

ANNUAL SUMMARIES

Atlantic Hurricane Season of 1988

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ABSTRACT

The 1988 hurricane season is summarized, including accounts of individual storms. Twelve tropical storms were tracked, of which five became hurricanes. Gilbert and Joan were devastating hurricanes in the Caribbean Sea and Gulf of Mexico, and Gilbert's sea level pressure fell to a new record minimum for Atlantic hurricanes.

1. Introduction

Nineteen tropical cyclones were tracked in the Atlantic–Gulf of Mexico–Caribbean region during 1988. Twelve of these reached tropical storm intensity with a maximum 1-min surface wind speed of 17 m s^{-1} (34 knots) or higher, and 5 of the 12 reached hurricane intensity with a wind speed of 33 m s^{-1} (64 knots) or higher. This compares to the past 50-year average of 9.5 tropical storms of which 5.6 became hurricanes. Tropical storm and hurricane tracks are shown in Fig. 1 and additional statistics are given in Table 1. These tracks and statistics are based on a “best track” post-analysis of all available data.

Four hurricanes and three tropical storms made landfall. Gilbert wreaked havoc from Jamaica westward across the Yucatan Peninsula to northeast Mexico and was responsible for an estimated 318 deaths. Joan moved across the extreme southern Caribbean and Central America and was responsible for 216 deaths.

Gilbert's sea level pressure fell to 888 mb in the northwest Caribbean Sea on 13 September, a new record minimum for western hemisphere tropical cyclones. The world record minimum sea-level pressure for tropical cyclones is 870 mb, measured in Typhoon Tip in the western Pacific Ocean in 1979 (Dunnavan and Diercks 1980).

Three hurricanes had a maximum 1-min wind speed of 64 m s^{-1} or higher during 1988 (Table 1); the last time three hurricanes attained this speed during a season was 1961. Also, 64 m s^{-1} is the highest wind speed on record for a hurricane as far south as Joan.

National Hurricane Center official track forecast errors were low this year, some 30 to 40 percent lower than the average for the previous ten years. These errors are given in Table 2. Hurricanes Gilbert, Helene and Joan accounted for most of this year's forecasts and their tracks were, for the most part, quite smooth, such

that persistence of the initial motion was the most important forecast factor.

2. Individual storms

a. Tropical Storm Alberto, 5–8 August

The season's first named storm originated within a trough that formed off the South Carolina coast on 4 August. A low-level circulation was detected on satellite imagery on the next day as a tropical depression formed. The depression moved northeastward in advance of an approaching front and reached tropical storm intensity on the 7th, while centered just south of Nantucket, Massachusetts. The assignment of tropical storm status is based on estimates of the 1-min surface wind speed using satellite data and the Dvorak (1984) technique.

Tropical storm warnings were issued on the 7th from Bar Harbor to Eastport, Maine, however, tropical storm force winds remained over the water to the east of Maine. Alberto moved over Nova Scotia without significant effect and became extratropical near Newfoundland.

b. Tropical Storm Beryl, 8–10 August

The first signs of a low-level circulation were within a low pressure area located on the Mississippi coast on 4 August. By the 8th, a depression formed when a well-defined surface circulation appeared in southeastern Louisiana. The circulation center drifted southeastward to the Gulf of Mexico as surface winds increased to tropical storm force and tropical storm warnings were issued from Morgan City, Louisiana to Pensacola, Florida on the morning of the 8th. The slowly moving storm reversed its course and moved northwestward across southeastern Louisiana on the 9th and dissipated on the 10th over west-central Louisiana.

A selection of surface observations is listed in Table 3. The maximum 1-min surface wind speed reported over land was 21 m s^{-1} at Gulfport, Mississippi. Over the Gulf of Mexico, an oil rig and a ship both reported

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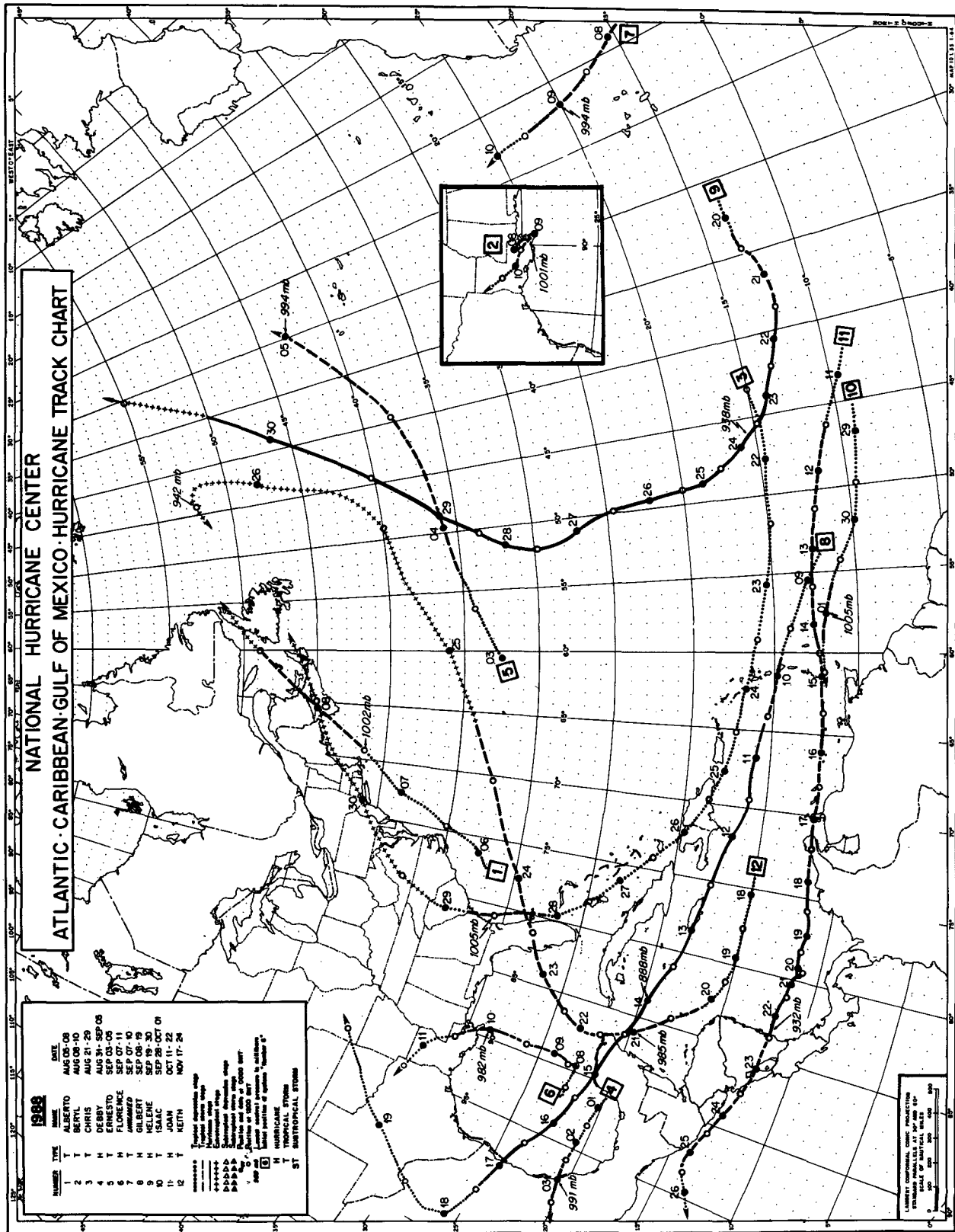


