NOAA Technical Memorandum NWS NHC 45

HURRICANE GILBERT (1988)

IN REVIEW AND PERSPECTIVE

Prepared by:

Edward N. Rappaport and Colin J. McAdie
National Hurricane Center

National Hurricane Center
Coral Gables, Florida
November 1991

UNITED STATES
DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary

National Oceanic and Atmospheric Administration
John A. Knauss
Under Secretary and Administrator

National Weather Service
Elbert W. Friday
Assistant Administrator

TABLE OF CONTENTS

HURRICANE GILBERT (1988) IN REVIEW AND PERSPECTIVE

Edward N. Rappaport
and
Colin J. McAdie

ABSTRACT

The evolution of Hurricane Gilbert is described. This very intense hurricane is placed in meteorological and historical perspective. The nature of tropical cyclones is first sketched out. Gilbert's size, one of its most remarkable attributes, is illustrated by comparison with two other very intense hurricanes (the Labor Day Hurricane of 1935 and Hurricane Camille of 1969) which, like Gilbert, had winds exceeding 155 mph at the time of their landfall. Damage caused by these intense hurricanes is explored. Gilbert's evolution and environment are then illustrated with satellite imagery, surface and deep-layer mean analyses, and reconnaissance aircraft data. Gilbert is then examined from a forecasting standpoint.

1. INTRODUCTION

On the evening of September 13, 1988, about 140 miles south of the western tip of Cuba, Hurricane Gilbert reached the lowest pressure (888 mb) ever recorded in an Atlantic tropical cyclone. This pressure also currently stands as the lowest sea-level pressure on record for the Western Hemisphere.[1] Accompanying Gilbert's Atlantic record-breaking minimum central pressure were estimated maximum sustained winds at the surface of 185 mph. The hurricane made landfall with a central pressure of 900 mb about 12 hours later near Isla de Cozumel, a resort area about 10 miles off the northeastern coast of the Yucatan peninsula (Fig. 1). This gave Gilbert the lowest central pressure at the time of landfall in 53 years, in the Atlantic. Sustained winds were near 160 mph at landfall (Table 1).

A total of 319 people were killed by Gilbert over a period of 11 days. As shown in Fig. 1, Gilbert crossed directly over the island of Jamaica, proceeded to make landfall at Cozumel, Mexico, then continued across the Bay of Campeche and made landfall again at La Pesca, a small fishing village on the Gulf coast of Mexico approximately 150 miles south of Brownsville, Texas. As Gilbert crossed the coast and proceeded inland, it caused torrential rains; subsequent flooding accounted for most of the deaths in the area of final landfall. The total damage caused by Gilbert is now estimated at $10 billion.

---

[1] The current world's record for lowest central pressure is held by Typhoon Tip, which reached 870 mb on October 12, 1979, over the western Pacific Ocean.

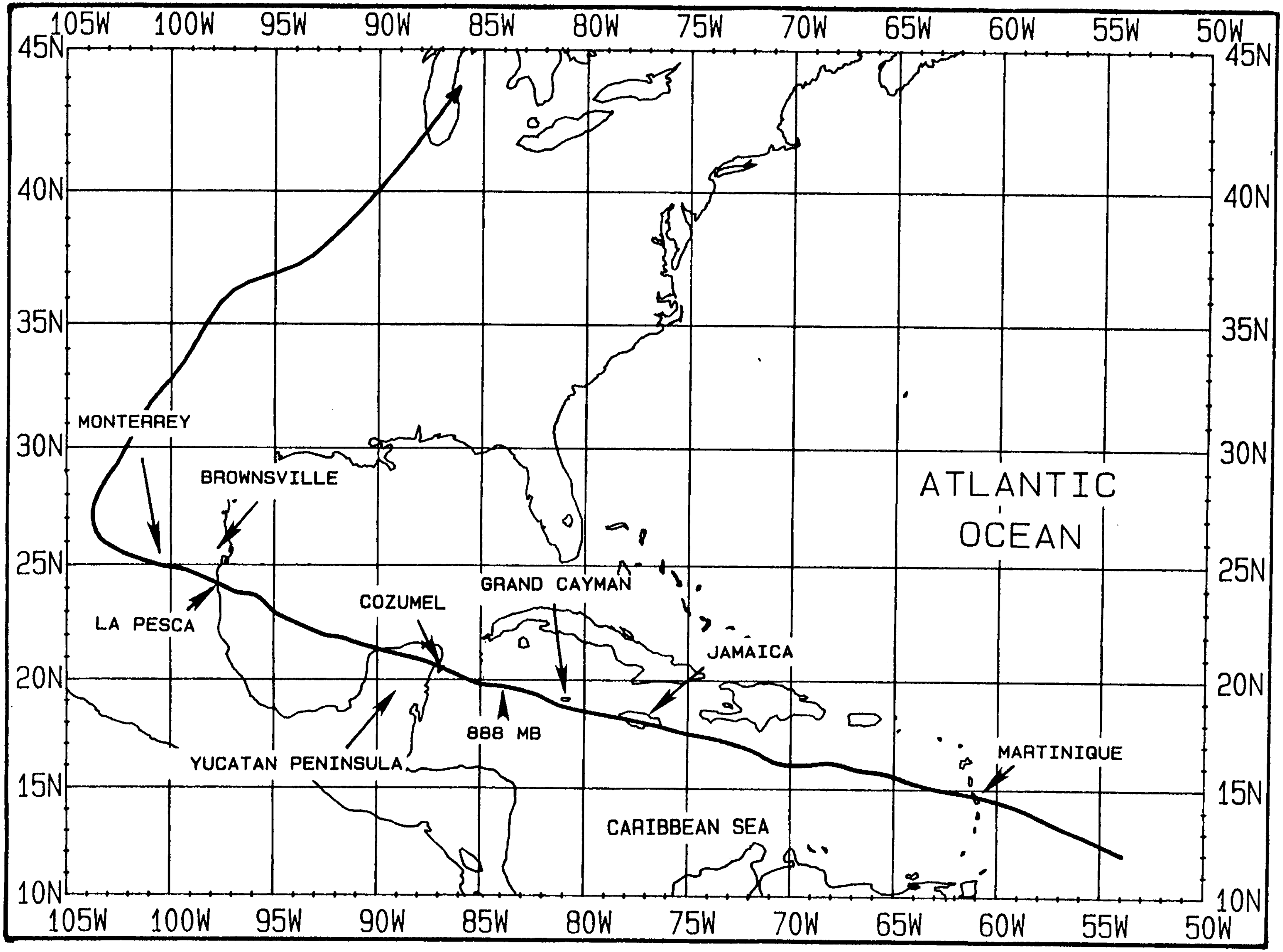


Fig. 1. Track of Hurricane Gilbert (September 8-19, 1988). Location at time of minimum central pressure (888 mb) indicated.

Table 1. Position, central pressure, and 1-min maximum sustained wind speed for Hurricane Gilbert (1988) at 6 h intervals and at landfall. Times are in UTC, which leads EDT by 4 hours.

Date	Time (UTC)	Lat. (°N)	Lon. (°W)	Pressure (mb)	Wind speed (kt)	Wind speed (mph)	
9/08	1800	12.0	54.0	1008	25	30	Tropical Depression
9/09	0000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
	0600	[illegible]	57.1	[illegible]	[illegible]	[illegible]	
	1200	14.0	58.6	[illegible]	30	35	
	1800	14.5	60.1	1004	35	40	
9/10	0000	14.8	61.5	1002	40	45	Tropical Storm
	0600	15.0	62.8	998	45	50	
	1200	15.3	64.1	993	50	60	
	1800	15.7	65.4	992	55	65	
9/11	0000	15.9	66.8	989	65	75	Hurricane
	0600	16.2	68.0	982	80	90	
	1200	16.1	69.5	975	95	110	
	1800	16.2	70.7	970	100	115	
9/12	0000	16.8	72.0	964	105	120	
	0600	17.3	73.7	962	110	125	
	1200	17.6	75.3	960	110	125	
	1800	18.0	76.9	960	110	125	
9/13	0000	18.3	78.5	960	110	125	
	0600	18.5	79.7	952	115	130	
	1200	18.8	81.1	934	125	145	
	1800	19.4	82.5	905	140	160	
9/14	0000	19.7	83.8	888	160	185	
	0600	19.9	85.3	889	155	180	
	1200	20.4	86.5	892	145	165	
	1800	20.9	87.8	925	130	150	
9/15	0000	21.3	89.5	944	100	115	
	0600	21.6	90.7	949	90	105	
	1200	21.9	91.7	950	85	100	
	1800	22.1	92.8	950	90	105	
9/16	0000	22.5	93.8	949	100	115	
	0600	22.9	94.8	946	110	125	
	1200	23.7	95.9	948	115	130	
	1800	23.9	97.0	950	115	130	
9/17	0000	24.4	98.2	964	80	90	
	0600	24.8	99.3	988	50	60	Tropical Storm
	1200	25.0	100.5	996	35	40	
	1800	25.4	101.9	1000	30	35	Tropical Depression
9/18	0000	26.0	103.2	1002	30	35	
	0600	27.6	103.7	1004	30	35	
	1200	29.3	102.6	1003	25	30	
	1800	31.5	101.3	1003	25	30	
9/19	0000	33.2	99.7	1002	25	30	
	0600	35.8	97.7	1001	25	30	
	1200	37.7	93.2	999	25	30	
	1800	40.2	89.9	998	25	30	Extra-tropical
9/20	0000	43.4	86.5	995	25	30	
	0600	Merged with Front					
At landfall:							
9/12	1700	17.8	76.8	960	115	130	Hurricane
9/14	1500	20.7	87.0	900	140	160	
9/16	2200	24.2	97.8	955	110	125	

2. TROPICAL CYCLONE CHARACTERISTICS AND CLIMATOLOGY

2.1 Life Cycle of a Tropical Cyclone

Briefly stated, a tropical cyclone is a rotating, convective system that develops over the tropical oceans. Just above the surface of these oceans we find the warm, moist air that is necessary to sustain the tremendous release of energy that characterizes these systems. The tropical cyclone may progress through three stages: tropical depression, tropical storm, and hurricane.

