# ANNUAL SUMMARIES

## Atlantic Hurricane Season of 1989

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ABSTRACT

A general overview of the 1989 hurricane season is presented. Eleven named tropical cyclones were tracked, seven of which reached hurricane strength. Three hurricanes and a tropical storm struck the U.S. mainland. The large Cape Verde-type hurricanes dominated the season for the second consecutive year as Hugo raked the islands of the northeast Caribbean and devastated portions of the Carolinas making it the costliest hurricane ever.

### 1. Introduction

The 1989 hurricane season had a total of 11 named tropical cyclones of which seven attained hurricane strength. This was the first year since the 1979 season that all of the named tropical cyclones had their origin associated with African waves (Avila 1990). Figure 1 presents the tropical storm and hurricane tracks while Table 1 contains the season statistics.

Total deaths attributed to the season stand at 84 with 56 of those on the U.S. mainland. Hugo was responsible for a total of 49 deaths, 21 on the U.S. mainland. Dollar damages for the season will certainly be the highest ever. Hurricane Hugo's damage is estimated to be near ten billion, seven in the continental United States.

Powerful Hurricanes Gabrielle and Hugo, categories four and five on the Saffir/Simpson Hurricane Scale (1989), respectively, continued the trend of the large Cape Verde-type hurricanes, which commenced in 1988 with Gilbert, Helene and Joan. The 1988–89 seasons produced the greatest number of category four/five hurricanes since the combined seasons of 1960–61 when a total of six occurred.

Four of the named systems (Tropical Storm Allison and Hurricanes Chantal, Hugo and Jerry) struck the U.S. coastline. All but Hugo took aim at the upper half of the Texas coast. Hurricane Dean made a direct hit on Bermuda, the first since Hurricane Emily in 1987. Allison was responsible for the wettest June on record in Louisiana after the storm dumped nearly 750 mm of rain over portions of west central Louisiana. Hugo, the strongest hurricane of the 1989 season, turned out to be the most costly hurricane in U.S. history.

Tropical Storm Karen, a late season storm in the northwestern Caribbean, dropped from 254 to 380 mm of rain over portions of western Cuba. Karen continued the 1980s trend of November tropical storms and hurricanes. It was the eighth named tropical cyclone in November during the past ten years, which is double the long term November average.

### 2. Individual storms

#### *a. Tropical Storm Allison: 24–27 June*

##### 1) SYNOPTIC HISTORY

Three meteorological phenomena contributed to the formation of Tropical Storm Allison. The combination of the remnants of the east Pacific Hurricane Cosme, the northern portion of a westward-moving tropical wave and a strong anticyclone at 200 mb over the Gulf of Mexico provided a favorable environment for the formation of Allison. Heavy thunderstorms began to develop over the Gulf of Mexico on 22 June and by 23 June the activity became concentrated over the northwest portion. Data from upper-air soundings indicated that the circulation from the remnants of Cosme was just to the southwest of Brownsville, Texas, at 1200 UTC 23 June. During the following 24 hours, a new broad surface circulation developed just off the upper Mexican coast.

Based upon surface observations along the coast and data from offshore oil rigs, the area of disturbed weather was upgraded to Tropical Depression Number Two at 1800 UTC 24 June. Early on the morning of 26 June, Air Force reconnaissance aircraft detected a large area of 22 m $s^{-1}$ winds at a flight level of 500 m, and the depression was officially upgraded to Tropical Storm

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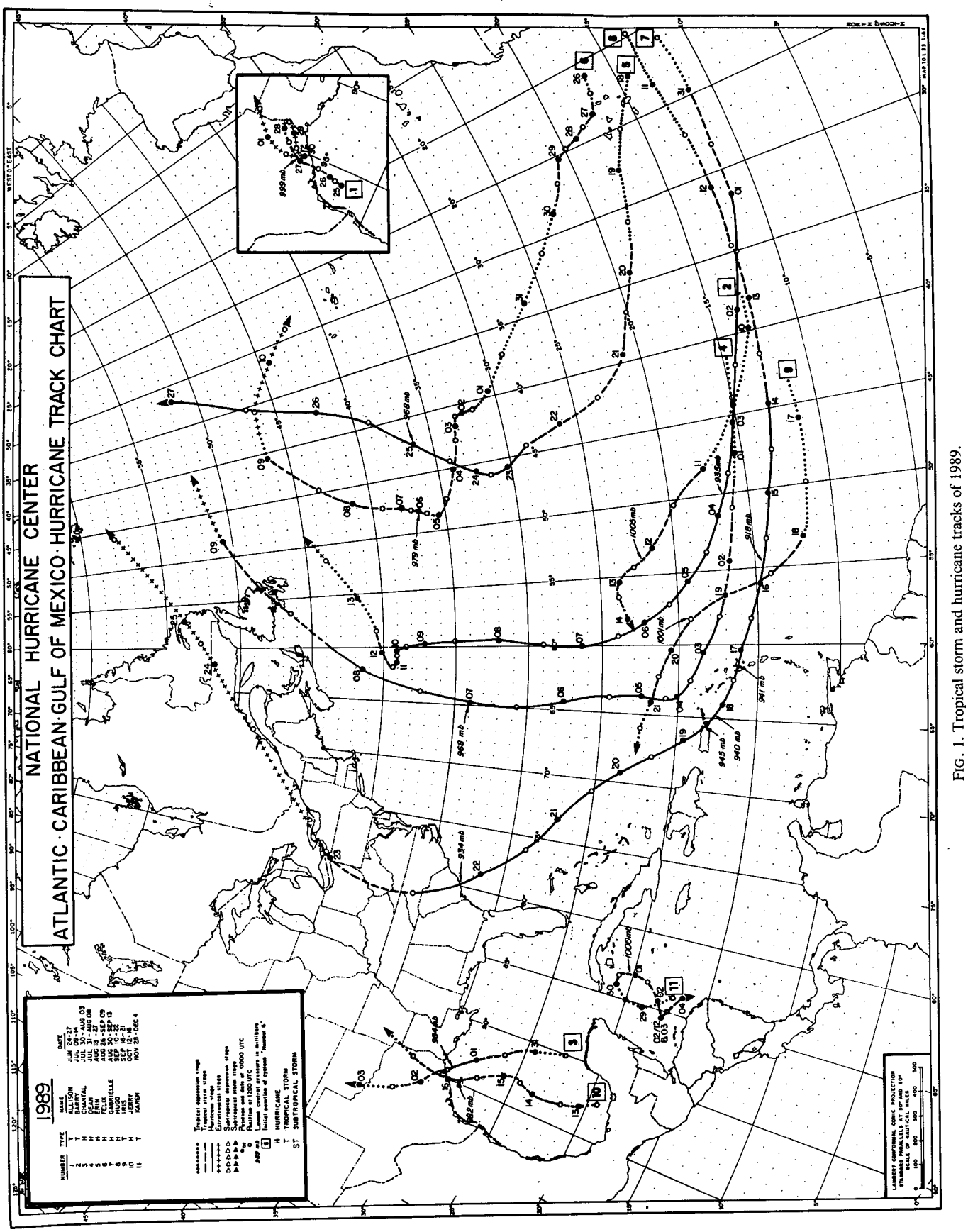


FIG. 1. Tropical storm and hurricane tracks of 1989.