FIG. 1. Tropical storm and hurricane tracks of 1988.

TABLE 1. 1988 Atlantic hurricane season statistics.

Number	Name	Class*	Dates**	Maximum 1-min wind ($m s^{-1}$)	Minimum sea-level press. (mb)	U.S. damage (\$ millions)	Deaths
1	Alberto	T	5-8 Aug	18	1002		
2	Beryl	T	8-10 Aug	23	1001	3.0	1
3	Chris	T	21-29 Aug	23	1005	0.5	4
4	Debby	H	31 Aug-5 Sep	33	991		10
5	Ernesto	T	3-5 Sep	28	994		
6	Florence	H	7-11 Sep	36	982	2.5	1
7	Unnamed	T	7-10 Sep	26	994		
8	Gilbert	H	8-19 Sep	82	888	50.0	318
9	Helene	H	19-30 Sep	64	938		
10	Isaac	T	28 Sep-1 Oct	21	1005		
11	Joan	H	10-23 Oct	64	932		216
12	Keith	T	17-24 Nov	32	985	3.0	

* 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.

1-min wind speeds of 24 $m s^{-1}$. The peak storm surge reported was 1.7 m above normal astronomical tide at Bayou Bienvenue, Louisiana. Storm rainfall totals ranged from 100 to 300 mm over the southern portions of Louisiana, Mississippi and Alabama, and east Texas also received amounts in the 300-mm range from the storm's remnants. A drowning death in Alabama has been attributed to Beryl and the U.S. damage estimate is \$3 million.

c. Tropical Storm Chris, 21-29 August

A tropical wave moved off the coast of Africa on 15 August. Its track across the tropical Atlantic followed the southern periphery of the subtropical high pressure ridge. By the 21st when the wave was halfway between Africa and the Lesser Antilles, satellite imagery indicated that a low-level circulation had formed. Now a depression, the system continued moving westward, eventually affecting the islands of the northeast Caribbean. Just over 100 mm of rain fell on Puerto Rico on the 24th, causing three deaths.

Early on the 28th, while the depression was accelerating northward just offshore of southeast Florida, a ship reported 21 $m s^{-1}$ sustained winds 95 km northeast

of the center. The system was upgraded to Tropical Storm Chris with tropical storm warnings issued from Savannah, Georgia to Cape Hatteras, North Carolina. The rapidly accelerating cyclone crossed the South Carolina coast by midday just north of Savannah. Table 4 gives a selection of surface observations associated with Chris. The maximum 1-min wind was 19 $m s^{-1}$ at the Savannah Light Tower.

Weakening to a depression over the Carolinas only 12 hours after becoming a storm, Chris merged with a cold front to become extratropical. Rainfall totals ranged from 75 mm to 130 mm in a swath from South Carolina through Pennsylvania and into Vermont. One death resulted from a tornado in South Carolina.

d. Hurricane Debby, 31 August-8 September

The tropical wave from which Debby originated was the same one that spawned Chris. While the northern part of this wave transformed into Chris near Florida, the southern portion of the wave continued moving westward. On 31 August, this disturbance became a tropical depression over the southeast Bay of Campeche in the Gulf of Mexico. Drifting slowly westward, the depression strengthened to a tropical storm early on 2 September. Later that day, based on an aircraft reconnaissance estimated surface wind of 36 $m s^{-1}$, Debby became the season's first and shortest-lived hurricane. The government of Mexico quickly issued hurricane warnings from Vera Cruz northward to Punta Jerez and the hurricane made landfall 6 hours later, near Tuzpan, late on the 2nd.

Weakened by mountainous terrain, the remnants of Debby were tracked across Mexico by satellite into the Pacific Ocean. The weak circulation drifted northward for several days before finally dissipating in the Gulf of California on 8 September. No meteorological observations were received from the landfall area, but

TABLE 2. Official track forecast errors (km) in the Atlantic. A track forecast error is defined as the great circle distance between the forecast position and a post-analysis best-track position for the same time. Errors are computed for all tropical cyclones with maximum 1-min surface wind speed of 17 $m s^{-1}$ (34 kt) or higher.

	Forecast period (h)					
	0	12	24	36	48	72
1988 averages	22	74	133	193	265	432
(Number of cases)	(152)	(152)	(131)	(118)	(108)	(89)
1978-87 averages	35	109	219	—	448	673

TABLE 3. Tropical Storm Beryl selected surface observations, August 1988.