Although tropical cyclones may be initiated by several mechanisms, of interest here is the westward-traveling tropical wave. A number of these waves travel uneventfully across the Atlantic at low latitudes every summer. In a few of these waves, an important transition takes place; a rotary (that is, closed) counterclockwise circulation may develop near the earth's surface from the open wave pattern. If the circulation is sufficiently well-defined, the system is designated a tropical depression. Official tracking begins, and wind speed estimates are made. If not yet requested, and the depression is within a reasonable distance from land, aircraft reconnaissance may begin. The depression receives a reference number, issued consecutively throughout the hurricane season. Gilbert, for example, became the twelfth tropical depression of 1988, and formed from tropical wave 38.

The tropical depression may continue to intensify. If the wind speed (sustained over 1 minute at about 30 feet above the surface) reaches 39 mph, the system receives the designation tropical storm, and is named. Gilbert became the seventh named system of 1988 on September 9 as its center passed over the island of Martinique in the Windward Islands. If the winds increase further to 74 mph, the tropical storm becomes a hurricane. Gilbert reached this stage fairly rapidly, within 30 hours of being named, becoming a hurricane on September 10 (local time, see Table 1).

The threshold wind speeds of 39 and 74 mph correspond to points on the Beaufort scale, developed during the early nineteenth century as an aid to the sailing ships of that era. Beaufort Force 8 (39-46 mph) is described as a "fresh gale". Beaufort Force 12 (74 mph or more), the highest on the scale, was considered the point at which, in deteriorating weather, a ship could no longer carry any sail.

2.2 Tropical Cyclone Data Base

If a tropical cyclone attains named status, its successive positions (given in degrees latitude and longitude) and estimated maximum sustained winds are archived by the National Hurricane Center (NHC) located in Coral Gables, Florida. This archive contains entries, at six-hourly intervals, for all tropical storms and hurricanes in the Atlantic, Caribbean, and Gulf of Mexico from 1886 to the present. Hurricane Gilbert is now the eight hundred and sixtieth entry in this permanent file, referred to informally as the "best track" file. The positions and wind estimates, established after the fact with all available information, are the "best" that can be given, hence the name.

Although there are some earlier records, a few even dating back to the European exploration of the New World, in general, reliable tracks can only be established beginning in the latter half of the nineteenth century. Estimates of the wind speed were generally less reliable over the open ocean until the advent of aircraft reconnaissance in the late 1940's.

2.3 Classification of Hurricanes

There are many possible ways to classify hurricanes, given their wide range of wind speeds (from 74 mph to perhaps 200 mph) and variety of damaging effects. As noted by Dunn and Miller (1960), there is no single classification system which can succinctly encompass all aspects of the hurricane. Possible criteria for classification include evaluation of damage (structural damage, beach erosion, effects on vegetation, fatalities, dollar cost, etc.) and characteristics of the hurricane itself (e.g., wind speeds, minimum central pressure, size). Given the uneven distribution of population along hurricane-prone coastlines, it is perhaps not surprising that compilations of hurricanes by various damage criteria produce quite different lists (Hebert and Case, 1990).

In the early 1970's, Herbert Saffir devised a damage scale based upon numerous on-site inspections of hurricane damage. His five-category scale has the advantage of relating ranges of sustained winds to specific effects on structures and vegetation (Table 2). Robert Simpson, a former director of the National Hurricane Center, added a further reference to expected storm surge which is the rise of a body of water above normal astronomical tide due to a tropical cyclone. The resulting scale, now known as the Saffir/Simpson scale, received the sanction of the National Weather Service in 1972 and has since come into widespread use. Another useful feature of the Saffir/Simpson scale, and part of its original intent, is that it allows coastal residents to compare conditions expected from an impending hurricane with conditions experienced in previous hurricanes affecting the same area (Simpson and Riehl, 1981). The scale is given in quick-reference form in Table 3.

From Table 3, we see that a hurricane reaches category 5 when its maximum sustained winds exceed 155 mph (135 kt). Gilbert reached category 5 on 13 September after exiting Jamaica. It remained a category 5 through landfall on the Yucatan peninsula.

2.4 Frequency of Severe Hurricanes

The best-track file, described in Section 2.2, is a reliable data base that can be used to estimate how often we might expect a hurricane of Gilbert's intensity to occur. Of the 875 cyclones in

Table 2. The Saffir/Simpson Scale

Category 1	Winds of 74 to 95 mph. Damage primarily to shrubbery, trees, foliage, and unanchored mobile homes. No significant damage to other structures. Some damage to poorly constructed signs. And/or: storm surge 4 to 5 feet above normal tide. Low-lying coastal roads inundated, minor pier damage, some small craft in exposed anchorages torn from moorings.
Category 2	Winds of 96 to 110 mph. Considerable damage to shrubbery and tree foliage; some trees blown down. Major damage to exposed mobile homes. Extensive damage to poorly constructed signs. Some damage to roofing materials of buildings; some window and door damage. No major damage to buildings. And/or: storm surge 6 to 8 feet above normal tide. Coastal roads and low-lying escape routes made impassable by rising water 2 to 4 hours before arrival of hurricane center. Considerable damage to piers. Marinas flooded. Small craft in unprotected anchorages torn from moorings. Evacuation of some shoreline residences and low-lying island areas required.
Category 3	Winds of 111 to 130 mph. Foliage torn from trees; large trees blown down. Practically all poorly constructed signs blown down. Some damage to roofing materials of buildings; some window and door damage. Some structural damage to small buildings. Mobile homes destroyed. And/or: storm surge 9 to 12 feet above normal tide. Serious flooding at coast and many smaller structures near coast destroyed; large structures near coast damaged by battering waves and floating debris. Low-lying escape routes made impassable by rising water 3 to 5 hours before hurricane center arrives. Flat terrain 5 feet or less above sea-level flooded inland 8 miles or more. Evacuation of low-lying residences within several blocks of shoreline possibly required.
Category 4	Winds of 131 to 155 mph. Shrubs and trees blown down; all signs down. Extensive damage to roofing materials, windows and doors. Complete failure of roofs on many small residences. Complete destruction of mobile homes. And/or: storm surge 13 to 18 feet above normal tide. Flat terrain 10 feet or less above sea-level flooded inland as far as 6 miles. Major damage to lower floors of structures near shore due to flooding and battering by waves and floating debris. Low-lying escape routes made impassable by rising waters 3 to 5 hours before hurricane center arrives. Major erosion of beaches. Massive evacuation of all residences within 500 yards of shore possibly required, and of single-story residences on low ground within 2 miles of shore.
Category 5	Winds greater than 155 mph. Shrubs and trees blown down; considerable damage to roofs of buildings; all signs down. Very severe and extensive damage to windows and doors. Complete failure of roofs on many residences and industrial buildings. Extensive shattering of glass in windows and doors. Some complete building failures. Small buildings overturned or blown away. Complete destruction of mobile homes. And/or: storm surge greater than 18 feet above normal tide. Major damage to lower floors of all structures less than 15 feet above sea-level within 500 yards of shore. Low-lying escape routes made impassable by rising water 3 to 5 hours before hurricane center arrives. Massive evacuation of residential areas on low ground within 5 to 10 miles of shore possibly required.

Table 3.

SAFFIR / SIMPSON HURRICANE INTENSITY CATEGORIES

CATEGORY	CENTRAL PRESSURE		WIND SPEED		DAMAGE
	MILLIBARS	INCHES (Hg)	MILES PER HR.	KNOTS	
1	≥ 980	≥ 28.94	74 - 95	64 - 83	MINIMAL
2	965 - 979	28.50 - 28.91	96 - 110	84 - 96	MODERATE
3	945 - 964	27.91 - 28.47	111 - 130	97 - 113	EXTENSIVE
4	920 - 944	27.17 - 27.88	131 - 155	114 - 135	EXTREME
5	< 920	< 27.17	> 155	> 135	CATASTROPHIC

the Atlantic data base through 1989, 512 or 59% have reached hurricane strength. Of these, only 21 (2%) have reached category 5 intensity (sustained wind speeds of greater than 155 mph). Tracks of these hurricanes are plotted in Fig. 2; periods during which sustained winds exceeded 155 mph are indicated by a heavier line. Names and dates of these hurricanes are given in Table 4.

Of the 21 hurricanes shown in Fig. 2, only eight have had category 5 status at the time of landfall, as indicated in Table 4, with two making U.S. landfall. These are the Labor Day Hurricane of 1935, striking the Florida Keys, and Hurricane Camille, which hit the coast of Mississippi in August, 1969. These two systems will be discussed more fully below, and will serve as a basis of comparison for Hurricane Gilbert. The tracks of these three landfalling category 5 hurricanes are shown in Fig. 3.

Using the historical data base, we can obtain a quantitative estimate of the average <u>return period</u> for these catastrophic hurricanes. By plotting the histogram (the relative frequencies) of maximum winds attained by all tropical cyclones over a certain

Table 4. Summary of Atlantic hurricanes during the period 1886-1989 having attained sustained winds greater than 135 kt (Saffir/Simpson category 5). Tracks are plotted in Fig. 2, as indicated by storm number. It should be noted that minimum central pressure, when known, will produce a somewhat different list if used as a criterion. Country or commonwealth affected by landfall, as indicated.