TABLE 1. 1989 Atlantic hurricane season statistics.

| Number | Name | Class* | Dates** | Maximum 1-min wind ($m\ s^{-1}$) | Minimum sea-level pressure (mb) | U.S. damage ($ millions) | U.S. deaths |
|---|---|---|---|---|---|---|---|
| 1 | Allison | T | 24–27 Jun | 23 | 999 | 500 | 11 |
| 2 | Barry | T | 9–14 Jul | 23 | 1005 | | |
| 3 | Chantal | H | 30 Jul–3 Aug | 36 | 984 | 100 | 13 |
| 4 | Dean | H | 31 Jul–8 Aug | 46 | 968 | | |
| 5 | Erin | H | 18–27 Aug | 46 | 968 | | |
| 6 | Felix | H | 26 Aug–9 Sep | 39 | 979 | | |
| 7 | Gabrielle | H | 30 Aug–13 Sep | 64 | 935 | | 8 |
| 8 | Hugo | H | 10–22 Sep | 72 | 918 | 700 | (49+) 21 |
| 9 | Iris | T | 16–21 Sep | 31 | 1001 | | |
| 10 | Jerry | H | 12–16 Oct | 39 | 982 | 70 | 3 |
| 11 | Karen | T | 28 Nov–4 Dec | 26 | 1000 | | |

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

Allison at 1200 UTC 26 June. However, based upon ship data received after the fact, post-analysis indicated that tropical storm strength was probably attained near 0000 UTC 26 June.

A frontal trough in the westerlies moving across the western United States by 1200 UTC 26 June caused Allison to commence accelerating toward the north. The center of the storm moved inland on the middle Texas coast near the northeast end of Matagorda Bay at 1300 UTC 26 June. During the following several days the weakening storm lost its tropical characteristics and made a 360 degree loop over extreme east Texas. Finally, late in the day on 30 June the extratropical system turned toward the northeast and began to accelerate toward the Ohio Valley.

#### 2) METEOROLOGICAL STATISTICS

Wind gusts to tropical storm force occurred in clusters of heavy showers and thunderstorms over the open waters of the Gulf of Mexico as early as 24 June. The strongest reported wind from the storm, an east wind of 26 $m\ s^{-1}$, occurred at the offshore platform 01T (located at 28.1°N, 94.4°W) at 1315 UTC 26 June. The observation was made in heavy rain from an anemometer at a height of 33 m. Strongest 1-min winds over land ranged from 18 to 23 $m\ s^{-1}$ with a gust to near 26 $m\ s^{-1}$. The Galveston weather office recorded the strongest 1-min wind speed of 23 $m\ s^{-1}$ at 1238 UTC on 26 June which was near the time Allison made landfall. The central pressure of the tropical storm was 1002 mb as it moved onshore along the central Texas coast at 1300 UTC 26 June. However, the central pressure continued to decrease during the day as Allison moved northward, and the lowest pressure of 999 mb occurred near 0000 UTC 27 June while the storm center was located just to the west-northwest of Houston, Texas. Figure 2 shows Allison at 1701 UTC 27 June after it weakened to a tropical depression.

Torrential rains accompanying Allison fell along the upper Texas coast and over the western two-thirds of Louisiana. Nearly 750 mm fell in a six-day period at the small community of Winnfield, Louisiana, while 254 to 380 mm fell along portions of the upper Texas coast. Table 2 contains a number of selected observations from Tropical Storm Allison.

#### 3) DEATHS AND DAMAGE

The death toll in Tropical Storm Allison was eleven, all attributed to drowning. Estimated dollar damage from Allison is near one-half billion dollars. Almost all damage occurred from flooding produced by the heavy rains.

### *b. Tropical Storm Barry: 9–14 July*

Barry originated from a tropical wave, which moved off the coast of Africa on 7 July. By the 9th, a tropical depression had formed from the wave midway between Africa and the Lesser Antilles. The depression tracked northwestward, reaching tropical storm strength on the 11th. Barry's estimated maximum winds and minimum central pressure were 23 $m\ s^{-1}$ and 1005 mb. The storm weakened to a depression on the 13th. It then dissipated into an elongated trough with several minor eddies. Barry's closest point of approach to land was about 880 km northeast of the Leeward Islands.

### *c. Hurricane Chantal: 30 July–3 August*

#### 1) SYNOPTIC HISTORY

Hurricane Chantal was the first hurricane of the 1989 Atlantic season. The system that provided the embryo for Chantal was first detected on 24 July as an intertropical-convergence-zone (ITCZ) disturbance near Trinidad just off the coast of South America. The system moved westward across the Caribbean with little

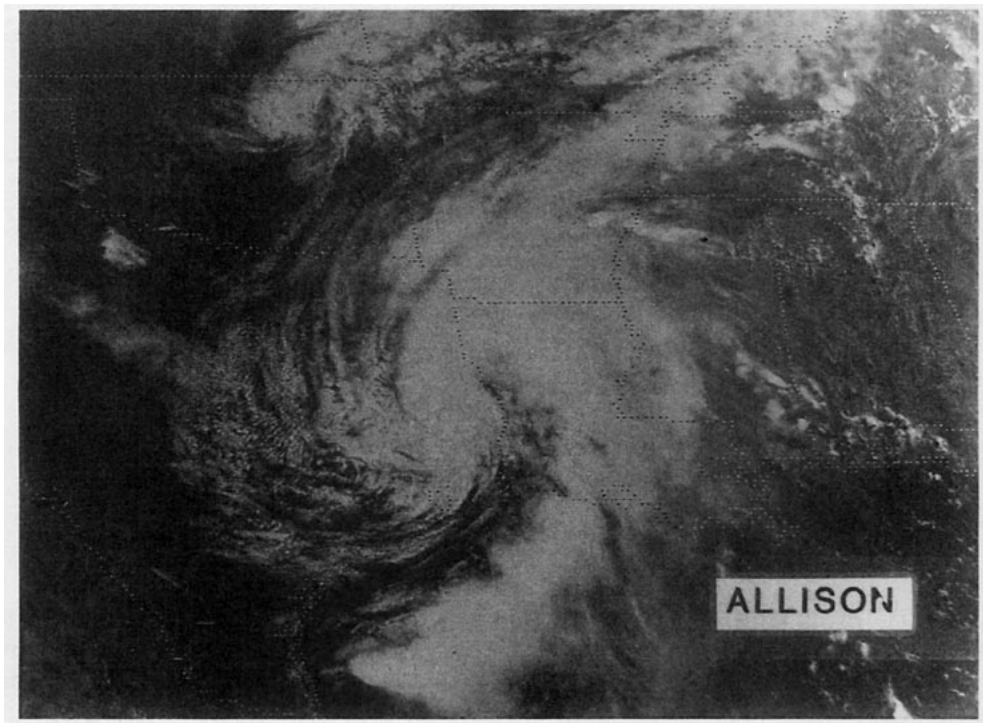


FIG. 2. GOES visible image of Allison after weakening to a tropical depression at 1701 UTC 27 June 1989. The center is located over eastern Texas.

development until approaching Honduras on the 27th when some organization began to occur. However the Central American land mass delayed any development of the system as it crossed into the Gulf of Mexico.