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)*		
Louisiana							
Bayou Bienvenue						1.7	
Bogalusa							76
Mandeville						0.9	
New Orleans (MSY)	1001.9	09/1030	11	16	09/0100		39
New Orleans (NBG)	1002.2	09/0955	9	15	09/0120		
New Orleans (NEW)	1001.9	09/0951	12	18	09/0705		71
Paris Road						1.5	
Reserve							101
Rigolets						0.9	
Thibadaux							132
Mississippi							
Bay St. Louis							254
Biloxi						1.0	
Gulfport	1005.3	09/0600	21	23	08/0900	1.4	
Keesler AFB	1006.4	09/0752	12	19			68
Pass Christian						1.2	
Alabama							
Bay Minette							106
Fairhope							171
Foley							261
Gulf Shores							254
Dauphin Island							
Sea Lab	1008.1	09/0550	17	24	09/0743		300
Mobile	1009.5	09/0851	12	17	09/0851	0.6	129
Point Clear							212
Silverhill							119
Stapleton							100
Florida							
Pensacola (PNS)	1011.7	09/0950	9	11	08/1714		32
Pensacola (NPA)	1010.7	09/0655	10	17	09/1404		59

* Time of 1-min wind speed.

TABLE 4. Tropical Storm Chris selected surface observations, August 1988.

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)*		
Georgia							
Fort Pulaski						+0.5	
Savannah Light Tower (SVLS1 70 ft ele.)			19	22	28/1500		
Savannah (SAV)	1009.6	28/1554	8		28/1351		
Tybee MARS			16		28/1545		
South Carolina							
Beaufort (NBC)	1008.7	28/1610	12	17	28/1155		49
Charleston (CHS)	1013.9	28/1800	15	18	28/1257		68
Charleston City						+0.2	18
Myrtle Beach (MYR)			10	18	28/1455	+0.3	41
North Carolina							
Cape Hatteras (HAT)	1019.9	29/0850	7	11	29/1650		
Oak Island			10	15	28/1745		
Wilmington (ILM)	1017.7	29/0850	7	12	28/1450		
Wrightsville Beach			10		28/1745		

* Time of 1-minute wind speed.

press reports indicated that inland flooding and mud slides caused 10 deaths in Mexico.

e. Tropical Storm Ernesto, 3–5 September

An area of disturbed weather associated with a tropical wave turned northwestward while still far out in the central tropical Atlantic. The system was just east of Bermuda on 2 September when ship observations indicated that a surface low pressure area was associated with it. Recurving toward the northeast, it became a tropical depression on the 3rd and was upgraded to a tropical storm 6 hours later, based on satellite intensity estimates and ship reports. Tropical Storm Ernesto accelerated northeastward and was absorbed by a large extratropical storm over the North Atlantic. The only land area affected by the storm was the Azores where sustained winds of 16 m s^{-1} were reported from the island of Flores as the center of Ernesto passed 370 km to the northwest.

f. Hurricane Florence, 7–11 September

On 7 September, a circulation formed in the south-central Gulf of Mexico within an area of cloudiness that previously had been associated with a frontal cloud band. The system quickly strengthened to a tropical storm, initially drifting eastward, and then turning northward during the next two days. On the 9th, it accelerated toward the northern Gulf Coast and became a hurricane just before making landfall over southeastern Louisiana. Hurricane warnings were issued from Cameron, Louisiana to Pensacola, Florida and tropical storm warnings were issued from Pensacola to Apalachicola, Florida. Florence quickly weakened as it moved over the New Orleans area and dissipated on the 11th in east Texas.

Florence was a hurricane for only 12 hours. The highest sustained wind near the surface was 36 m s^{-1} , reported from an oil rig near the Mississippi River Delta. Florence's lowest surface pressure, estimated from Air Force reconnaissance, was 982 mb. Rainfall totals ranged up to 100 mm along the path of the storm. Storm surge water levels rose from 1 to 2 m above normal along the southeast Louisiana and Mississippi coasts just east of where the center moved ashore. Table 5 gives selected surface observations associated with Florence. Several tornadoes and inland river flooding were reported from the western Florida panhandle, far from the center of the hurricane. As a result of Florence, one fisherman died in Mobile Bay while trying to secure his boat. The damage total is estimated at \$2 500 000, primarily in southeastern Louisiana.

g. Unnamed Tropical Storm, 7–10 September

While Florence and Gilbert were forming further west, an area of disturbed weather moved off the African coast. On 7 September, based on satellite imagery,

the area became a depression while only 160 km off the African coast. An after-the-fact review of ship data indicated that the depression actually reached tropical storm strength that same day when at least three nearby ships reported winds of 18 m s^{-1} . The storm moved north-northwestward for the next two days and merged with a large low-pressure trough. The storm track remained east of 25 degrees west longitude and there were no effects to land.

h. Hurricane Gilbert, 8–19 September

1) TRACK AND INTENSITY

Gilbert was detected on satellite imagery as a tropical wave on 3 September, near the coast of Africa. The wave moved westward without distinction across the tropical Atlantic and a low-level circulation developed within the wave on the 8th, several hundred miles east of the Lesser Antilles. The track of Gilbert in Fig. 1 begins at tropical depression stage at this time.

A reconnaissance aircraft investigated late on the 9th and the depression was upgraded to a tropical storm based on a 21 m s^{-1} flight-level wind speed and a sea-level pressure estimate of 1003 mb. Gilbert was monitored by aircraft for the next week as it intensified and moved across the Caribbean and Gulf of Mexico. The direction of motion of Gilbert's center was rather steady, being toward 280 degrees over the eastern Caribbean and gradually turning toward 300 degrees by the time of final landfall at the northeast coast of Mexico. A recurvature toward the northeast occurred only after the hurricane was well inland over Mexico.

Figure 2 is a time series of the minimum sea-level pressure measurements or estimates obtained by U.S. Air Force and NOAA reconnaissance during the 70 aircraft penetrations into the center of Gilbert. The average duration between center penetrations was 2.4 h for the 7-day period.

Gilbert is estimated to have become a hurricane late on the 10th while centered to the south of Puerto Rico, when an aircraft reported a wind speed of 36 m s^{-1} at the 700-mb level and a sea-level pressure of 984 mb.