Number	Storm name	Maximum wind		Date (UTC) attained	Landfall as category 5
1	Not named	140 kt	160 mph	Sept 13, 1928	(Puerto Rico)
2	Not named	140	160	Sept 5, 1932	(Bahamas)
3	Not named	140	160	Sept 3, 1935	(US)
4	Not named	140	160	Sept 19, 1938	
5	Not named	140	160	Sept 16, 1947	(Bahamas)
6	Dog	160	185	Sept 6, 1950	
7	Easy	140	160	Sept 7, 1951	
8	Janet	150	175	Sept 28, 1955	(Mexico)
9	Cleo	140	160	Aug 16, 1958	
10	Donna	140	160	Sept 4, 1960	
11	Ethel	140	160	Sept 15, 1960	
12	Carla	150	175	Sept 11, 1961	
13	Hattie	140	160	Oct 30, 1961	
14	Beulah	140	160	Sept 20, 1967	
15	Camille	165	190	Aug 17, 1969	(US)
16	Edith	140	160	Sept 9, 1971	(Nicaragua)
17	Anita	150	175	Sept 2, 1977	
18	David	150	175	Aug 30, 1979	
19	Allen	165	190	Aug 7, 1980	
20	Gilbert	160	185	Sept 14, 1988	(Mexico)
21	Hugo	140	160	Sept 15, 1989	

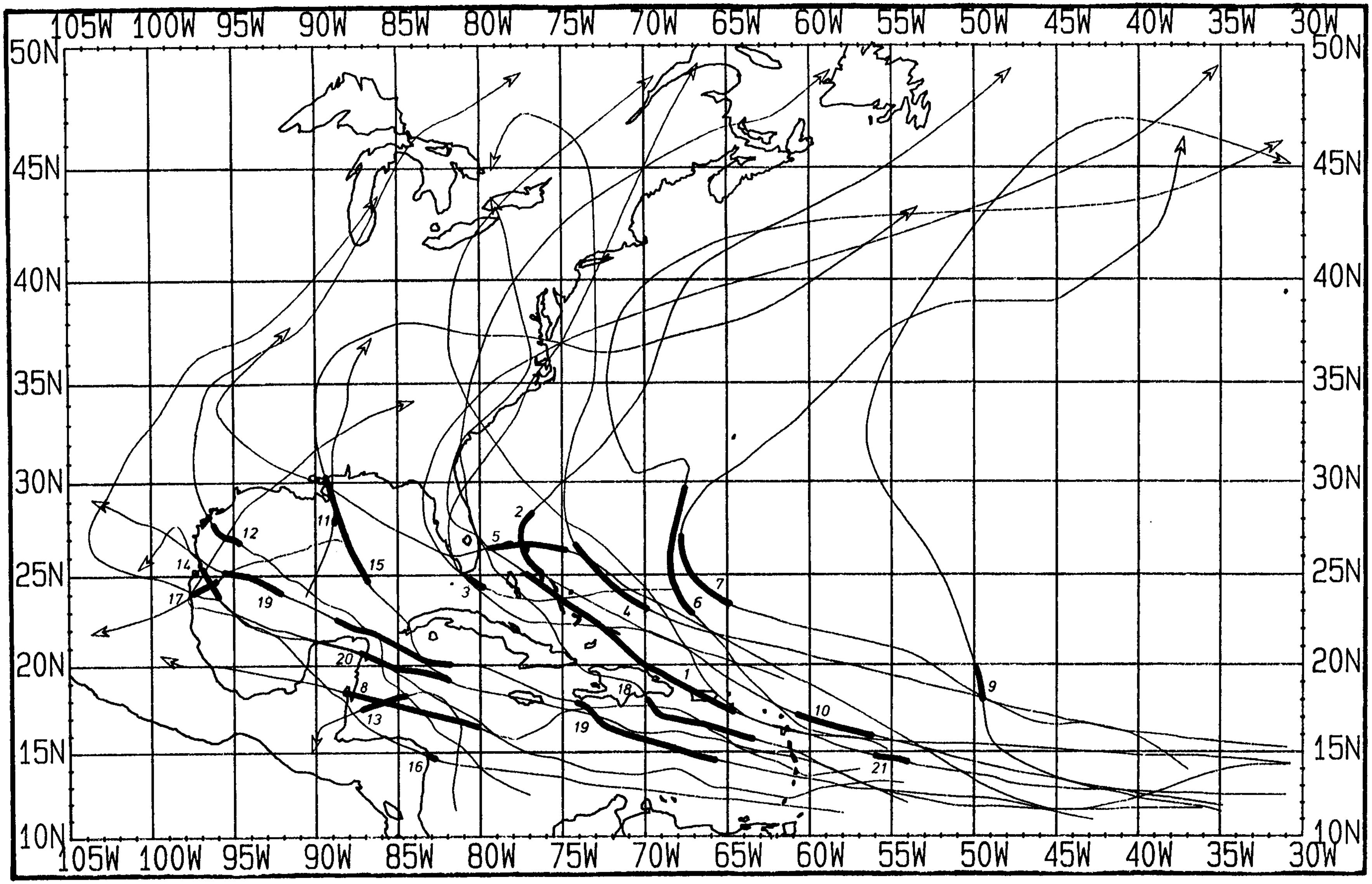


Fig. 2. Tracks of all tropical cyclones in the Atlantic basin (1886-1989) having maximum sustained winds exceeding 135 kt (155 mph) during some period. Tracks are shown in bold when this threshold is exceeded. Systems are identified in Table 4.

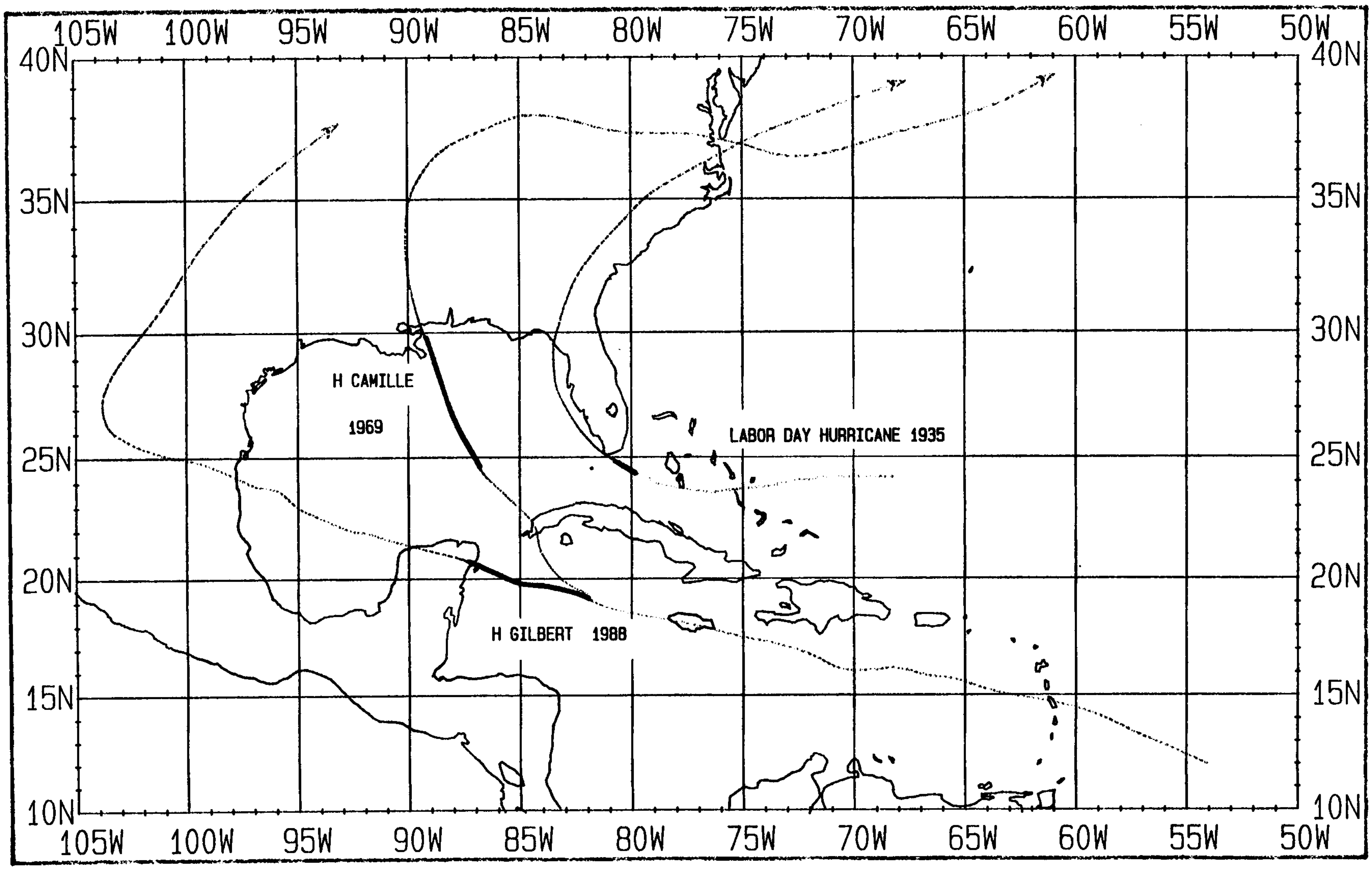


Fig. 3. Tracks of the Labor Day Hurricane of 1935, Hurricane Camille and Hurricane Gilbert. The Labor Day Hurricane and Hurricane Camille are the only two category 5 landfalls on the United States coastline since 1886. Plotting convention as in Fig. 2.

period, then finding a mathematical function that describes the shape of the plot, it is possible to obtain a probability of occurrence for a certain range of maximum winds (in our case, those meeting the category 5 criterion of exceeding 155 mph). Such a plot is shown in Fig. 4 for the period 1946-1989. This time period was chosen to include only the era of aircraft reconnaissance, but is long enough to smooth out short-term variations. From Fig. 4, it can be estimated that about 4.5% of all tropical cyclones will reach category 5 strength. This in turn gives a mean return period of about 2.3 years. This means that, on average, a hurricane can be expected to attain category 5 status somewhere in the Atlantic basin about once every 2.3 years.

Further, it can also be estimated that only about 1.4% of all tropical cyclones, on average, will reach Gilbert's maximum intensity (185 mph), giving a mean return period for the entire basin of 7.4 years. Note that although Gilbert attained a record low pressure, the maximum sustained winds were not record-breaking; and examination of Table 4 shows that Gilbert's winds have been equalled or exceeded three times since 1947. This gives an observed mean return period of 11 years, which is in reasonably good agreement with the smoothed estimate of 7.4 years.