Satellite pictures and ship data confirmed that a tropical depression formed as early as 1200 UTC 30 July as the disturbed weather moved off the northwestern Yucatan Peninsula. Based on estimates by satellite analysts using the Dvorak technique (1984), Tropical Storm Chantal likely formed about 575 km

TABLE 2. Tropical Storm Allison selected surface observations, June 1989.

| Location | Minimum sea-level pressure | | Maximum surface wind speed ($m\ s^{-1}$) | | | Storm surge (tide height above normal) (m) | Rain** (storm total) (mm) |
|---|---|---|---|---|---|---|---|
| | Pressure (mb) | Date/time (UTC) | 1-minute average | Peak gust | Date/time (UTC)* | | |
| Texas | | | | | | | |
| Corpus Christi (WSO) | 1005.8 | 26/2150 | 10 | 14 | 25/1950 | 0.7 | 36 |
| Palacios (WSO) | 1002.9 | 26/1953 | 7 | | 26/1754 | | |
| Galveston (WSO) | 1003.3 | 27/0030 | 23 | 25 | 26/1238 | 0.8 | 200 |
| Houston Hobby (HOU) | 1001.5 | 26/2350 | 13 | 20 | 26/1643 | | 302 |
| Houston Intercontinental (IAH) | 999.9 | 27/0042 | 18 | 24 | 27/0052 | | |
| Alvin (WSO) | | | 9 | 17 | 26/1457 | | 167 |
| Houston downtown | | | | | | | 274 |
| Port Arthur/Beaumont (WSO) | 1003.3 | 27/0653 | 13 | 21 | 27/0653 | 0.9 | |
| Louisiana | | | | | | | |
| Lake Charles (WSO) | 1004.1 | 27/0752 | 19 | 25 | 27/1250 | | 380 |
| Shreveport (WSO) | 1007.4 | 27/2151 | 10 | 18 | 27/— | | 234 |
| Baton Rouge (WSO) | | | | | | | 262 |
| Winnfield | | | | | | | 750 |
| Gorum Fire Tower Natchitoches Parish | | | | | | | 487 |
| Kentucky | | | | | | | |
| Louisville (WSFO) | | | | | | | 121 |

* Time of 1-min wind speed.

** Includes rainfall associated with the remnants of Allison.

southeast of Galveston, Texas, at 0600 UTC on the 31st. However due to the uncertainty of infrared satellite interpretation, formal upgrading of the system did not occur until the first Air Force reconnaissance aircraft arrived in the system at 1224 UTC 31 July.

Strengthening Tropical Storm Chantal moved toward the northwest at 5 m $s^{-1}$ in response to weak ridging extending westward across Florida. During the afternoon of the 31st, an Air Force reconnaissance plane found 41 m $s^{-1}$ winds at 500 m and Chantal was upgraded to a hurricane at 2200 UTC.

Hurricane Chantal, continuing to strengthen, moved north-northwestward toward the upper Texas coast and made landfall as a category 1 hurricane. Figure 3 shows the hurricane shortly after making landfall on the upper Texas coast. The center of Chantal continued moving northwestward and dissipated in southwestern Oklahoma after 0000 UTC 3 August.

#### 2) METEOROLOGICAL STATISTICS

The center of Hurricane Chantal crossed the upper Texas coast at High Island near 1300 UTC 1 August with sustained winds estimated at 36 m $s^{-1}$ and a minimum pressure of 986 mb. Galveston reported the strongest sustained winds of 31 m $s^{-1}$ while Sea Rim State Park, located just southwest of the Texas/Louisiana border, recorded 24 m $s^{-1}$. A summary of selected meteorological observations is presented in Table 3.

Rainfall associated with Chantal varied considerably. Houston's Hobby Airport reported 181 mm in 6 hours and 218 mm in 24 hours, whereas Houston Intercontinental Airport had only 31 mm in 6 hours and 52 mm in 24 hours. Unofficially, Friendwood, southeast of Hobby, had a storm total of 508 mm and Clear Lake, northeast of Alvin, had 406 mm. Most of the rain in Chantal occurred on the left or southern side of the track producing serious flooding mainly in portions of Galveston, Brazoria, and Fort Bend Counties.

Storm tides at High Island were 2.1 m above MSL. Kemah and Sabine Pass reported 1.2 m above MSL and storm tides at the Galveston Flagship Pier were 1.1 m above MSL. There was extensive beach erosion from High Island to Sea Rim State Park.

#### 3) DEATHS AND DAMAGE

Thirteen deaths were attributed to Chantal and, just as in Allison, all were the result of drowning. The main effects from Chantal were flooding by torrential rains and beach erosion. Wind effects were relatively light. Total damage is estimated to be near 100 million dollars.

### *d. Hurricane Dean: 31 July–8 August*

The tropical wave from which Dean developed moved off the northwest coast of Africa on 27 July and became a depression on 31 July. The depression attained tropical storm strength by 1 August and was

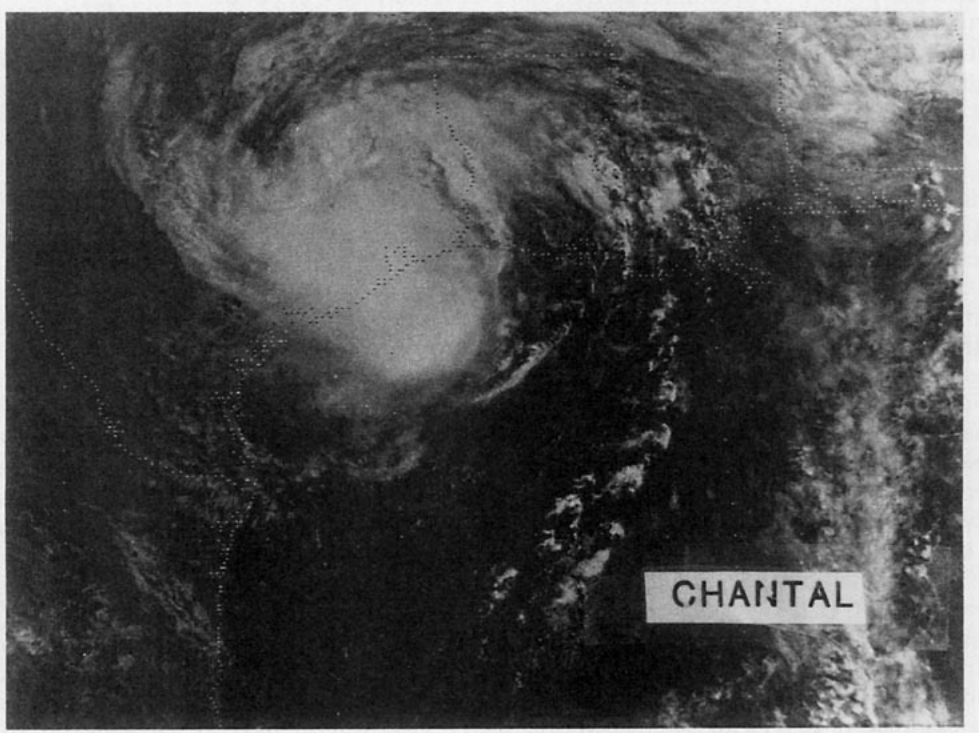


FIG. 3. GOES visible image of Hurricane Chantal at 1531 UTC 01 August 1989, shortly after landfall on the upper Texas coast.