The central pressure decreased to near 960 mb by the 12th, when the center passed directly over the length of Jamaica. Figure 3 is a satellite picture showing the eye over the eastern tip of this island. A 1-min wind speed of 52 m s^{-1} was measured at Robert Manley International Airport near Kingston and 54 m s^{-1} was reported by a nearby ham radio operator. The center moved back over water on the 13th and the hurricane began to intensify rapidly as the center passed some 30 km to the south of Grand Cayman Island, where a 1-min wind speed of 61 m s^{-1} was reported.

The central pressure dropped from 962 mb at 2245 UTC 12 September to 888 mb at 2152 UTC 13 September. This is a deepening rate of 3.2 mb h^{-1} sustained for a period of 23 h. Willoughby et al. (1989) describe

TABLE 5. Hurricane Florence selected surface observations, September 1988.

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)*		
Louisiana							
Tower (GDIL1)**	999.5	09/2300	19	21	09/2200		
Tower (P26)**	999.0	09/2311	27		09/1711		
Tower (BURL1)**	988.0	10/0200	29	34	09/2300		
Coast Guard (8R3)	987.0	10/0200	26	28	09/2300		
Belle Chase (NBG)	990.9	10/0735	15	22	10/0555		
Tower (MP73)**	995.0	10/0711	36		10/0511		
New Orleans (NEW)	994.3	10/0751	18	27	10/0725		
Moisant (MSY)	994.5	10/0851	18	24	10/0750		25
Mid Lake Causeway			19	26	10/0800		
Paris Road					10/0620	1.4 [†]	
Bayou Bienvenue					10/0800	1.8	
Industrial Canal					10/0800	1.7	
West End Marina					10/0800	1.2	
Rigolets					10/0900	0.9	
North Lake Causeway					10/1200	1.1	
Mississippi							
Keesler AFB	1005.8	10/0530	8	10	10/0003		43
Hancock Co.							
Emergency Ops. Ctr.	1005.8	10/0730	25 ^{††}		10/1000		132
McComb (MCB)	1005.2	10/1200	8		10/0750		
Jackson (JAN)			9		10/2057		
Pass Christian						1.6	
Alabama							
Dauphin Island	1008.1	09/2330	18	22	10/0012		
Mobile (MOB)	1008.8	10/0043	12		09/2352	0.6	73
Florida							
Pensacola (NPA)	1008.8	09/2255	10		09/0245		131
Pensacola (PNS)	1009.4	10/0748	8		10/0450		70

* Time of 1-min wind speed.

** Height unknown.

† Gage failed.

†† Estimated.

the procedure used to determine the 888-mb sea level estimate from the 700-mb D-value measured on a NOAA aircraft in the center of the hurricane. The peak 700-mb wind speed measured during this flight was 89 m s^{-1} , 11 km north of the center. The maximum best-track 1-min surface wind speed estimate is 82 m s^{-1} . Figure 4 is a satellite picture of the center near this time.

Gilbert made landfall on the Yucatan Peninsula on the 14th. A satellite picture of the eye at the coast is shown in Fig. 5. The highest 1-min wind speed at landfall is estimated at 72 m s^{-1} . Gilbert weakened over land and then moved across the Gulf of Mexico for two days with a central pressure staying near 950 mb. The final landfall occurred late on the 16th as the center moved inland (Fig. 6) near La Pesca, Mexico. The peak landfall wind speed is estimated at 57 m s^{-1} . Table 5 lists selected U.S. landfall observations. The 30 m s^{-1} 1-min wind speed reported from South Padre

Island, Texas was over 200 km north of the center. Gilbert weakened after moving inland and recurved across Texas and Oklahoma where it merged with a frontal low-pressure system.

2) FLOODING

Coastal storm surge flooding produced tides up to 2.7 m above normal on the northeast coast of Jamaica and 1.5 m above normal at Grand Cayman. It is likely that higher surges were associated with the two Mexico landfalls. The highest surge value reported from Texas (Table 6) was 1.8 m at south Padre Island.

Inland flash flooding in Jamaica was the result of over 700 mm of rain over interior mountains during 10–14 September. Gilbert's large horizontal extent resulted in significant rainfall as far away as Venezuela and Costa Rica. The highest rainfall total from Texas was 137 mm.

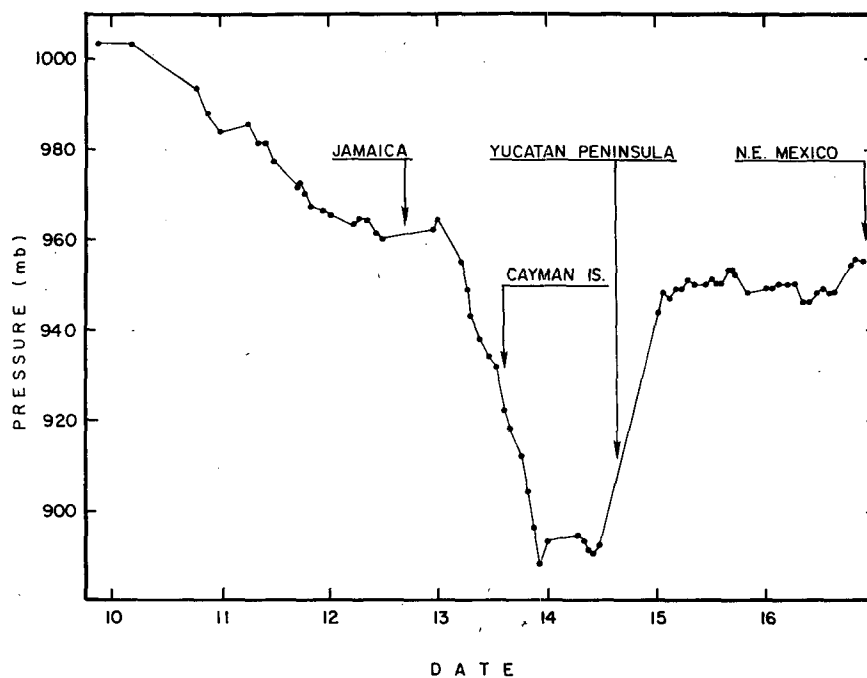


FIG. 2. Hurricane Gilbert's minimum sea level pressure as a function of time, September 1988. Dates start at 0000 UTC. Pressure values are from aircraft reconnaissance center fix data and are either dropsonde measurements or estimates based on flight-level D-values.