Because of the large-scale steering patterns that are likely to occur over the tropical Atlantic during hurricane season, certain sections of coastline are relatively more likely to be struck by a tropical cyclone than others. This can be quantified by again referring to the best track file and extracting the subset of storms that have affected the section of coastline in question. It is possible to use that subset of storms to compute mean return periods (Neumann, 1987) for that area. In order to compare the return periods for the areas affected by the three landfalling category 5 hurricanes mentioned above, let us take circular areas of radius 75 n mi (Neumann, 1987) centered upon the three landfall sites. The resulting return periods are shown in Table 5. We can infer from Table 5 that the U.S. Gulf coast is relatively less likely to be affected by a catastrophic hurricane than is southern Florida. The mean return periods for the northern Yucatan peninsula fall about midway between the other two areas.

Table 5. Mean hurricane return periods (years) for three locations of previous category 5 landfall, within circles of radius 75 n mi.

Saffir/Simpson category	1	2	3	4	5
Upper Florida Keys	4	7	10	17	34
Cozumel, Mexico	6	11	18	34	79
Mississippi Gulf coast	8	18	29	60	150

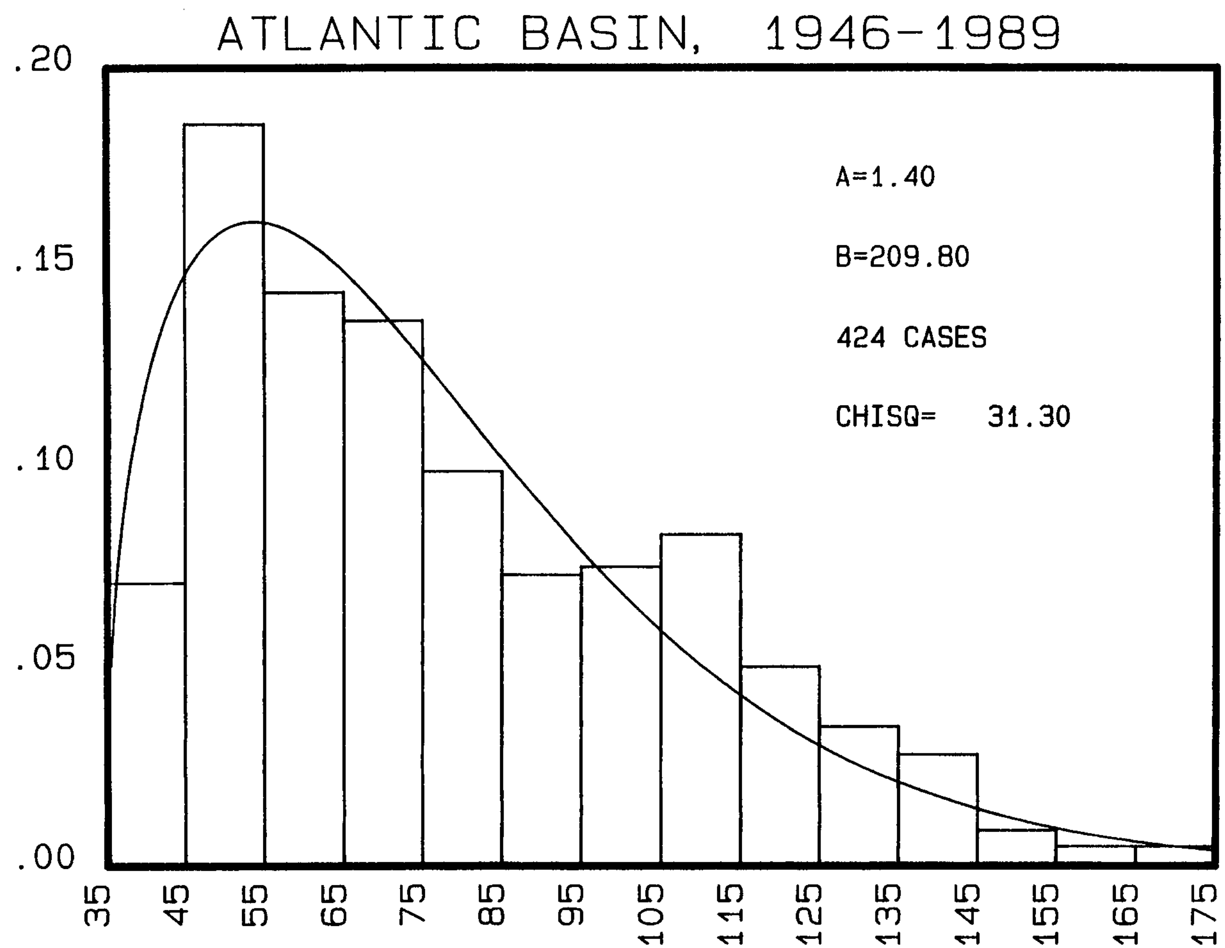


Fig. 4. Frequency distribution of maximum sustained winds attained by all tropical cyclones in the Atlantic basin (1949-1989). A Weibull function (Tsokos, 1972) is fitted to the distribution in order to obtain smoothed estimates of mean return periods (see text). Cases are confined to the era of aircraft reconnaissance.

2.5 Differences Among Hurricanes

As discussed above, hurricanes are conveniently categorized by the Saffir/Simpson scale. While the scale itself relates the magnitude of the sustained winds to potential damage, it must be remembered that two hurricanes having identical maximum winds can vary considerably in other ways, for example in size and shape. In addition, the observed effects at landfall can vary depending upon topography of the area of landfall, direction of approach, shape of the sea bottom, quality of local construction, and many other factors.

Let us consider the differences in size of the Labor Day Hurricane of 1935, Camille, and Gilbert, three landfalling category 5 hurricanes. One way of quantifying the size of a hurricane is by considering the extent of hurricane force winds. That is, assuming that the hurricane is roughly circular in shape, and that the winds continue to decrease as one travels away from the eye, at what point do the winds fall below 74 mph? At what point do they fall below 39 mph? These quasi-circular boundaries, enclosing hurricane and tropical storm force winds, respectively, can be thought of as moving along with the hurricane, expanding and contracting as conditions change. It should also be pointed out that these circular boundaries are usually somewhat offset to the right of center. That is, the winds on the right-front quandrant (looking from the circulation center toward the direction of motion) are usually stronger than those on the left-front. This is because the forward motion of the system as a whole is, in effect, added onto the speed of the winds circulating around the center.

Defining these wind speed boundaries for an event in progress can be difficult. Aircraft measurements, if available, currently provide the best estimate of the wind field; however, the winds at flight level (perhaps 10,000 ft) will usually not be experienced at the surface. For example, the roughness of the surface (even a water surface) produces a drag on the air, and some reduction of flight-level winds must be applied to account for this. Land exerts more drag than does water, for a further reduction.

Even though some reduction at the surface can be expected, measurement at the surface is another problem entirely. Problems are caused by the very severity of the event; meteorological instrumentation, if present at all, is often destroyed or carried away. One is then left to determine wind speeds based on the apparent force applied to buildings of known structural strength, as was done for Hurricane Camille (Saffir, 1972); having done so over a wide area, it is then possible to map out a wind field capable of causing the observed damage.

As one proceeds farther back in time, before the era of aircraft reconnaissance, we must rely on the first-hand observations of those who found themselves in the hurricane's path.

2.5.1 The Labor Day Hurricane of 1935

The Labor Day hurricane of 1935 was a very small, compact system that caused catastropic damage along a 30-mile section of the upper Florida Keys. This hurricane reached category 5 intensity just prior to landfall on the evening of September 2, 1935, with maximum sustained winds of 160 mph. Passage of the hurricane resulted in 408 deaths. Some idea of the ferocity of this hurricane is given by eyewitness accounts of an 18-ft length of 6" x 8" timber becoming airborne three hours prior to landfall. Sections of the Overseas Railway, completed in 1912, were obliterated by the subsequent storm surge. Track and ties were washed off concrete viaducts built 30 ft over the mean water level. Damage to the rail line was so extensive that the Florida East Coast Railway decided not to rebuild it, and sold the right-of-way to the State of Florida. A highway was eventually constructed along the route (Tebeau, 1971).

It is perhaps also worth noting that at the time of this event, only about 500 residents lived in the path of the hurricane. An additional 684 Civilian Conservation Corps workers were in the area on a highway construction project. At last count (1980 Census), the population over the same area had increased to almost 11,000. The potential for catastrophe is clearly present should a similar event occur.

Several observations are available at the time of landfall which allow us to make some deductions about the size and intensity of this hurricane. Among these observations is a pressure measurement taken with an aneroid barometer aboard a boat moored to the northern side of a railroad embankment at Craig, Florida. Wind shift observations at nearby locations put Craig nearly dead center beneath the calm eye. The needle of the barometer, as certified by Capt. Iver Olson, passed onto the temperature scale of the dial to a point corresponding to +10 degrees Centigrade. Subsequent laboratory testing of the instrument conducted by the Weather Bureau found that the reading corresponded to a pressure of 892 mb or 26.35 inches of mercury. This became the record low sea-level pressure for the Western Hemisphere; the record stood for 53 years, until finally broken by the 888 mb central pressure estimated for Gilbert in September, 1988.

For purposes of comparison, we would like to estimate the size of this hurricane. To this end, we can examine the record of wind measurements taken at the Miami Weather Bureau Office, located about 75 mi to the northeast. These records show (using the appropriate conversions) a maximum 1-min average wind of 41 mph during the time of hurricane passage through the Keys.

Given the magnitude of the wind (160 mph) at the radius of maximum wind, and that radius (about 7 mi, from observations, and also Ho et al., 1987), and the fact that Miami marked the approximate extent of tropical storm (gale) force winds, we can use a mathematical relationship[2] to give wind estimates at points in between. Thus we can surmise that hurricane force winds (wind speeds at least 74 mph) extended only about 25 miles from the center of the hurricane to the right of track, and somewhat less to the left. These wind envelopes for tropical storm and hurricane force winds are drawn to scale in Fig. 5. Supporting this size estimate, Simpson, et al., (1970) state in passing that hurricane force winds were experienced over a diameter of less than 35 miles. This is considerably smaller than Hurricane Camille, the only other occurrence of a U.S. landfalling category 5 hurricane.

