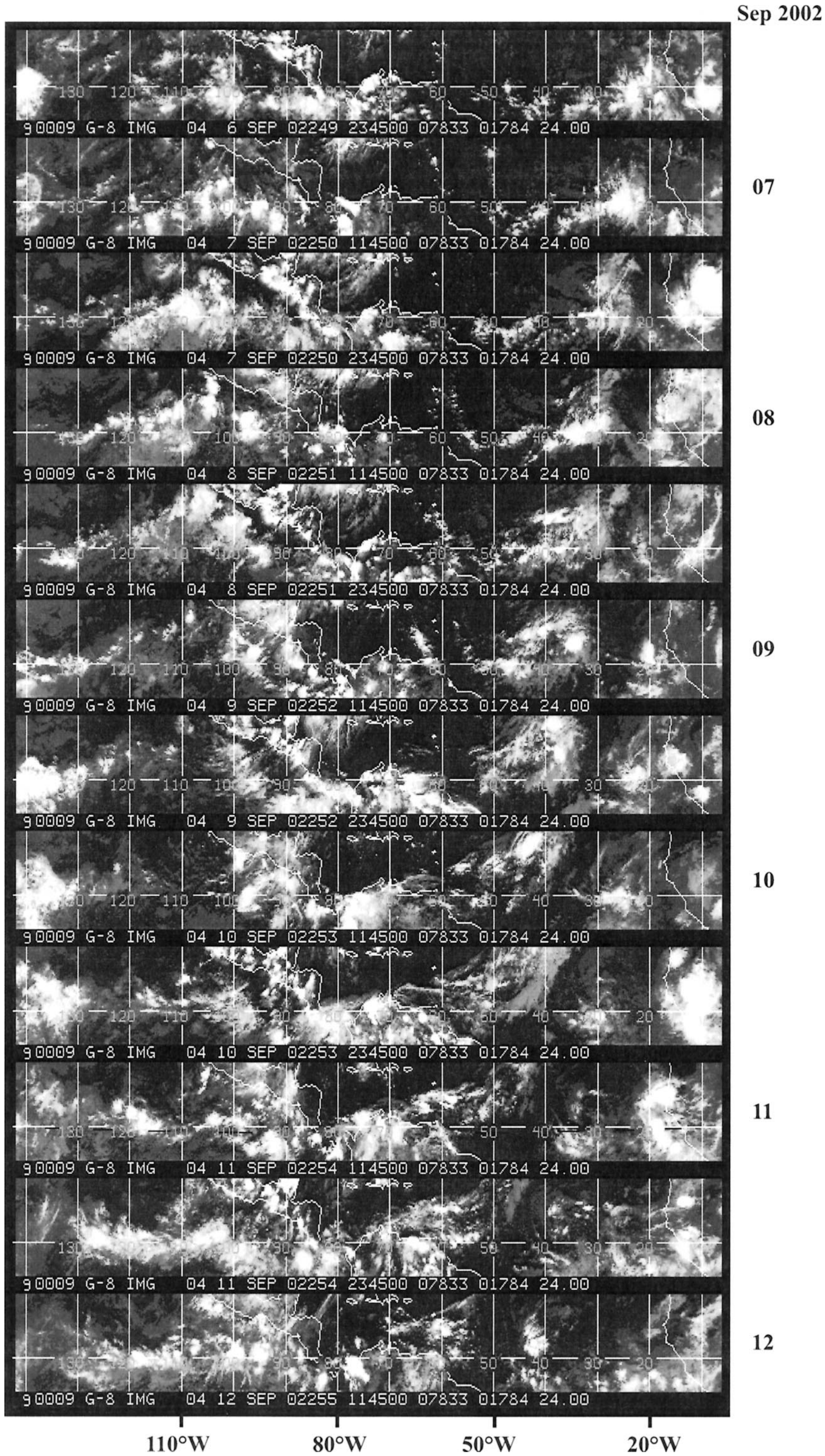


FIG. 7. Hovmöller diagram of twice-daily infrared satellite images over the tropical Atlantic basin from 6 to 12 Sep 2002.