TABLE 3. Hurricane Chantal selected surface observations, August 1989.

| Location | Minimum sea-level pressure | | Maximum surface wind speed ($m\ s^{-1}$) | | | Storm tide (tide height above MSL) (m) | Rain (24-h total) (mm) |
|---|---|---|---|---|---|---|---|
| | Pressure (mb) | Date/time (UTC) | 1-minute average | Peak gust | Date/time (UTC)* | | |
| Texas | | | | | | | |
| Houston Intercontinental (IAH) | 993.5 | 01/1700 | 14 | 25 | 01/1550 | | 52 |
| Houston Hobby (HOU) | 996.3 | 01/1538 | 18 | 34 | 01/1428 | | 218 |
| Houston WSO Alvin | | | 12 | 20 | 01/1547 | | 178 |
| Galveston WSO | 997.4 | 01/0935 | 31 | 37 | 01/1132 | | 167 |
| Downtown Houston | | | | | | | 168 |
| Galveston Flagship Pier | | | | | | 1.1 | |
| Galveston Pier 21 | | | | | | 0.9 | |
| Kemah | | | | | | 1.2 | |
| High Island | | | | | | 2.1 | |
| Port Arthur | 1002.0 | 01/1220 | 13 | 22 | 01/1353 | | 30 |
| Sabine Pass | | | | | | 1.2 | |
| Sea Rim State Park | 996.4 | 01/1200 | 24 | 28 | 01/1200 | | |
| Louisiana | | | | | | | |
| Lake Charles | 1006.4 | 01/1026 | 12 | 17 | 01/1640 | | |
| Cameron | | | | | | 1.3 | |
| New Orleans Moisant A. | 1013.5 | 01/0100 | 12 | 19 | 31/1501 | | 58 |
| New Orleans Lakefront | | | 7 | 12 | 01/0003 | | |
| Mid Lake Ponchartrain Cswy. | | | 13 | 18 | 31/2000 | | |
| E. Lake Ponchartrain Hwy 11 | | | 11 | 17 | 31/1600 | | |
| Paris Road | | | | | | 1.0 | |
| Mississippi | | | | | | | |
| Biloxi | | | | | | 0.8 | |

* Time of 1-min wind speed.

upgraded to a hurricane on the morning of 2 August, immediately after the first report of hurricane-force surface winds from an Air Force reconnaissance plane.

By 3 August the hurricane decreased in forward motion and turned toward the northwest, in response to a collapsing ridge to the north and a developing upper-level trough off the U.S. east coast. By 4 August Dean turned more toward the north as the upper-level trough off the U.S. deepened. This northward direction of motion continued with an increase in forward speed to near 8 $m\ s^{-1}$, bringing the eastern eyewall over the island of Bermuda near mid-afternoon on 6 August. Highest sustained winds reported were 36 $m\ s^{-1}$ with gusts to 50 $m\ s^{-1}$ at the U.S. Naval Annex on the western end of the island.

The lowest pressure reported by reconnaissance aircraft was 970 mb, just after the hurricane passed Bermuda. However, after the last aircraft penetrated the cyclone, the cloud pattern observed in satellite imagery became even better organized with a well-defined eye embedded within a small but cold central dense overcast. Based on satellite estimates, the minimum pressure (968 mb) and maximum winds (46 $m\ s^{-1}$) likely occurred near 0000 UTC 7 August.

After passing Bermuda, Dean turned and accelerated toward the northeast. The cyclone passed over Sable Island, Nova Scotia, producing sustained winds of 34 $m\ s^{-1}$ with gusts to 40 $m\ s^{-1}$. Dean then began slowly to lose tropical characteristics as it moved over southeastern Newfoundland. The cyclone became extratropical over the north Atlantic while moving toward the northeast at about 23 $m\ s^{-1}$.

There were no reported deaths due to Hurricane Dean. Since the hurricane veered away from the northeast Caribbean, no significant damage was reported from the Leeward or Virgin Islands. Personal injuries reported on Bermuda totalled 16 and damage estimates were near 9 million dollars.

### *e. Hurricane Erin: 18–27 August*

Erin began as an African wave, which moved off the African coast on 16 August. The wave developed into a tropical depression at 0000 UTC 18 August while located just southeast of the Cape Verde Islands. Steering currents guided the developing depression toward the northwest and it became Tropical Storm Erin at 1800 UTC 19 August. A continued favorable environment elevated Erin to hurricane strength at 1200 UTC 22 August. By the morning of 23 August a short-wave trough in the westerlies turned Erin toward the northeast. Based upon satellite imagery, Erin strengthened to a 968-mb hurricane with peak winds of 46 $m\ s^{-1}$ by 0000 UTC 25 August. Thereafter, Erin began to accelerate toward the northeast in advance of the frontal trough, weakened to tropical storm strength by 0000 UTC 27 August and became extratropical a short time later.

*f. Hurricane Felix: 26 August–9 September*

Tenacious is the best word to describe Felix. Beginning as a tropical wave that moved off the African coast on 25 August, Felix persevered mostly in the shadow of the much larger and more intense Hurricane Gabrielle, to become the longest lasting tropical cyclone of the season. After emerging from the African coast, Felix turned toward the northwest into a large trough that dominated the eastern Atlantic. During the time period from 25 August to 5 September Felix strengthened to a storm, weakened to a depression, regained storm status and finally attained hurricane strength.

Based upon satellite imagery, the hurricane's minimum central pressure of 979 mb and top winds of 39 m $s^{-1}$ occurred near 0000 UTC 6 September. Four days after becoming extratropical, Felix maintained its identity and remained a large nontropical storm off the coast of Spain.

*g. Hurricane Gabrielle: 30 August–13 September*

Hurricane Gabrielle was a classic Cape Verde-type tropical cyclone. It developed from an African wave near the Cape Verde Islands, tracked westward across the tropical Atlantic while strengthening to a large category four hurricane and eventually recurved into the northern North Atlantic.

Gabrielle had its beginnings as a tropical wave that moved off the coast of Africa on 28 August. The developing wave reached tropical depression strength on the morning of 30 August. A distinct outflow pattern at the 200-mb level provided ventilation for the budding storm and, based upon satellite imagery from the European METEOSAT, the depression was upgraded to Tropical Storm Gabrielle at 0000 UTC 31 August. Gabrielle tracked toward the west-northwest for the next several days and the first reconnaissance aircraft into Gabrielle found a central pressure of 935 mb at 2040 UTC 3 September. The hurricane's central pressure remained in the low 940-mb range for the next three days and strongest measured flight-level (3 km) winds during this period were near 72 m $s^{-1}$. Strongest 1-min surface winds were estimated to be near 64 m $s^{-1}$.

A major trough in the westerlies began to develop over the northwest Atlantic by the evening of 3 September and Gabrielle turned toward the northwest in response to the change in the steering flow associated with the trough. During the next several days Gabrielle continued to turn toward the north and passed about 560 km to the northeast of the northeastern Caribbean Islands. By 10 September Gabrielle became nearly stationary about 880 km east-southeast of Cape Cod, Massachusetts. Located in the center of a broad trough with the westerly jet stream well to the north, the weakening hurricane drifted slowly westward and weakened to tropical storm strength on the 10th and to a depression on the 12th. Another frontal trough moving off the northeastern U.S. coast turned Gabrielle toward the northeast, and by 13 September the depression lost most of its tropical characteristics as it merged with a developing North Atlantic storm off Newfoundland.