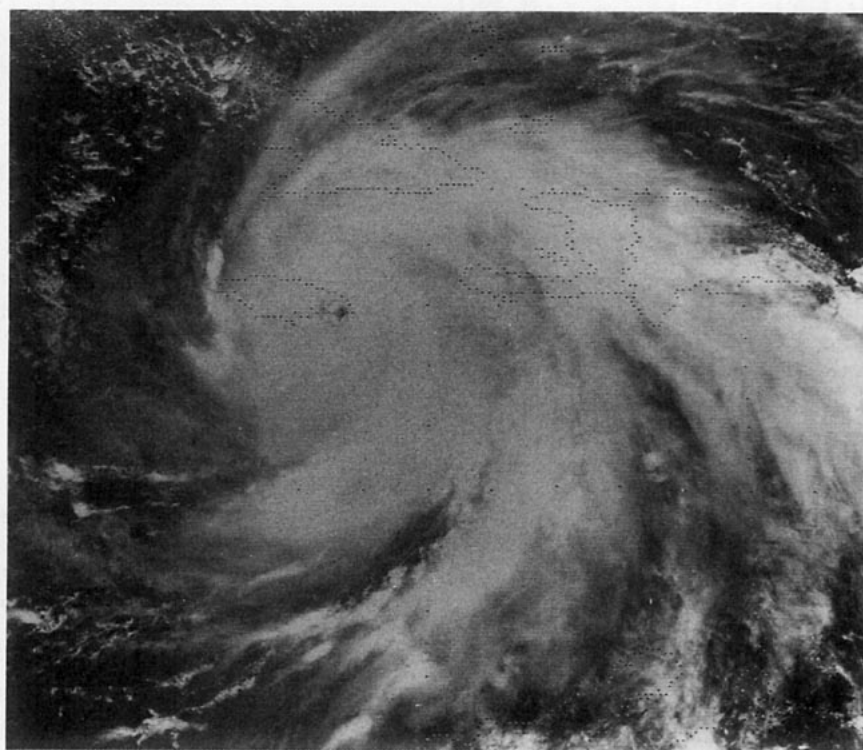


FIG. 3. Geostationary, visible satellite picture of Hurricane Gilbert at 1701 UTC, 12 September 1988, as its center begins to move directly across Jamaica.

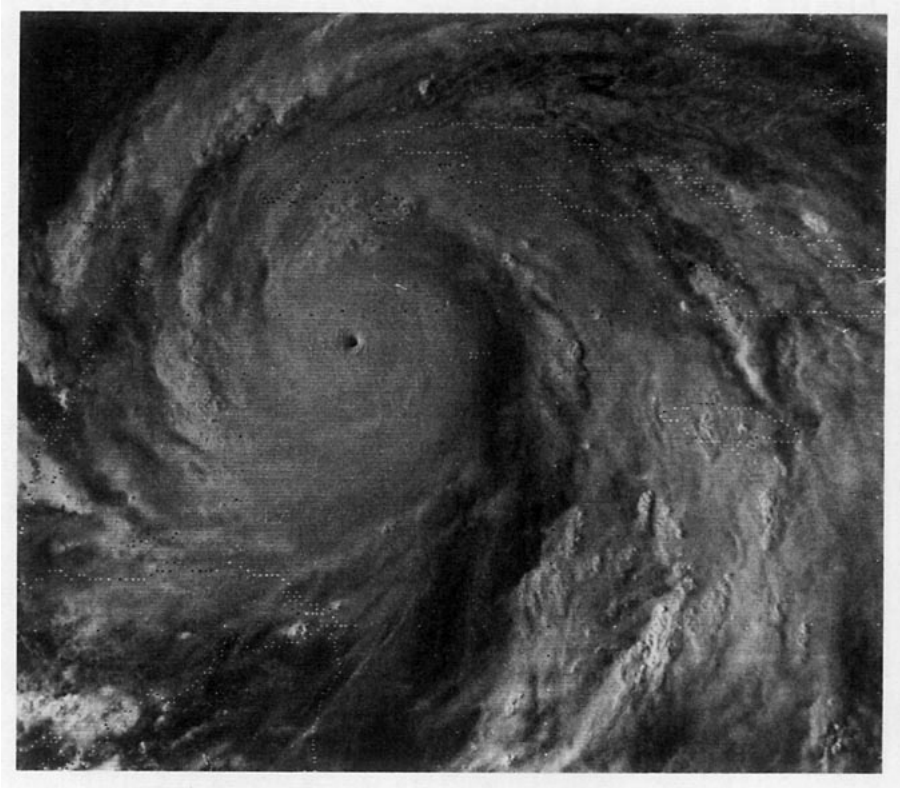


FIG. 4. Geostationary, visible satellite picture of Hurricane Gilbert at 2131 UTC 13 September 1988, 21 min prior to the 888-mb sea level pressure estimate.