TABLE 8. Homogenous comparison of official and CLIPER average track forecast errors (n mi) for all tropical and subtropical cyclones in the Atlantic basin (including depressions) for the 2002 season. Longer-term averages for the 10-yr period 1992–2001 are shown for comparison.

	Forecast period (h)				
	12	24	36	48	72
Average 2002 official error	41	72	104	138	200
Average 2002 CLIPER error	57	113	177	243	385
Average 2002 error relative to CLIPER (%)	−28	−36	−41	−43	−48
(2002 number of cases)	(287)	(257)	(228)	(201)	(166)
Average 1992–2001 official error	46	83	119	154	232
Average 1992–2001 CLIPER error	54	109	169	230	346
Average 1992–2001 error relative to CLIPER (%)	−15	−24	−30	−33	−33
(1992–2002 number of cases)	(2887)	(2642)	(2409)	(2170)	(1764)
Average 2002 official error relative to 1992–2001 mean (%)	−11	−13	−13	−10	−14
Average 2002 CLIPER error relative to 1992–2001 mean (%)	6	4	5	6	11

3. Weaker systems

This section briefly summarizes tropical wave and tropical depression activity during 2002. The methodology for tracking tropical waves over the Atlantic basin has been discussed previously (e.g., Pasch and Avila 1994). Figure 7 is a Hovmöller diagram of infrared satellite imagery over the tropical Atlantic during 6–12 September 2002. Note the westward-propagating cloud patterns associated with tropical waves in this diagram. For example, the feature over the eastern part of the area (which moved off the African coast on 9 September) corresponds to the tropical wave that spawned Isidore near Trinidad on 14 September. During 2002, 64 tropical waves were identified and tracked. This number is comparable to the values observed in past years. Pasch and Avila (1994) have indicated that there is no apparent relationship between the number of waves tracked during a season and the amount of tropical storm or hurricane activity in that season. Typically, over 60% of a season's tropical storms and hurricanes originate from tropical waves. However, in 2002 only 25% of the named systems developed from tropical waves. This is consistent with what has been observed in other El Niño years and with what was suggested by Gray (1984)—namely, that the presence of El Niño induces an environment in the Atlantic basin that is generally hostile for the formation of tropical cyclones from tropical waves.

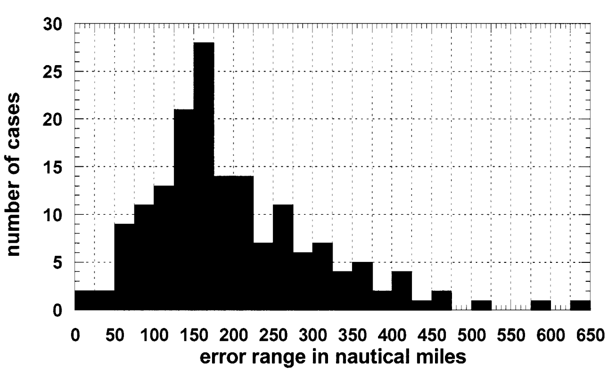


FIG. 8. Histogram of 72-h official track forecast errors (n mi) in the Atlantic basin for 2002.

Tropical depressions

There were two tropical depressions in the Atlantic in 2002 that did not strengthen into tropical storms: Tropical Depressions 7 and 14. Both originated from tropical waves.

A tropical wave moved from Africa to the eastern Atlantic Ocean on 1 September, accompanied by a low-level circulation and a fairly well-organized area of deep convection. This convection soon dissipated, and the wave was disorganized for the next several days while moving west-northwestward. By 7 September, the system acquired enough organized convection to be identified as Tropical Depression 7. This was a short-lived depression. Increasing vertical shear quickly caused its dissipation on 8 September while it was located about 850 n mi southeast of Bermuda.

A weak tropical wave moved through the Lesser Antilles on 9 October. Convection increased in association with the wave on 12 October when it reached the southwestern Caribbean Sea, and a broad low pressure area formed later that day. The low moved northward near the east coast of Nicaragua on 13 October, and it became better organized. The system developed sufficient organized convection to be designated Tropical Depression 14 by 1200 UTC 14 October while centered about 120 n mi north-northeast of Cape Gracias a Dios on the border of Honduras and Nicaragua.