Gabrielle was a very large hurricane. The eye diameter never decreased to less than 37 km, and the majority of the time while the hurricane was most intense the eye diameter, based upon aircraft reconnaissance, ranged from 75 to 90 km (Fig. 4). Hurricane-force winds at the surface frequently extended outward 185 km from the center while flight-level winds of 52 m $s^{-1}$ occasionally extended outward to near 185 km. Gabrielle's powerful winds covered a very large area of the ocean and generated large ocean swells, which pounded the shores of the northeastern Caribbean Islands as well as Bermuda and the North American mainland from central Florida to the Canadian Maritimes. Swells ranged from 3 to 5 m along portions of the U.S. east coast and were as high as 7 to 10 m along the south coast of Nova Scotia. The large swells from Hurricane Gabrielle were responsible for 8 deaths along the mid-Atlantic and New England coasts. Accidents ranged from people being swept from jetties while watching the large swells to boats capsizing while trying to enter or leave inlets.

*h. Hurricane Hugo: 10–22 September*

1) SYNOPTIC HISTORY

Hugo, another classic Cape Verde-type hurricane, left a path of death and destruction across the islands of the northeastern Caribbean and over portions of the Carolinas. The origin of Hugo was detected on satellite imagery on 9 September when a cluster of thunderstorms moved off the coast of Africa. A tropical depression formed to the southeast of the Cape Verde Islands and moved westward at 9 m $s^{-1}$ across the tropical Atlantic Ocean, becoming a tropical storm on the 11th and a hurricane on the 13th while located about 2000 km east of the Leeward Islands.

Hugo gradually turned toward the west-northwest and slowed its forward speed as it headed for the Leeward Islands in response to low pressure to the north of Puerto Rico, which represented a weakness in the westward extension of the subtropical high pressure ridge.

Hugo moved directly over the island of Guadeloupe at 0500 UTC on the 17th. The hurricane continued to decelerate and turned toward the northwest. The eye moved over St Croix 24 hours later on the 18th with a forward speed of 4 m $s^{-1}$. The hurricane began to accelerate its forward speed and the eye moved over the island of Vieques, Puerto Rico, at 1200 UTC and then over the extreme eastern tip of mainland Puerto Rico 1300 UTC on the 18th.

Early on the 19th the hurricane was north of Puerto Rico moving toward the north-northwest at 6 m $s^{-1}$.

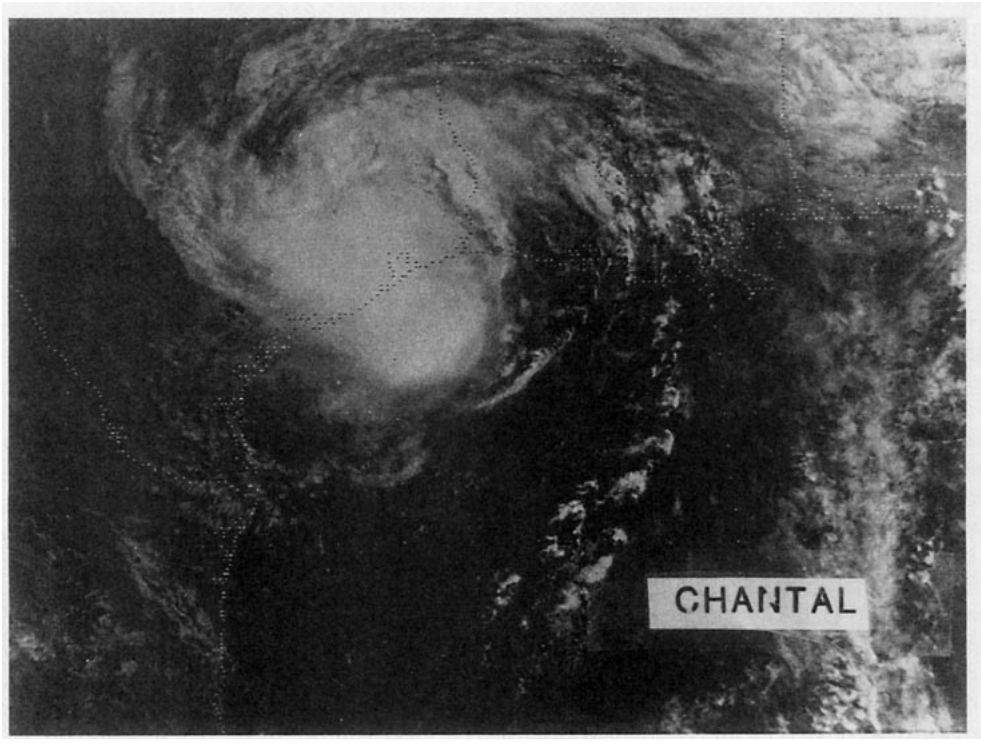


FIG. 4. GOES visible image of Hurricane Gabrielle at 1231 UTC 06 September 1989, over open Atlantic.

By this time the weakness in the subtropical high pressure ridge had diminished and the hurricane's motion was under the influence of the ridge and of an upper-level low pressure system centered over Georgia. Hugo's track curved gently to the northwest over the next few days as the low pressure center moved southwestward and altered the steering flow pattern. By the 21st Hugo was centered a few hundred kilometers east of north Florida (Fig. 5). Hugo began a gradual turn and accelerated toward the north during the following 24 hours in response to the steering flow associated with a major extratropical low that was advancing eastward across the central U.S.

The final landfall was made on the South Carolina coast near Charleston at Sullivans Island at 0400 UTC on the 22nd with the eye moving northwestward at 12 m $s^{-1}$. Moving inland and weakening, the center passed between Columbia and Shaw Air Force Base around 0800 UTC. By 1200 UTC, Hugo had weakened to a tropical storm and passed just west of Charlotte, North Carolina, to near Hickory.

The storm moved northward across extreme western Virginia, West Virginia, eastern Ohio and to near Erie, Pennsylvania, by 0000 UTC on the 23rd and transformed into an extratropical storm. The storm was tracked for two more days as it moved northeastward across eastern Canada and into the far north Atlantic Ocean.

### 2) METEOROLOGICAL STATISTICS

A reconnaissance aircraft first reached Hurricane Hugo on the 15th several hundred miles east of the Leeward Islands. It reported a central pressure of 918 mb, a wind speed of 85 m $s^{-1}$ at an altitude of 500 m and a surface wind speed of 72 m $s^{-1}$. This turned out to be Hugo's maximum intensity and designated the cyclone as a category five hurricane. Table 4 lists selected observations from Hurricane Hugo.

On the 17th, just before Hugo's eye passed over Guadeloupe, an aircraft reported 70 m $s^{-1}$ at 700 mb. A surface pressure of 941.4 millibars has since been reported from Guadeloupe. It is estimated that the hurricane's maximum 1-min surface wind had decreased to 62 m $s^{-1}$ at this time. The maximum surface wind was again estimated at 62 m $s^{-1}$ when the eye passed over St Croix at 0600 UTC on the 18th.