2.5.2 Hurricane Camille

The second hurricane within the last 104 years known to have category 5 strength at the time of landfall in the United States is Camille. Hurricane Camille made landfall on the evening of August 17, 1969 near Waveland, Mississippi. The maximum sustained winds at landfall are estimated to have been 190 mph. A surface pressure of 909 mb (26.85") was recorded at Bay St. Louis, Mississippi, near the point of landfall. For United States landfalls, the minimum central pressure of 909 mb is second only to the 892 mb measured during the Florida Keys hurricane discussed above. It is estimated that along the Gulf coasts of Louisiana, Mississippi, and Alabama about 200,000 people sought shelter in advance of the oncoming hurricane; there were 256 fatalities.

A storm surge of 22 ft above mean sea level, in conjunction with the intense winds, caused nearly complete destruction along the entire Mississippi coast, extending inland for three or four blocks. Many beachfront areas were virtually leveled, with numerous buildings carried off their foundations. Power and telephone failures reached areas 90 miles inland. Coastal counties were without electrical service for as long as 15 days.

Although Camille was throughout its life a relatively small, but intense system, it was considerably larger than the Florida Keys hurricane of 1935. Prior to landfall, the National Hurricane Center estimated that Camille's hurricane force winds extended out 80 miles to the east and 60 miles to the west; tropical storm force winds were estimated to reach out 230 miles to the east and 115 miles to the west (Fig. 5). These distances agree reasonably well with those deduced from post-event investigations (U.S. Army Engineer District, 1970).

Unfortunately, no land-based anemometers survived near the point of landfall, as is usually the case in severe events. One recording anemometer was left running (on double-scale) aboard an offshore oil rig. The rig was located about 12 miles east of

---

[2] The function used here is of the form vr^{x}=constant, where v is wind speed, and r is distance from the center. x is determined empirically. (See, for example, Simpson and Riehl [1981], p. 197.)

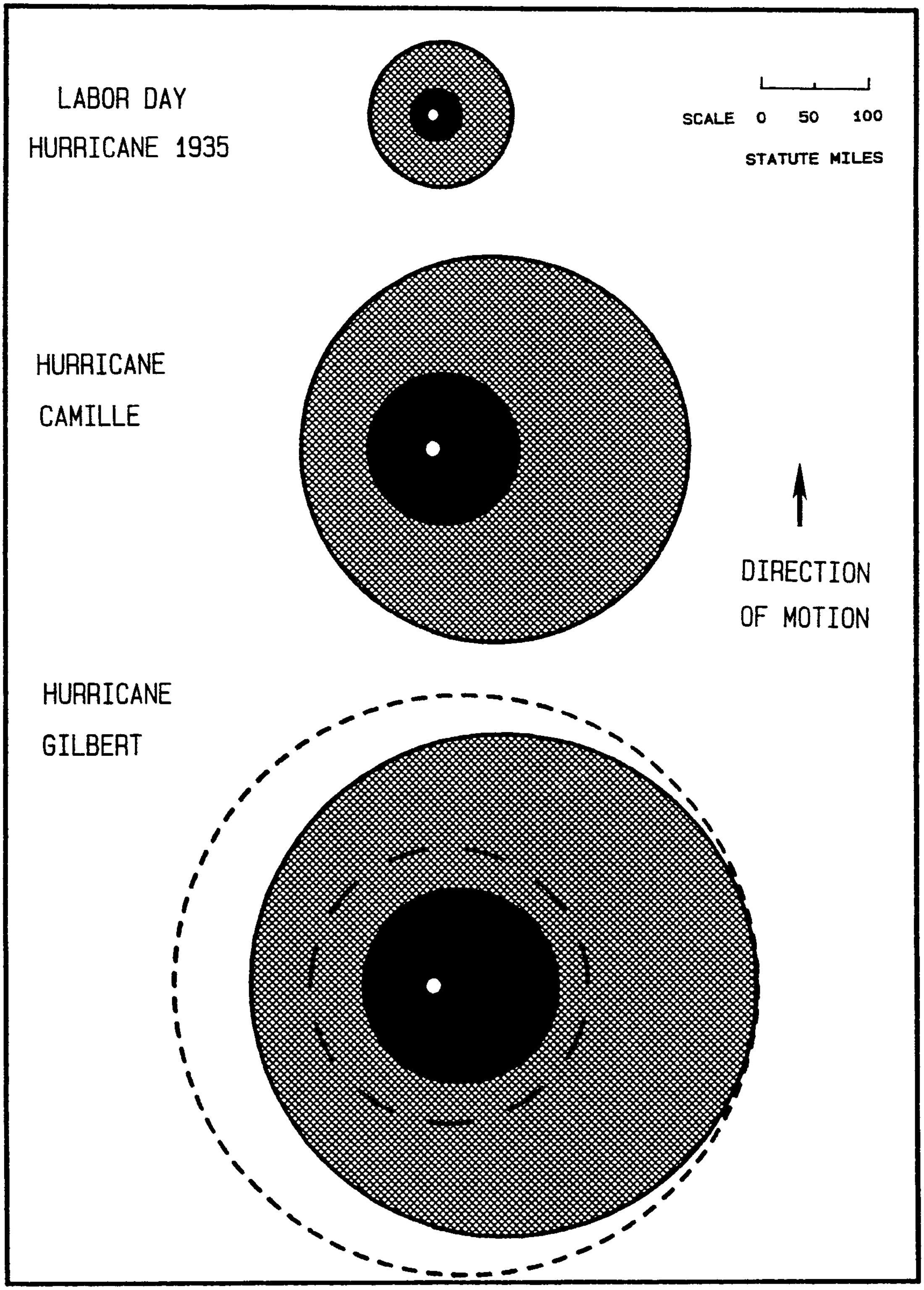


Fig. 5. Schematic size comparison of three landfalling category 5 hurricanes at the time of landfall. Solid circles indicate extent of hurricane force winds (at least 64 kt or 74 mph). Cross-hatched circles indicate extent of tropical storm force winds (at least 34 kt or 39 mph). Dashed circles indicate Hurricane Gilbert's greatest extent, which occurred two days later just prior to final landfall. Systems are oriented with motion towards top of page.

Camille's track. Camille, with an estimated radius of maximum winds of 9 miles, passed the rig about two hours prior to landfall The recorded peak gusts show a steady increase to 172 mph, at which point the paper jammed. It is worth noting that while this was to become the highest recorded wind speed during the event, it was also merely the point at which the paper jammed, not necessarily the peak gust generated by the hurricane.

Herbert Saffir did a detailed investigation after landfall of the damage done to structures in the affected area (Saffir, 1972). He examined the construction methods, materials used, and calculated the failure stresses required on a number of damaged or destroyed buildings. Among these was the Mississippi Power Company building, a seven-story building in Gulfport. It is located on U.S. 90, directly across the highway from the beach, about 18 miles east of the point of landfall.

Knowing of the recorded 172 mph gust on the drilling rig, and the anemometer height (100 ft), Saffir looked for damage on the power company building. He found several failures of 1/2" thick glass windows, and calculated the necessary wind loading required for breakage. He found the damage on the upper levels of the building consistent with winds of at least 172 mph, and possibly somewhat higher. This established that the winds recorded two hours earlier aboard the off-shore rig had indeed been experienced on the coast.

Some reduction of wind must be taken into account as one approaches ground level, although it is not always clear what this reduction should be. In his study, Saffir used a standard engineering reduction, and found a probable value of 145 mph at 30 ft above ground, based on a wind of 172 mph at 100 ft. He then examined other buildings and calculated their failure modes. Unfortunately the other buildings he examined all should have been, and in fact were, destroyed at wind speeds of less than 145 mph. It is thus somewhat difficult to establish from observed damage what the peak gusts might have been that night at street level.

It is interesting to note that, even using a conservative set of wind speed estimates (Dikkers, et al., 1971), 50-year design winds (95 mph) were exceeded over a 60-mile section of coastline, while 100-year design winds (105 mph) were exceeded over about half that length. The Mississippi Power Company building, examined by Saffir in his study, was built to a design speed of 150 mph (corresponding to a 370-year event), and suffered only minor damage.

2.5.3 Hurricane Gilbert

2.5.3.1 Gilbert prior to category 5 status. Although Hurricane Gilbert will perhaps remain most noted for its record-breaking low pressure, impressive size, and landfall as a category 5 system, it caused tremendous damage with a direct hit on the island of Jamaica 2 days earlier as a category 3 hurricane.

The eye passed directly over the island. It is estimated that 500,000 people, fully one-fifth of the population, were left homeless. Forty-five people were killed there. The island's electrical and water delivery systems were completely incapicitated. Many homes were poorly constructed and could not withstand winds of 125 mph, let alone higher gusts.

The damage done to Jamaica is grim evidence that a category 3 hurricane is quite capable of causing loss of life and serious economic dislocation.

After exiting Jamaica, Gilbert began its rapid deepening, with a drop in central pressure of 72 mb in about 24 hours. About 6 hours before reaching its maximum intensity, Gilbert passed 30 miles south of the Cayman Islands. The Cayman Islands are quite flat, and there was some concern for the residents' welfare. In fact, the islands emerged with only minor damage. There were some roofs removed, and numerous instances of homes partially filled with sand. Surprisingly, electrical power was restored to George Town by that afternoon, and to the rest of the island by the following day. There were no casualties.

There are several reasons for the unexpectedly light damage on the Cayman Islands. First, as Gilbert underwent its explosive deepening, it exhibited a very steep wind profile; that is, from the maximum wind near the center, the strength of the winds decreased very rapidly with distance from the center (e.g., Fig. 12a). At the time of closest approach to Grand Cayman, Gilbert had maximum sustained winds of 145 mph, putting it at category 4 strength. The National Hurricane Center at that time estimated that hurricane force winds extended outward 60 miles from the center. The only wind measurement on the island during the passage of the hurricane was that taken by a recording anemometer maintained by the Mosquito Research and Control Unit, at West Bay, on the northwest end of the island. The anemometer, located atop a 40-ft tower, recorded a gust to 157 mph between 7 and 8 AM, local time. Unfortunately, the recorder is considered accurate only to plus or minus 20 mph. The lower end of this range (137 mph) would imply a sustained 1-min average of about 104 mph, while the upper end (177 mph) would imply a 1-min average of 145 mph. The lower estimate, if reduced to the standard 30-ft level, gives a sustained wind of 100 mph.