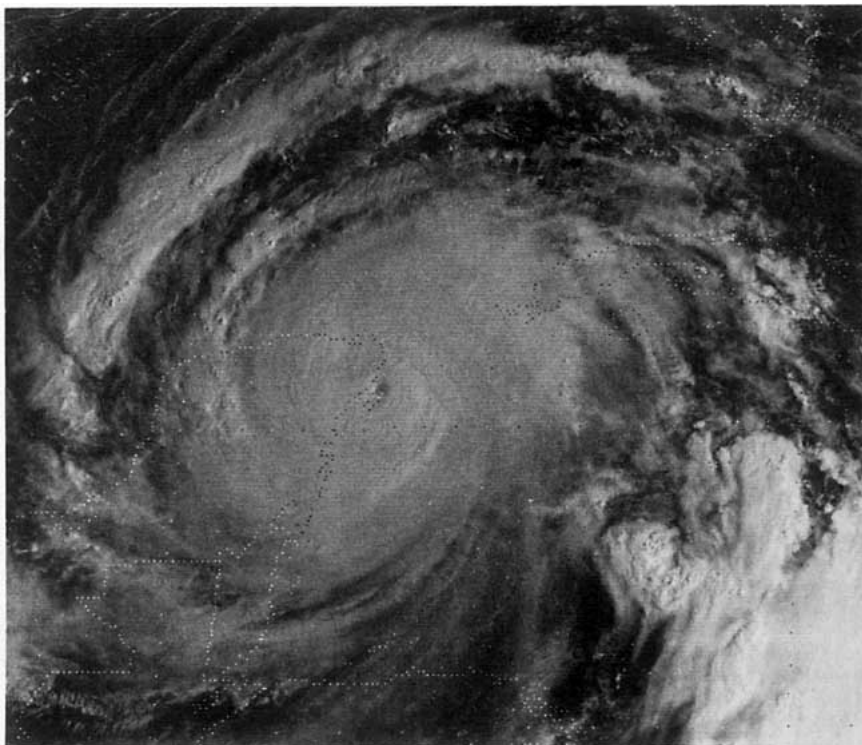


FIG. 5. Geostationary, visible satellite picture of Hurricane Gilbert at 1331 UTC 14 September 1988, as its center approaches Cozumel, Mexico.

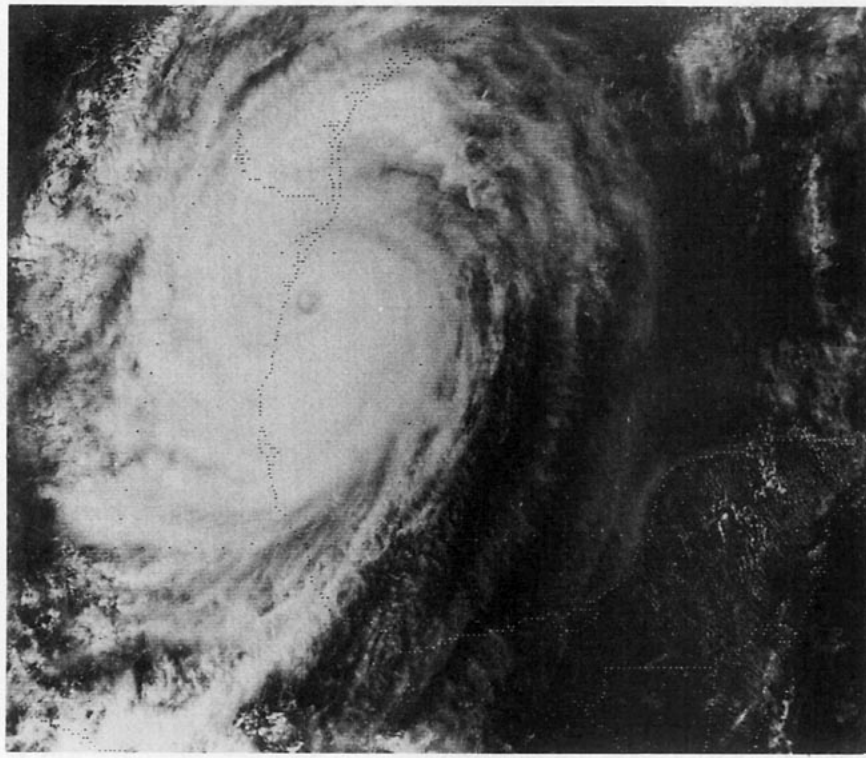


FIG. 6. Geostationary, visible satellite picture of Hurricane Gilbert at 1931 UTC, 16 September 1988, as it makes a final landfall near La Pesca, Mexico.

3) HURRICANE WARNINGS

Hurricane warnings were issued for seven countries. The south coasts of the Dominican Republic and Haiti were first; followed by Jamaica; the Cayman Islands; the south coast of Cuba east of Camaguey and the Province of Pinar del Rio and the Isle of Youth; the Yucatan Peninsula of Mexico from Chetumal to Champoton and northeast Mexico from Tampico

northward; and the U.S. Texas coast from Port O'Connor southward.

4) DEATHS AND DAMAGES

The death toll is estimated to be 318, including: Mexico 202, Jamaica 45, Haiti 30, Guatemala 12, Honduras 12, Dominican Republic 5, Venezuela 5, United States 3, Costa Rica 2 and Nicaragua 2. The

TABLE 6. Hurricane Gilbert selected surface observations, September 1988.

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							
Beeville							114
Brownsville	995.3	16/2135	21	30	16/1809		137
Corpus Christi	1006.8	16/1952	16	27	17/0631		67
Flour Bluff							119
Galveston	1011.0	15/2100	11	17	16/1254	1.3	6
North Padre Island			19	26		1.3	
Port Arthur	1012.0	15/2115	10	14	15/2048	1.2	1
South Padre Island	997.6	16/2210	30	37	17/0118	1.8	
Victoria	1009.8	15/2055	13	18	15/2119		31

* Time of 1-min wind speed.

deaths reported from Costa Rica, Guatemala, Honduras, Nicaragua and Venezuela were caused by inland flash flooding.

Damage estimates include \$2 billion each for Jamaica and Mexico. The U.S. damage total is \$50 million, much of this from 29 confirmed tornadoes in south Texas. The approximate total international damage estimate for Gilbert is \$5 billion.

i. Hurricane Helene, 19–30 September

On 15 September, as Gilbert was entering the Gulf of Mexico, a tropical wave moved off the African coast. The convective activity associated with the wave organized into a depression on the 19th, increased to tropical storm intensity on the 20th and became a hurricane on the 21st, while located over the midtropical Atlantic. Helene began a northward turn on the 23rd and for the next week moved northward. On the 28th Helene began to turn toward the northeast and accelerated. It became an extratropical system on the 30th in the far north Atlantic.