When the eye passed over the island of Vieques, Puerto Rico, the estimated maximum 1-min wind speed had decreased to 57 m $s^{-1}$. On the island of Culebra, just north of Vieques, an anemometer reading of a gust to 76 m $s^{-1}$ was reported from the ship *Night Cap* located in the harbor there. Maximum wind speeds were also estimated at 57 m $s^{-1}$ one hour later when the eye passed over the eastern tip of Puerto Rico. However, the highest recorded wind speed over land was 46 m $s^{-1}$ with a gust to 54 m $s^{-1}$ at Roosevelt

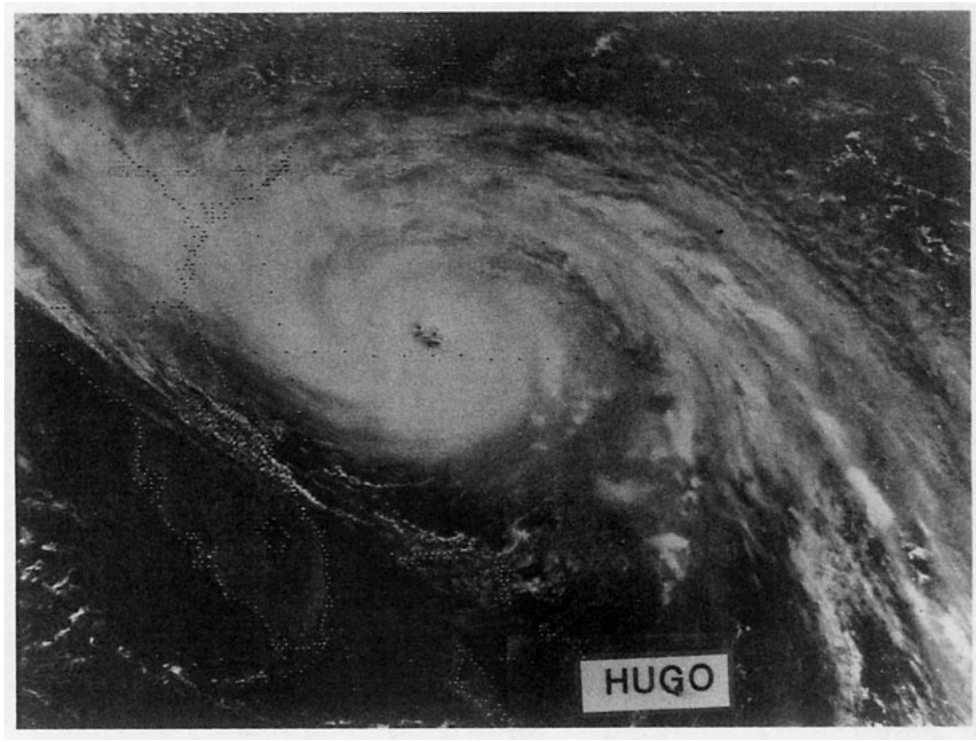


FIG. 5. GOES visible image of Hurricane Hugo at 1801 UTC 21 September 1989, approaching South Carolina coast.

Roads. The highest winds reported at San Juan International Airport were 35 m $s^{-1}$ with a gust to 41 m $s^{-1}$. Rainfall totals ranged up to a maximum of 234 mm at Gurabo in the eastern interior of Puerto Rico. The lowest surface pressure reading from Puerto Rico was 946.1 mb at Roosevelt Roads.

As Hugo moved away from Puerto Rico and headed for the southeastern U.S., its central pressure rose to 966 mb on the 19th and the maximum winds decreased to 46 m $s^{-1}$. Then, during the final thirty hours before landfall near Charleston, Hugo began to reintensify. Just before landfall, a reconnaissance measurement of 934 mb and 72 m $s^{-1}$ winds at an altitude of 3.6 km are the basis of the estimate of the highest 1-min wind speed of 62 m $s^{-1}$ at landfall.

A report of 39 m $s^{-1}$ with a gust to 48 m $s^{-1}$ was received from downtown Charleston. The National Weather Service office at the Charleston Airport measured 35 m $s^{-1}$ with a gust to 44 m $s^{-1}$. A report of 38 m $s^{-1}$ with a gust to 48 m $s^{-1}$ was received from Folly Beach. A hurricane chaser from Miami, Jim Leonard, measured 936.5 mb with a portable barometer on the Savannah Highway just west of Charleston. A report of 933 mb from Mt. Pleasant is unofficial. No wind observations are available from near Bulls Bay where the maximum 1-min winds of 62 m $s^{-1}$ are estimated to have occurred. The ship *Snow Goose* was anchored in the Sampit River 8 km west of Georgetown and measured a pressure of 984.5 mb and sustained winds of 54 m $s^{-1}$ from a three-cup Tradewind anemometer located on the ship's mast at an elevation of 18.5 m.

Hugo was still estimated to be of hurricane strength when its center passed just west of Shaw Air Force Base where winds of 30 m $s^{-1}$ with a gust to 49 m $s^{-1}$ and 959.6 mb pressure were reported. The Columbia WSFO, just west of the center, reported winds of 24 m $s^{-1}$ with gusts to 31 m $s^{-1}$. In North Carolina, winds of 31 m $s^{-1}$ with gusts to 44 m $s^{-1}$ were reported from Charlotte as the center went by, and Hickory had a gust to 36 m $s^{-1}$. Sustained wind speeds in the 15 to 21 m $s^{-1}$ range were reported along and east of the weakening storm's path as it moved northward to Canada.

Few direct tide gauge measurements of the storm surge water levels have been received. The tide station in Charleston near the Custom House measured a water level of 3.9 m above mean lower low water, which converts to a storm tide of 3.2 m above mean sea level or a storm surge of 2.4 m above the predicted normal astronomical tide height. As far north as Hatteras, North Carolina, the storm surge was reported at 1.2 m above the predicted tide. In addition, a considerable number of high water marks gathered by survey teams indicate that the storm tide was 3.0 to 3.6 m above mean sea level at Folly Beach and ranged to near 6.1 m at Bulls Bay, 3.9 to 4.9 m at McClellanville, 3.9 m

TABLE 4. Hurricane Hugo selected surface observations, September 1989.