Lacking any other observations, a wind speed for Grand Cayman can be estimated (see footnote 2). Given the diameter of eye at the time (about 17 mi) and the extent of hurricane force winds, standard assumptions give winds of about 93 mph at Grand Cayman, with gusts to perhaps 120 mph. This is in agreement with the lower bound on the wind obtained from the anemometer. The observed damage is also more consistent with the lower bound.

It should also be noted that Grand Cayman has a relatively strict building code, with most residences built of concrete block and stucco. While some roofs were lost, there were few buildings with heavy damage.

Equally important perhaps is the fact that the island, with a population of about 20,000, had recently updated its evacuation plan; there was timely clearance of the low-lying areas. Another mitigating factor is the very deep water to the southeast of the island. This operates as a control on the storm surge that is most damaging in the presence of a shallow offshore shelf. Storm surge on Grand Cayman was reported to be about 5 ft.

2.5.3.2 Category 5 landfall on the Yucatan peninsula. Hurricane Gilbert is, as of this writing, the most recent hurricane during the last 104 years known to have made landfall as a category 5 system, in the Atlantic. Although Gilbert had caused significant damage prior to reaching its record-breaking central pressure, the Yucatan peninsula took the full brunt of Gilbert at near maximum intensity. It is estimated that 120,000 people were evacuated, including 6,000 tourists from Cancun's high-rise resort strip. A storm surge of between 15-20 ft carried ocean-going freighters onto the beach, and undermined many seemingly well-constructed beach-front buildings. Gilbert left 70,000 people on the peninsula homeless; some residential areas on Cozumel were virtually leveled. The peninsula was left without power or telecommunications. There were 52 deaths there.

Gilbert is notable not only for its intensity, but also for its size. Aircraft reconnaissance indicated that hurricane force winds reached 100 miles to the right of track, with tropical storm force winds reaching out 250 miles. The resulting areas are shown schematically in Fig. 5. It should be noted that Gilbert was not at its maximum size at the time of landfall on Cozumel. Maximum size (shown by the dotted outline in Fig. 5) occurred in the Bay of Campeche prior to final landfall. At this time, Gilbert's tropical storm force winds extended over a north-south distance of more than 500 miles.

2.5.3.3 Final landfall. Hurricane Gilbert, having regained winds of 125 mph as it crossed the Bay of Campeche (Fig. 1), made landfall a third and final time at La Pesca, Mexico, as a category 3 hurricane. The largest single death toll attributable to Gilbert, however, occurred not at the coast but in the city of Monterrey, Mexico. Monterrey is situated about 175 miles inland from the Gulf of Mexico, and is the industrial hub of northern Mexico. The city sits at the foot of the Sierra Madre Mountains. With several peaks exceeding 10,000 ft, the mountain range caused a significant lifting of Gilbert's moisture-laden air, resulting in torrential rains. This normally arid area is crossed by several usually dry river beds which became quickly swollen with the influx of water.

The Santa Catarina River, which runs through Monterrey, was not only dry, but had been dry for so long that its bed had been utilized as space for public parks. Four buses, carrying an estimated 200 people, left Monterrey and traveled west along a road that runs beside the Santa Catarina. As Gilbert continued to dump rain in the mountains to the southwest, the Santa Catarina filled and quickly exceeded its banks; the torrent washed the buses off the road and into the river. Rescue efforts were mounted by the local police, with the unfortunate additional loss of four of their lives. The final death toll was put at 150. Bodies were found as far as 20 miles downstream.

In the United States, although there was some beach erosion along the south Texas coast, most of the damage was caused by a series of tornadoes spawned by the larger circulation of the dying hurricane. There were two deaths attributed to tornadoes in San Antonio. Significant tornado damage was also reported at Kelly Air Force Base, just west of San Antonio, and at Del Rio, Texas.

Gilbert was also ultimately beneficial, as its remnants brought wide-spread rain to the American midwest. The timing was ideal, just prior to the planting of the winter wheat crop in northern Texas, Oklahoma, and Kansas.

3. OBSERVATIONS AND ANALYSES OF GILBERT AND ITS ENVIRONMENT

3.1 Satellite Imagery

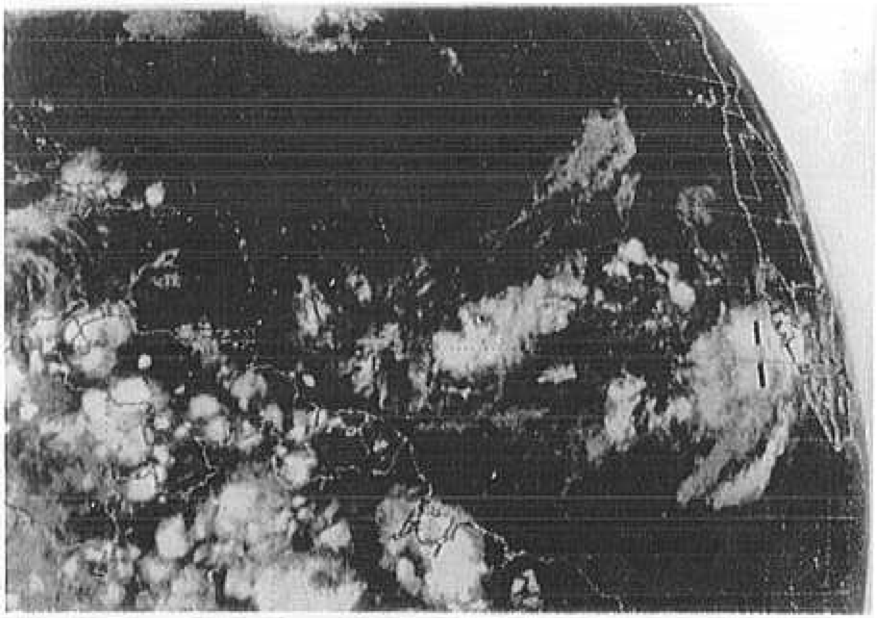
Satellite imagery provides unique documentation of tropical cyclone development. The NHC made extensive use of satellite data to monitor the evolution of Hurricane Gilbert and its environment. In fact, during Gilbert's early development, the storm's position, intensity and size were determined almost exclusively from Geostationary Operational Environmental Satellite (GOES) imagery. The imagery showed that Gilbert occurred during a period of heightened tropical cyclone activity in the Atlantic basin with the lifetimes of three other Atlantic tropical cyclones, Ernesto, Florence and an "unnamed" storm (see NHC, 1988a, 1988b) overlapping with Gilbert. In this section, Gilbert's development is reviewed from a sequence of GOES-East photographs spanning September 3-19, 1988.

Early on September 3, meteorologists at the NHC noted that the 38th tropical wave of the 1988 season (this informal wave count commenced 1 May) passed westward across the coastline of Africa into the far eastern Atlantic Ocean. Hurricane Gilbert would later form from this wave but Gilbert's extraordinary development was not foretold by the imagery from the first few days of September.

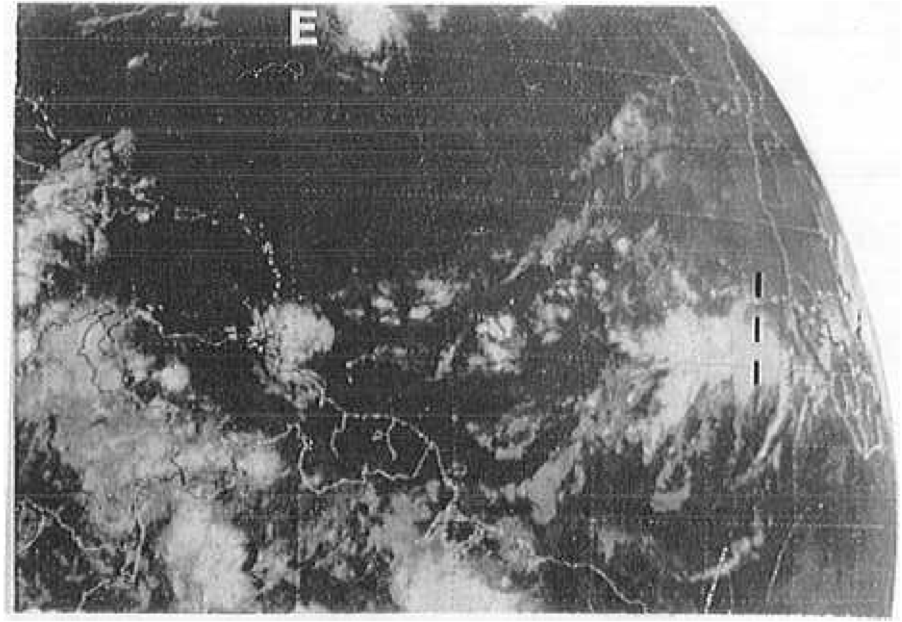
The axis of tropical wave 38 is indicated in Fig. 6 by a dashed line superimposed on the infrared images. Bright white areas indicate cold, high clouds within the upper-level outflow from intense thunderstorms, or widespread cloudy areas with more modest rainfall rates. On September 3 the brightest clouds within the Intertropical Convergence Zone (ITCZ) over the eastern Atlantic were associated with wave 38 (Figs. 6a and 6b). Using animation of the imagery of September 3, analysts detected for the first time in this system a transitory embedded low- to mid-level cyclonic circulation within the region of enhanced brightness.

Wave 38 moved toward the west or west-northwest at about 15 mph.