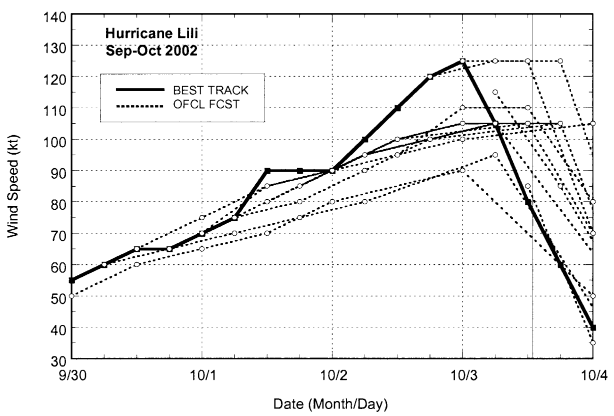
The cyclone moved erratically for the next 12 h before it began accelerating north-northeastward early on 15 October. Southwesterly vertical shear associated with a deep-layer trough over the southeastern United States prevented further development and may have contributed to a persistent elongation of the circulation. The center made landfall on the south coast of central Cuba on 16 October, and the cyclone was absorbed by a cold front late that day.

An Air Force Reserve Hurricane Hunter aircraft reported a minimum pressure of 1002 mb on multiple

TABLE 9. Homogenous comparison of official and SHIFOR average intensity forecast errors (kt) for all tropical and subtropical cyclones in the Atlantic basin (including depressions) for the 2002 season. Longer-term averages for the 10-yr period 1992–2001 are shown for comparison.

	Forecast period (h)				
	12	24	36	48	72
Average 2002 official error	5.5	9.0	11.3	14.5	20.8
Average 2002 SHIFOR error	7.4	12.0	15.6	18.0	22.0
Average 2002 error relative to SHIFOR (%)	−26	−25	−28	−19	−5
(2002 number of cases)	(287)	(257)	(228)	(201)	(166)
Average 1992–2001 official error	6.2	10.0	12.9	15.5	19.2
Average 1992–2001 SHIFOR error	8.0	12.5	16.0	19.0	22.4
Average 1992–2001 error relative to SHIFOR (%)	−23	−20	−19	−18	−14
(1992–2001 number of cases)	(2877)	(2629)	(2394)	(2148)	(1761)
Average 2002 official error relative to 1992–2001 mean (%)	−11	−10	−12	−6	8
Average 2002 SHIFOR error relative to 1992–2001 mean (%)	−8	−4	−3	−5	−2

occasions on 15 October. The maximum flight-level winds observed were 37 kt. The ships *Explorer of the Sea* and ZCBU5 (name unknown) reported 29-kt winds at 0800 and 0500 UTC 15 October, respectively. There were no significant observations of winds from land stations. Although the depression caused locally heavy rains over portions of Jamaica, Cuba, and the Cayman Islands, there are no reports of damage or casualties.



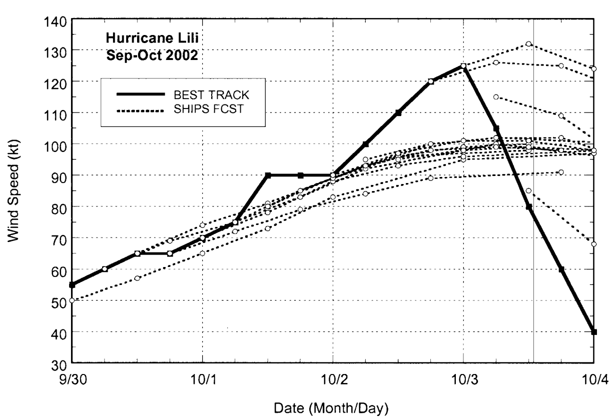


FIG. 9. (top) Official and (bottom) SHIPS intensity forecasts (dashed lines) for Hurricane Lili. The best-track intensity is given by the thick solid lines. Time of landfall is indicated by the solid vertical line.