| Location | Minimum sea-level pressure | | Maximum surface wind speed ($m\ s^{-1}$) | | | Storm surge (tide height above normal) (m) | Rain (storm total) (mm) |
|---|---|---|---|---|---|---|---|
| | Pressure (mb) | Date/time (UTC) | 1-minute average | Peak gust | Date/time (UTC)* | | |
| Guadeloupe | 941.1 | | | | | | |
| St. Maarten | | | | | | | |
| Juliana Airport | | | 21 | 35 | 18/0200 | | |
| Puerto Rico | | | | | | | |
| Gurabo | | | | | | | 234 |
| Isla de Culebra | | | | 76 | | | |
| Isla Verde | 970.3 | 13/1415 | | | | | |
| Luquillo | 956 | 18/1300 | | | | | |
| Roosevelt Roads | 946.1 | 18/1250 | 46 | 54 | 18/1158 | | |
| San Juan | 970.3 | 18/1444 | 35 | 41 | 18/1350 | | 76 |
| Florida | | | | | | | |
| Jacksonville | | | 9 | 11 | 21/2035 | | trace |
| St. Augustine | 1003.5 | 22/0200 | 7 | 13 | 21/1900 | | |
| Georgia | | | | | | | |
| Fort Pulaski | | | | | | 0.4 | |
| St. Simons Island | | | 10 | 21 | 22/0100 | | |
| Savannah Light Tower | 989.6 | 22/0300 | 26 | 30 | 22/0400 | | |
| Savannah WSO | 993.5 | 22/0353 | 15 | 24 | 22/0553 | | 155 |
| South Carolina | | | | | | | |
| Beaufort | 984 | 22/0455 | 14 | 23 | 22/0700 | | 151 |
| Charleston AFB | 943.2 | 22/0423 | | | | | |
| Charleston city | | | 39 | 48 | 22/0340 | | 162 |
| Charleston Pier P | 942 | | | | | 2.4 | |
| Charleston WSO | 942.1 | 22/04— | 35 | 44 | 22/0503 | | 150 |
| South Carolina | | | | | | | |
| Charleston | | | | | | | |
| Savannah hwy | 936.5 | 22/0405 | | | | | |
| Columbia AT&T | 971.7 | 22/0800 | | 44 | 22/0654 | | |
| Columbia WSFO | | | 24 | 31 | 22/0609 | | |
| Florence | 989.1 | 22/0750 | 20 | 28 | 22/0547 | | |
| Folly Beach C-MAN | 940 | 22/0400 | 38 | 48 | 22/0400 | | |
| Georgetown EOC | | | 36 | | 22/0300 | | 95 |
| Mt. Pleasant | 933 | 22/0405 | 37 | 43 | 22/0345 | | 206 |
| Myrtle Beach AFB | 993.5 | 22/0455 | 23 | 34 | 22/0555 | | 58 |
| Sampit River | 984.5 | 22/0442 | 54 | | | | |
| Shaw AFB | 959.6 | 22/0655 | 30 | 49 | 22/0655 | | |
| Summerville | | | | | | | 152 |
| North Carolina | | | | | | | |
| Asheville | 989.9 | 22/1150 | 10 | 17 | 22/1050 | | 49 |
| Boone | | | | | | | 176 |
| Cape Fear River | | | | 31 | 22/0545 | | |
| Carolina Beach | | | | | | 0.9+ | |
| Charlotte | 978.0 | 22/0945 | 31 | 44 | 22/1003 | | 80 |
| Greensboro | 998.1 | 22/1153 | 19 | 24 | 22/1108 | | 36 |
| Hatteras | 1013.1 | 22/0730 | 12 | 15 | 22/0050 | 1.2 | 15 |
| Hickory | 980.5 | | 15 | 36 | 22/1046 | 1.8+ | |
| Holden Beach | | | | 26 | 22/0555 | | |
| Ocean Isle | | | | | | 2.1+ | |
| Raleigh | 1004.6 | 22/0930 | 13 | 21 | 22/1050 | | 11 |
| Wilmington | 1004.5 | 22/0500 | 13 | 24 | 22/0452 | | 20 |
| Virginia | | | | | | | |
| Norfolk | 1008.8 | 22/1950 | 12 | 17 | 22/2050 | 0.1 | 5 |

* Time of 1-min wind speed unless only gust is given.
+ Estimated.

at Myrtle Beach, and 2.4 to 3.0 m at Holden Beach, North Carolina.

Rainfall totals along the southeast U.S. coast ranged from a trace at Jacksonville to 155 mm at Savannah to a maximum of 206 mm at Mt. Pleasant near Charleston to 58 mm at Myrtle Beach to 15 mm at Hatteras. A 240-km wide swath of 76 to 203 mm of rain spread inland across South Carolina. The swath continued over western North Carolina with a maximum of 176 mm reported at Boone. Rainfall totals

were in the 50- to 100-mm range across western Virginia, West Virginia, western Pennsylvania, eastern Ohio and western New York.

3) DEATHS AND DAMAGE

The total number of deaths associated with Hugo is estimated at 49 as follows:

| | | | |
|---|---|---|---|
| South Carolina | 13 | Antigua and Barbuda | 1 |
| North Carolina | 1 | Guadeloupe | 11 |
| Virginia | 6 | Montserrat | 10 |
| New York | 1 | St. Kitts and Nevis | 1 |
| Puerto Rico | 2 | | |
| U.S. Virgin Islands | 3 | | |

Damage figures are astronomical and Hugo is the costliest hurricane in U.S. history. Estimates total near the ten billion dollar mark with seven billion occurring on the U.S. mainland.

*i. Tropical Storm Iris: 16–21 September*

The tropical wave that spawned Tropical Storm Iris moved off the northwest coast of Africa on 12 September immediately behind the wave that spawned Hurricane Hugo. The wave moved westward and became a tropical depression in the wake of Hugo which was then approaching the Lesser Antilles on 16 September.

The tropical depression reached tropical storm strength at 0000 UTC 18 September while located about 725 km east of Barbados. For the next 24 hours, Iris persisted on a general northwesterly track under strong shearing from the outflow of Hugo. Air Force reconnaissance reports at 1809 UTC 19 August, when the center was 435 km northeast of Antigua, indicated that the maximum flight-level winds at 500 m were 37 m $s^{-1}$ and the sea level pressure was 1001 mb. Satellite-estimated winds were near 23 m $s^{-1}$ at that time and in much better agreement with the Dvorak pressure/wind relationship. Thus, it was concluded that Iris probably was just below hurricane strength at that time.

As Hugo moved away from the influence of Puerto Rico and Hispaniola, it reintensified, increasing the shear over Iris. Thus, the strengthening of Iris was short-lived and it weakened rapidly thereafter while following in the wake of Hugo. Iris' low-level center was completely exposed the next day as a result of Hugo's outflow shearing away the convection. It is estimated that Iris weakened to a tropical depression 435 km northeast of San Juan, Puerto Rico, by 0000 UTC 21 September and dissipated about 370 km east-northeast of Turks Island by 0000 UTC 22 September.

*j. Hurricane Jerry: 12–16 October*

1) SYNOPTIC HISTORY

On 23 September a westward-moving tropical wave emerged from the northwest coast of Africa and moved across the tropical Atlantic into the Caribbean Sea with no additional signs of organization. The wave's westward motion decreased over the Yucatan Peninsula where a broad area of low pressure became evident in the surface pressure field and in the low cloud motions. On the morning of 12 October the wave moved off the Yucatan Peninsula into the Bay of Campeche and developed into a tropical depression.

The depression moved slowly toward the north-northwest and strengthened to a tropical storm by 0000 UTC on the 13th. Tropical Storm Jerry moved generally northward at near 4 m $s^{-1}$ on the 13th while continuing to strengthen. After some hesitation in forward speed, some shearing and a temporary turn to the northeast on the 14th, Jerry turned back toward the north-northwest on the 15th. The shear diminished, deep convection began developing near the center of the storm, and the cyclone reached hurricane status by 1800 UTC on the 15th. Steering currents became somewhat stronger as a high pressure ridge built over the eastern Gulf of Mexico, and Hurricane Jerry's forward motion increased to slightly more than 5 m $s^{-1}$ as it moved toward the upper Texas coast.