The hurricane remained at sea throughout its existence and was monitored solely by satellite. A well-defined eye was observed for a number of days and it is estimated that Helene's winds reached a maximum of 64 m s^{-1} on the 23rd. Figure 7 is a satellite view of Helene near the time of maximum intensity. Helene

was estimated to be a hurricane for 9 days, making it the longest-lived hurricane for this season.

j. Tropical Storm Isaac, 28 September–1 October

The origin of Isaac was traced back to a weak disturbance located near the African coast on 23 September. The westward moving disturbance gradually became better organized and became a depression on the 29th. It was upgraded to a tropical storm late on the 30th when an Air Force reconnaissance plane reported flight-level winds of 26 m s^{-1} , while its center was about 370 km east southeast of Barbados. Tropical storm warnings were issued for the islands of Barbados, the Grenadines, St. Vincent, St. Lucia, Dominica and Martinique and tropical storm watches were posted for the islands of Trinidad, Tobago and Grenada. Nevertheless, the storm quickly weakened and dissipated. No reports of damage or death were associated with Isaac.

k. Hurricane Joan, 10–23 October

Joan originated as a low-latitude disturbance near the coast of Africa on 5 October and, by the 10th, a tropical depression formed in the midtropical Atlantic. The depression strengthened to a tropical storm on the 11th, which then moved across the southern Windward Islands on the 14th.

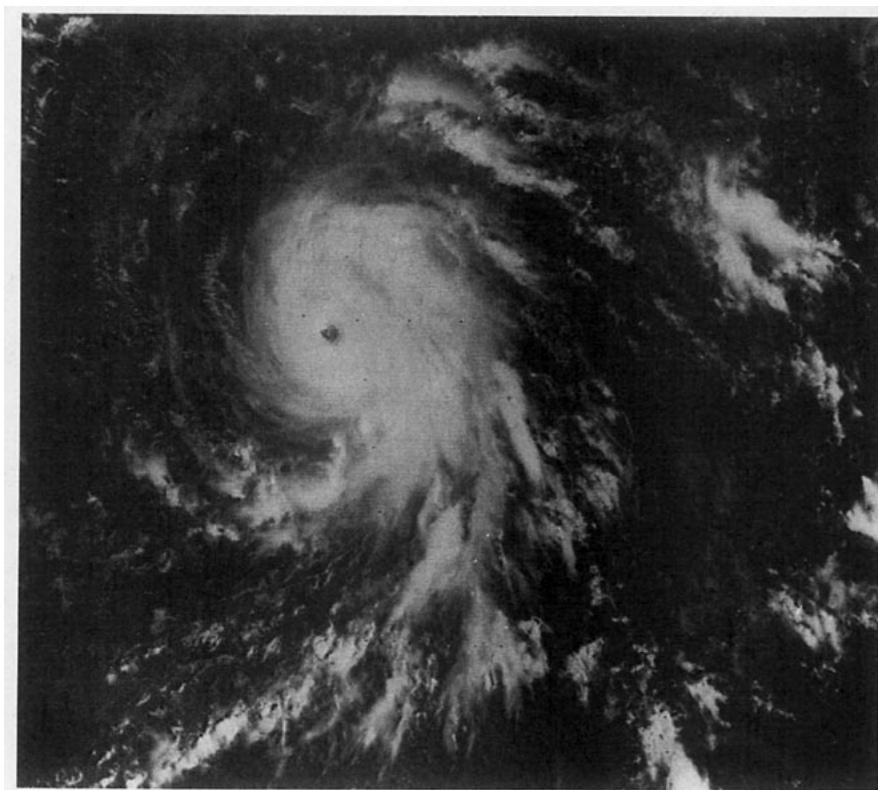


FIG. 7. Geostationary, visible satellite picture of Hurricane Helene at 1301 UTC 23 September 1988, far out in the Atlantic Ocean.

Joan's track across the extreme southern Caribbean was unusually far south. The storm moved along the north coast of Venezuela, passing over the Netherlands Antilles and the Paraguana Peninsula of Venezuela and the Guajira Peninsula of Colombia. On the 17th, Joan strengthened to a hurricane as it was heading away from Colombia and when its center was only 60 km off the coast and near some mountainous terrain.

Late on the 17th, a reconnaissance aircraft reported a wind speed of 57 m s^{-1} at an altitude of near 500 m while located 22 km north of the center. The extrapolated minimum sea level pressure was 986 mb a few minutes later. Empirical relationships between wind and pressure, as described by Holliday (1969), support a 1-min surface wind speed of, at most, $35\text{--}40 \text{ m s}^{-1}$ for a central pressure of 986 mb. To the extent that the aircraft flight level wind represents a 1-min surface wind, it is somewhat of a "rogue" outlier to the empirical pressure-wind relationship.

Joan continued to strengthen as it moved across the southwest Caribbean. On the 20th, it slowed, weakened, executed a small cyclonic loop, and then resumed a

westward motion and strengthened. The central pressure is estimated to have reached a minimum of 932 mb at landfall on the coast of Nicaragua early on the 22nd. The highest 1-min wind speed estimate at landfall is 64 m s^{-1} . The center crossed the coast at Bluefields. Figure 8 is an infrared satellite image showing Joan's well-defined eye just prior to landfall. Joan weakened as it moved across Central America and into the eastern Pacific Ocean, where it became Tropical Storm Miriam.

Tropical storm warnings were issued for a number of countries across the southern Caribbean from Barbados westward to Colombia. Hurricane warnings were issued for Nicaragua and offshore islands of Colombia. Flash flood and mud slide warnings were issued for Panama, Costa Rica, Nicaragua and Honduras.

Joan was responsible for an estimated 216 deaths across the southern Caribbean including: Nicaragua 148, Costa Rica 28, Colombia 25, Venezuela 11, and Panama 4. The total damage estimate was \$2 000 000 000, with nearly half of that occurring in Nicaragua.