4. Forecast verification

The National Hurricane Center issues an advisory package every 6 h for each tropical and subtropical cyclone in the Atlantic (and eastern North Pacific) basin. This advisory package contains forecasts of the location of the center of the tropical cyclone and of the maximum 1-min surface wind speed of the cyclone. The forecasts are valid 12, 24, 36, 48, and 72 h after the synoptic time of the advisory (0000, 0600, 1200, and 1800 UTC). Forecasts are verified by comparison with a best-track postanalysis of each storm. Track forecast errors are defined as the great-circle distance between a forecast position and the best-track position for the forecast verification time. Wind speed forecast errors are defined as the absolute value of the difference between the forecast wind speed and the best-track wind speed for the forecast verification time.

In previous years, forecasts were excluded from verification when the cyclone was extratropical or below tropical storm strength at either the initial time or the verifying time. These exclusions were a continuation of a tradition started in the 1960s and early 1970s when the only available guidance models were statistical in nature, and these models were derived from datasets that excluded such cases. Today, the primary guidance models (at least for track guidance) are dynamical and are run on all tropical and subtropical cyclones, including depressions. Therefore, beginning in 2002, tropical depression–stage forecasts are included in the verification statistics. Only extratropical cases are excluded.

Table 8 lists the 2002 average official track forecast errors for the Atlantic basin. Errors for the Climatology and Persistence (CLIPER) model (Neumann 1972) are also listed, as well as the average official errors for the previous 10 yr. The CLIPER model represents a ‘‘no skill’’ baseline level of accuracy, and the 2002 average official track errors range from 28% to 48% less than the corresponding CLIPER errors. For comparison, the 1992–2001 average improvements over CLIPER are listed in the table; these ranged from 15% to 33%. Also, the 2002 official track errors were 10% to 14% less than the previous 10-yr average official errors. These low official track errors continue a trend of decreasing track errors since 1970, as most recently documented by Franklin et al. (2003b). This trend is the direct result of improvements in numerical weather prediction track model guidance. Even though the average official 72-h track error for 2002 was only 200 n mi, there were a number of rather large errors. In fact, 60% of the errors are greater than 200 n mi. Figure 8 shows a histogram of 72-h official track errors, and it is seen that there are three cases of errors larger than 500 n mi.

Table 9 is analogous to Table 8, except it contains wind speed (intensity) forecast errors. The Statistical Hurricane Intensity Forecast (SHIFOR) model (Jarvinen and Neumann 1979) is the ''no skill'' baseline intensity forecast model. Although the 2002 average official intensity forecast errors are generally 20% or so smaller than the corresponding SHIFOR errors at 12–48 h, there is very little skill at 72 h. Also, the 2002 average official intensity forecast error at 72 h is slightly larger than the previous 10-yr average. This continues a trend of little improvement in official intensity forecasts in recent years at 72 h (and only modest improvements at shorter forecast periods). While track forecast guidance models are state-of-the-art dynamical prediction models that skillfully predict the steering currents that control the motion of a tropical cyclone, intensity guidance has lagged behind. The dynamics of the inner core play an important role in tropical cyclone intensity change, and dynamical models do not yet have the resolution or observations to simulate adequately the structure of the inner core of a tropical cyclone. Currently, the best operational intensity guidance is the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria and Kaplan 1999). SHIPS is a statistical/dynamical model that relates intensity changes to concurrent atmospheric and oceanic variables and to atmospheric variables predicted by a global dynamical model. A major limitation of SHIPS is its inability to predict extreme events, that is, rapid intensification and rapid weakening. Hurricane Lili is a good case in point. Figure 9 shows a series of official and SHIPS intensity forecasts for Lili. Neither the official forecasts nor the primary guidance (SHIPS) anticipated Lili's rapid strengthening and even more rapid weakening as it approached the coast. In the years to come, further enhancements in observations and modeling of tropical cyclones should lead to substantial improvements in the prediction of intensity change by dynamical models, including the much-needed ability to forecast extreme intensity change events.

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