Based on aircraft reconnaissance reports, Hurricane Jerry deepened 13 mb over a 13-hour period prior to landfall on the 15th. While this does not qualify as rapid deepening, it is approximately twice as fast as the deepening observed on 12 and 13 October. Figure 6 shows Hurricane Jerry as a category-one hurricane just prior to striking the upper Texas coast.

The center of Hurricane Jerry made landfall on Galveston Island near Jamaica Beach at approximately 0030 UTC 16 October as a category one hurricane. No hurricane has made landfall on the upper Texas coast as late in the season as did Jerry. Once over land, Jerry turned toward the north and then north-northeast over eastern Texas at an increasing forward speed. The hurricane weakened rapidly and was downgraded to a tropical storm by 0600 UTC on the 16th, and to a tropical depression by 1200 UTC. Later that afternoon, the remnants of Jerry were absorbed by a frontal trough over southwest Arkansas.

2) METEOROLOGICAL STATISTICS

Maximum 1-min surface winds of 34 m $s^{-1}$ with gusts to 45 m $s^{-1}$ were measured at Scholes Field on Galveston Island as the eyewall passed over the airport. The observation site lost power near this time, and the observer estimated maximum sustained winds reached 36 m $s^{-1}$ with gusts of 50 m $s^{-1}$ shortly after the power outage. The Galveston Weather Service Office, located to the east of Scholes Field, reported sustained winds of 21 m $s^{-1}$ with gusts to 39 m $s^{-1}$. Table 5 lists selected observations from Hurricane Jerry.

An extrapolated minimum pressure of 982 mb was reported by a NOAA aircraft and by an Air Force plane on the 15th, just prior to landfall. The minimum pressure of 983 mb at the time of landfall was reported

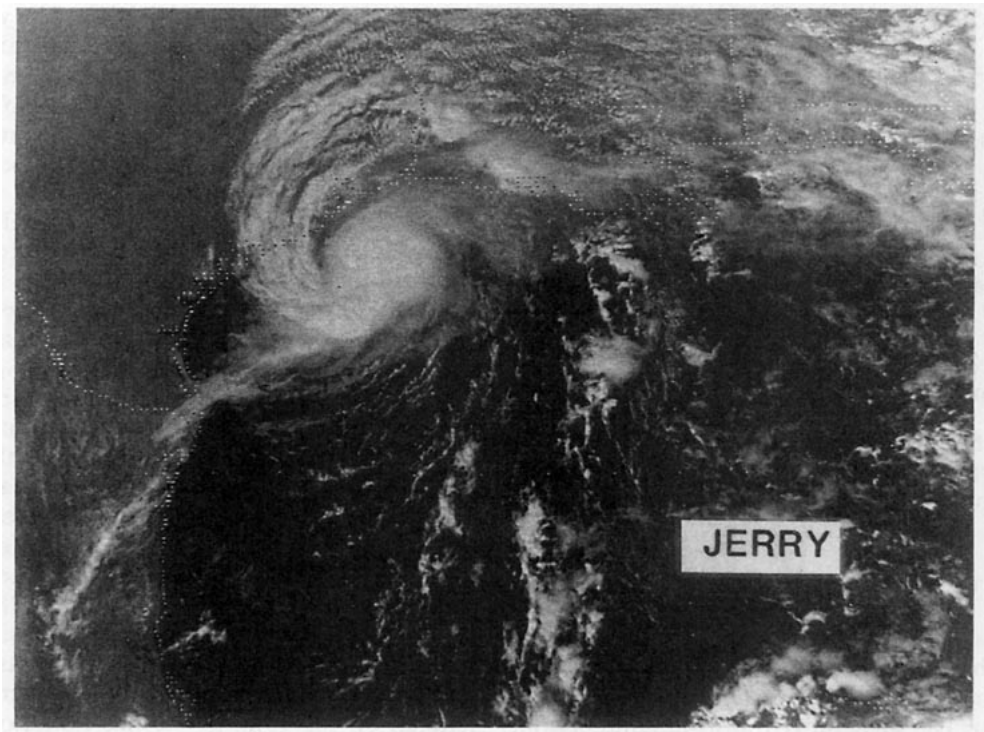


FIG. 6. GOES visible image of Hurricane Jerry at 1931 UTC 15 September 1989, approaching upper Texas coast.

from an Air Force plane as the eye passed over Galveston Island.

Largest rainfall totals occurred at Silsbee, Friendship and Anahuac, Texas, where 24-hour totals ending the morning of 16 October were 163, 121 and 114 mm, respectively.

3) DEATH AND DAMAGE

The death toll in Jerry was three, again as in Allison and Chantal, all by drowning. The American Insurance Association reports 35 million dollars as the insured property damage for Texas. Hurricane damage estimates for past storms, however, have often been two to three times the insured property damage, and the final damage total is estimated to be near 70 million dollars.

*k. Tropical Storm Karen: 28 November–4 December*

Karen, the late season storm, had its start from a tropical wave that moved off the west coast of Africa

TABLE 5. Hurricane Jerry selected surface observations, October 1989.

| Location | Minimum sea-level pressure | | Maximum surface wind speed ($m\ s^{-1}$) | | | Storm tide (height above MSL) (m) | Rain** (mm) |
|---|---|---|---|---|---|---|---|
| | Pressure (mb) | Date/time (UTC) | 1-minute average | Peak gust | Date/time (UTC)* | | |
| Texas | | | | | | | |
| Scholes field, Galveston | 987.6 | 16/0034 | 34 | 45 | 16/0034 | | 30 |
| Galveston WSO | 994.2 | 16/0018 | 21 | 39 | 16/0100 | | 37 |
| Houston Hobby (HOU) | 997.0 | 16/0250 | 13 | 17 | 15/2350 | | 4 |
| Houston Intercontinental (IAH) | | | 9 | 15 | 16/0150 | | trace |
| Houston WSO, Alvin | | | | | | | 6 |
| Anahuac | | | | | | 1.6 | 114 |
| Flagship Pier, Galveston | | | | | | 1.8 | |
| Baytown | | | | | | 2.1 | |
| Sabine Pass | | | | | | 0.7 | |
| Friendship | | | | | | | 121 |
| Silsbee | | | | | | | 163 |

* Time of 1-min wind speed.
** 24 hour total ending 16/1200 UTC.

on 13 November. Convection associated with the system did not become concentrated until 24 November, when under the influence of a well-established 200-mb anticyclone, organized convection began to develop to the south of Jamaica. A broad low-level circulation gradually began to develop during the following several days as the wave drifted toward the west. Satellite imagery indicated, and aircraft reconnaissance confirmed, that the 15th tropical depression of the season formed by 1200 UTC 28 November.

The depression drifted toward the north-northwest reaching tropical storm strength by 0000 UTC 30 November near the Isle of Youth, Cuba. By 1800 UTC Karen reached a minimum central pressure of 1000 mb with strongest winds of 26 m $s^{-1}$. Karen was a wet storm that dumped from 254 to 380 mm of rain over portions of western Cuba.

By the afternoon of 30 November, strong high pressure over the Gulf of Mexico forced Karen to begin to move toward the south and southwest for the following several days. Finally by 0600 UTC 4 December, an Air Force reconnaissance aircraft was unable to locate a circulation center and the last advisory on Karen was issued. However during the following day or two remnants of Karen were tracked over Nicaragua.

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