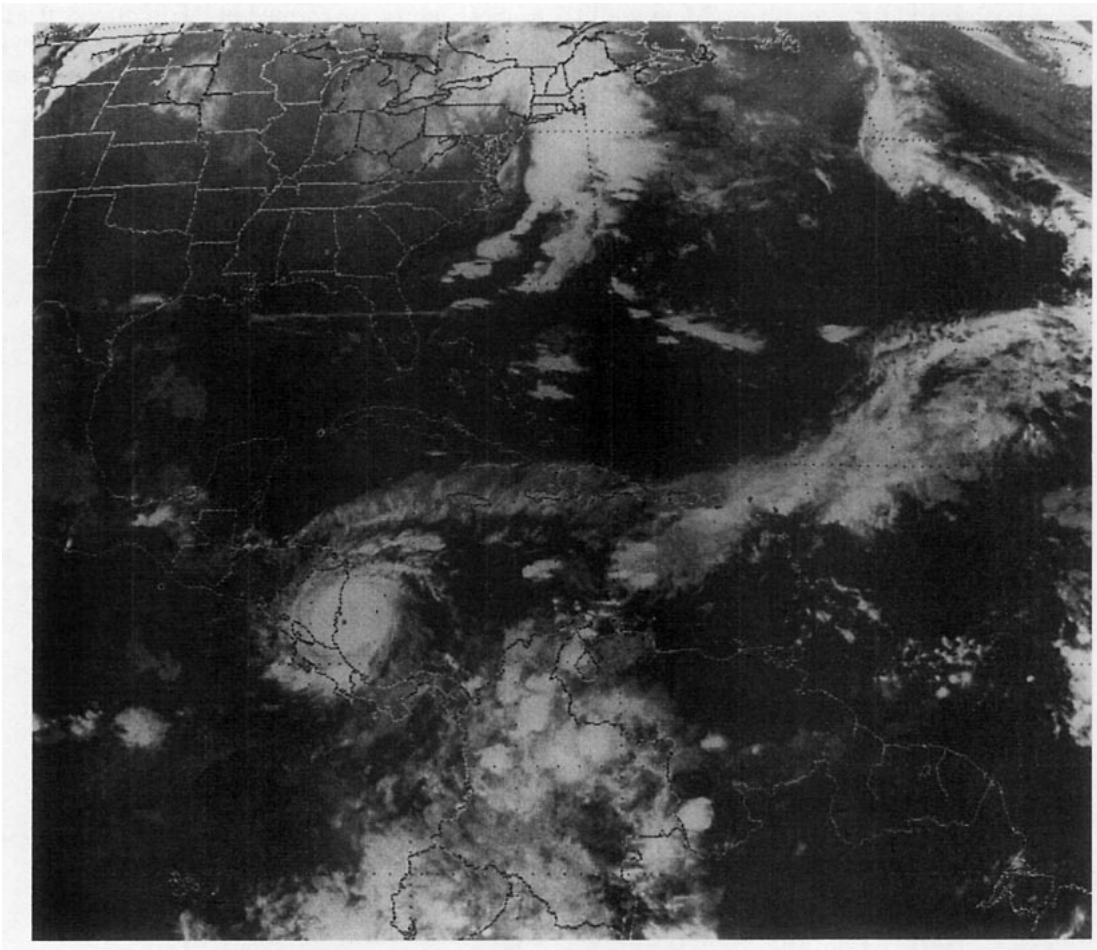


FIG. 8. Geostationary, infrared satellite picture of Hurricane Joan at 0601 UTC 22 October 1988, showing the eye approach Bluefields, Nicaragua.

TABLE 7. Tropical Storm Keith selected surface observations, November 1988.

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)*		
Florida							
Boca Chica	1009.5	23/0855	16	22	23/0255		
Bradenton			23		23/0500	1.8	
Brandon	999.3	23/0800					113
Bushnell							140
Daytona Beach	1003.1	23/1010	14	19	23/0939	0.6	150
Fetherston	1000.0	23/0800		26	23/0800		57
Fort Myers	998.6	23/0300		24	23/0645		11
Fort Myers Beach						1.8	
Flamingo			14		22/2150		
Indian Rocks Beach	998.0	23/0557	18	24	23/0559		
Key West	1009.5	22/2050	14	17	22/1445		5
Largo							282
Macdill AFB			28	31	23/0655		
Melbourne			13	23	23/0022		
Naples			23	31	23/0500		
New Port Richey			23	32			127
Orlando							149
Safety Harbor				33	23/0615		
Tampa Airport	1000.7	23/0720	14	21	23/0550		
Tampa 76-m elevation				36	23/0615		
Titusville							196
Venice	995.0	23/0705					
West Palm Beach	1004.4	23/1235	14	21	23/1321		1
Bermuda	987.5	24/2055	21	35	24/1920		

* Time of 1-min wind speed, except when only a gust is given.

1. Tropical Storm Keith, 17–24 November

The last storm of the season began as a tropical wave near the coast of Africa on 5 November. The wave moved westward for 12 days and acquired the low-level circulation of a tropical depression in the west-central Caribbean on the 17th. Keith reached tropical storm strength on the 20th when its center was located only 140 km off the coast of eastern Honduras.

Keith moved northwestward, its center crossing the northeast tip of the Yucatan Peninsula on the 21st. Reports from ships in the path of the storm indicated that Keith was close to hurricane force just prior to this landfall.

Now in the southern Gulf of Mexico, the storm turned toward the northeast on the 22nd, into the wake of a frontal trough trailing across central Florida. Keith's center made landfall on the Florida west coast near Sarasota early on the 23rd, then moved across the state and off the east coast near Melbourne. Table 7 lists selected surface observations. The highest 1-min wind speed reported in Florida was 28 m s⁻¹ at Macdill Air Force Base, to the north of the center. Tropical-storm-force winds were also reported from south of the center at Naples. The lowest sea-level pressure reading was 995 mb at Venice. Rainfall was concentrated north of the center with amounts ranging up to 282 mm at

Largo. Storm surge water heights were 1.8 m above normal at Bradenton and Fort Myers Beach. Two tornadoes were reported in St. Petersburg prior to landfall. The damage estimate for Florida is \$3 000 000.

The center of Keith passed 230 km to the north of Bermuda on the 24th, as it accelerated towards the North Atlantic and Bermuda's highest 1-min wind speed was 21 m s⁻¹. Keith finally evolved into an extratropical storm with winds to hurricane force in the far North Atlantic.

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