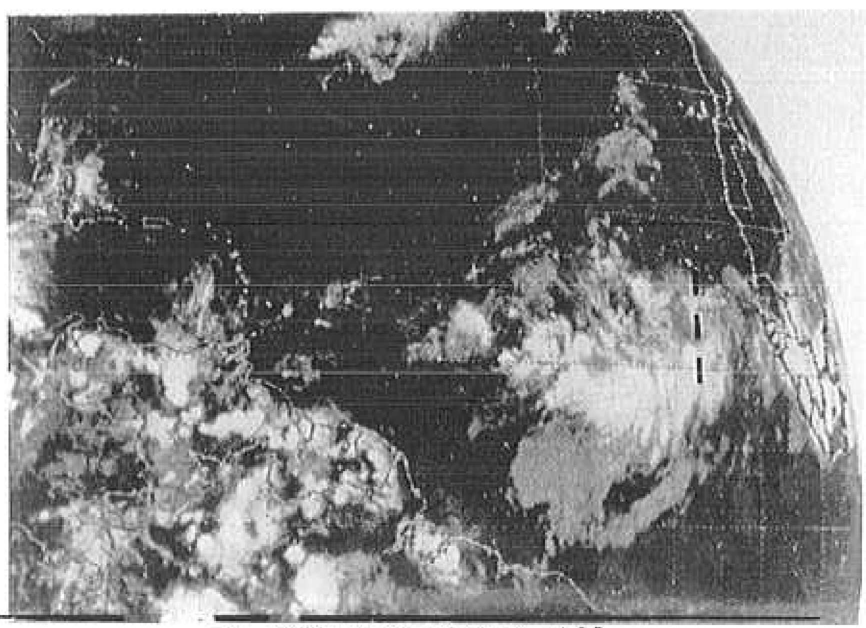
Fig. 6. GOES-EAST infrared satellite imagery from September 3-19, 1988. Dashed line denotes axis of the tropical wave that developed into Gilbert. G and arrow-head identify clouds associated with Gilbert during system's depression and storm stages. E, F and U denote Ernesto, Florence and an "unnamed" storm, respectively. Times are UTC.



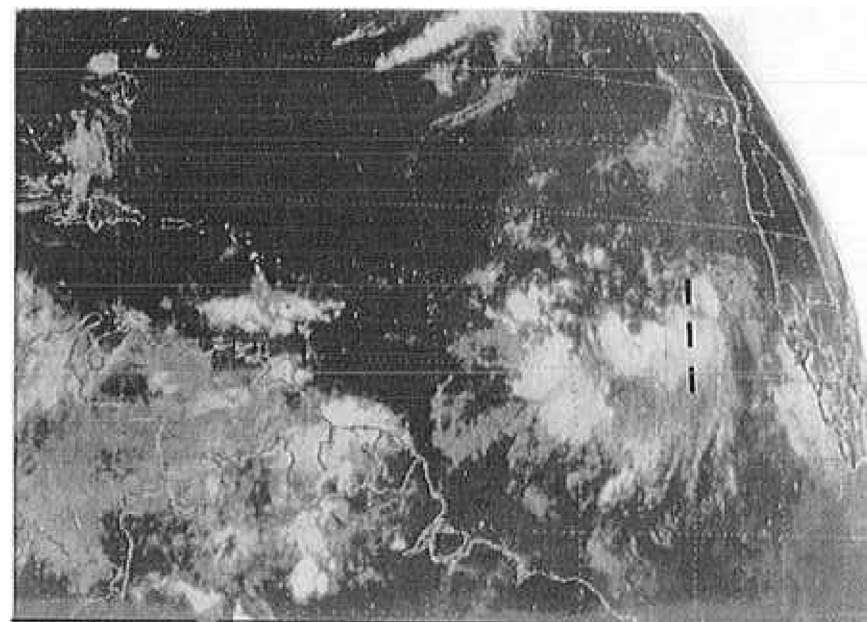
a) 0001 3 September 1988



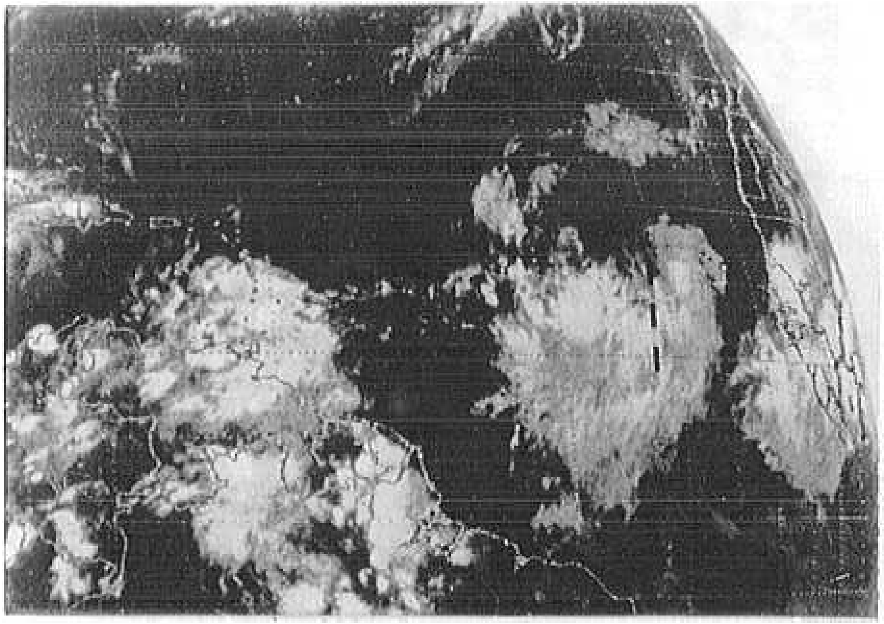
) 201 September 988



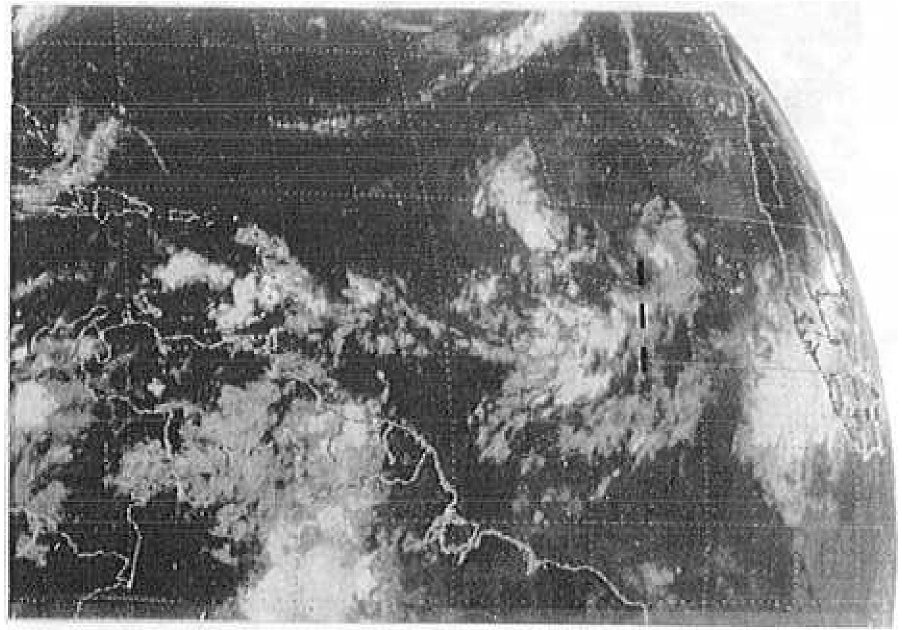
c) 0001 4 September 1988



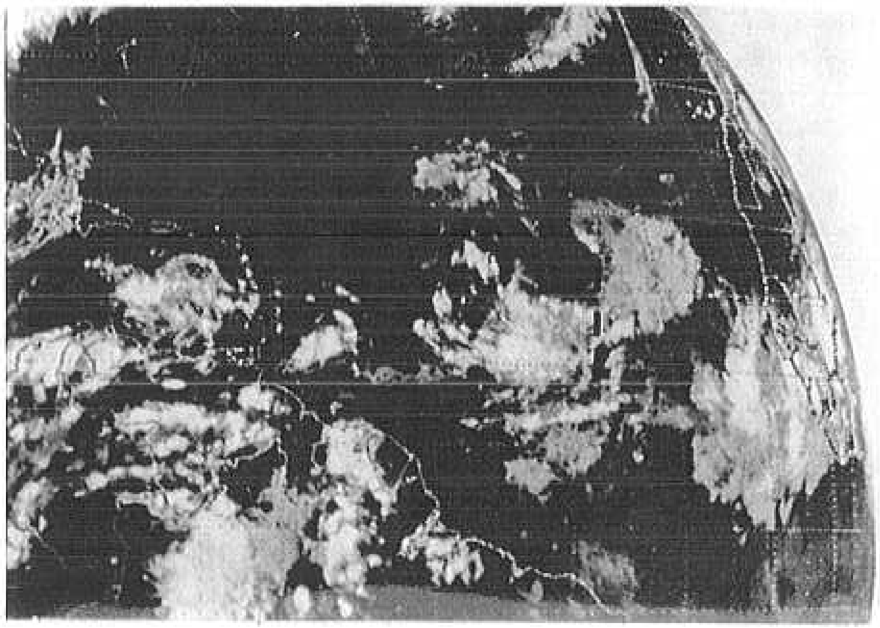
d) 1201 4 September 1988



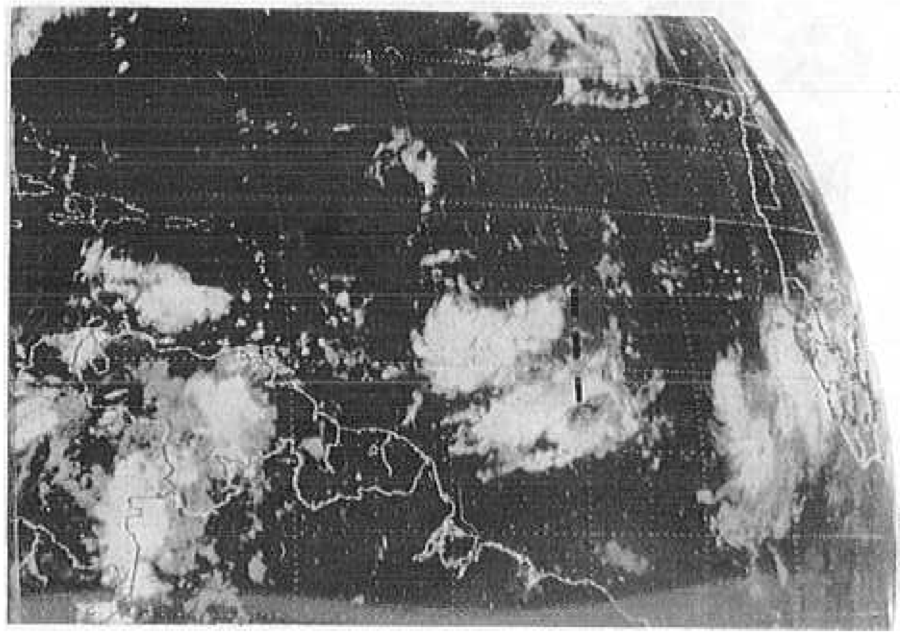
0001 September 988



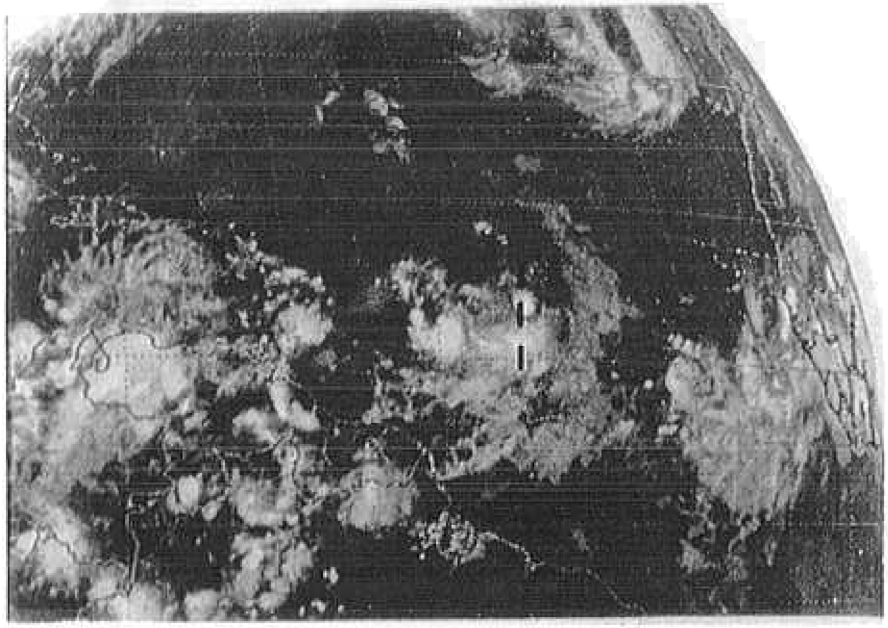
201 Sep ember 988



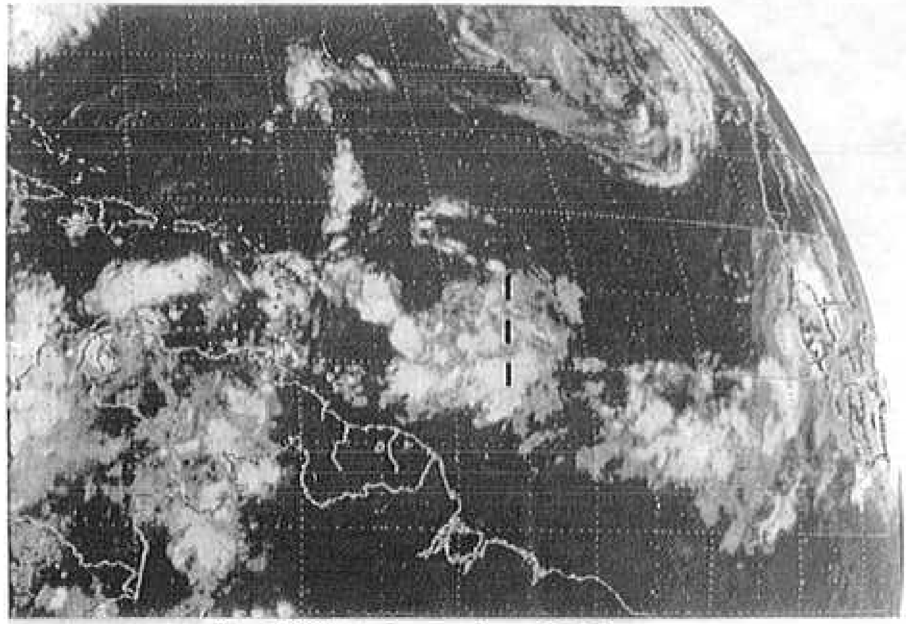
g. 0001 September 88



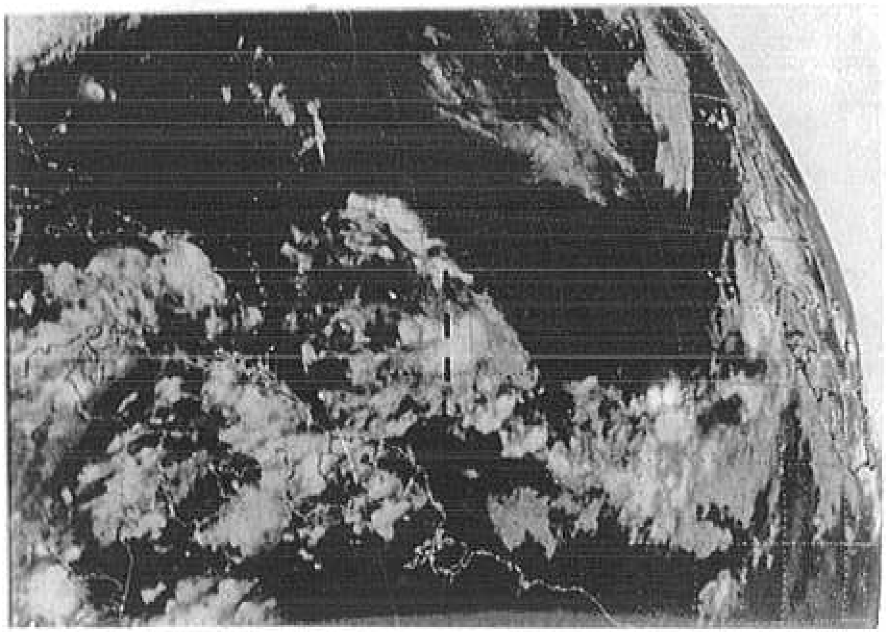
201 Sep embe 988



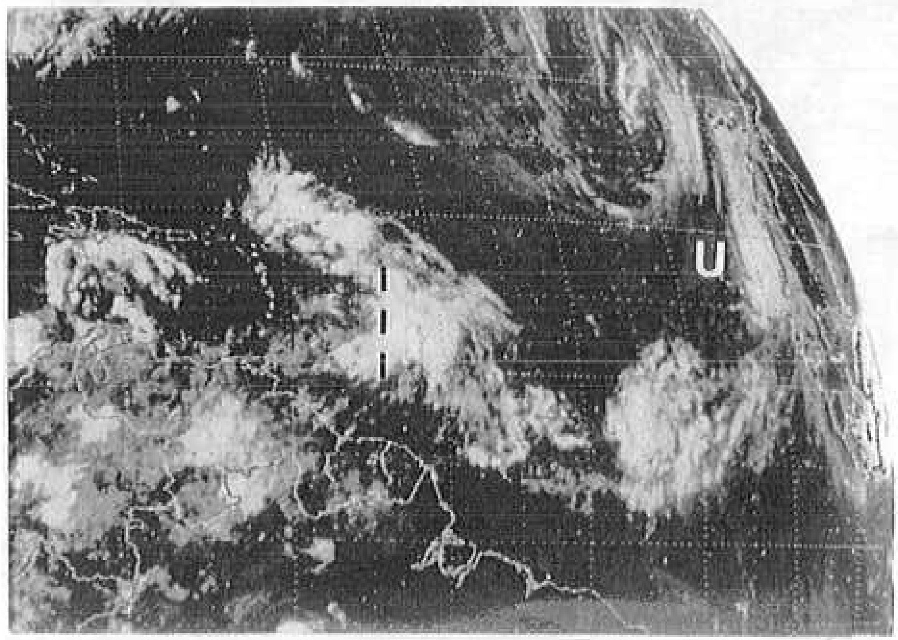
i) 0001 7 September 1988



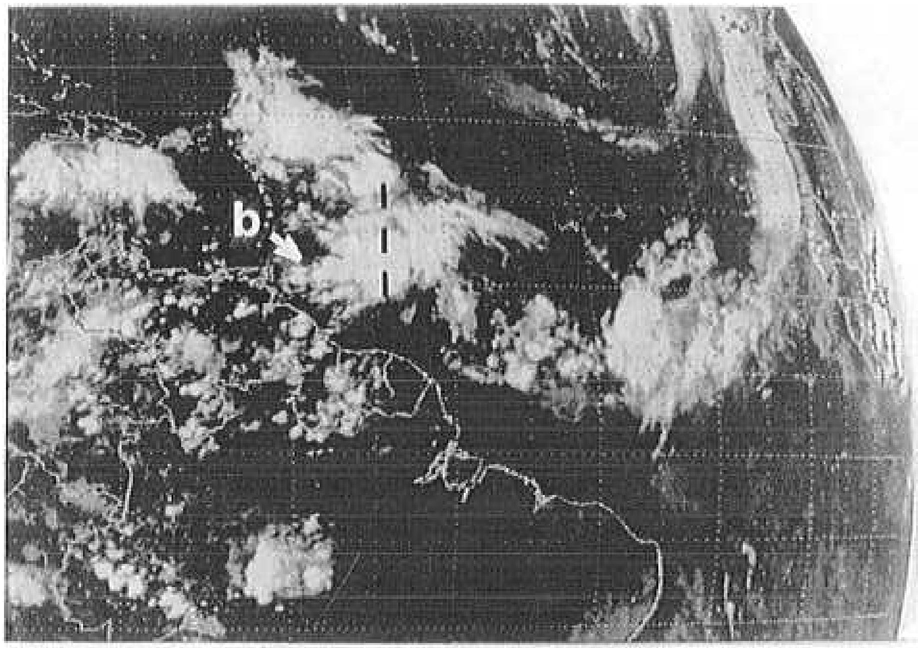
j) 1201 7 September 1988



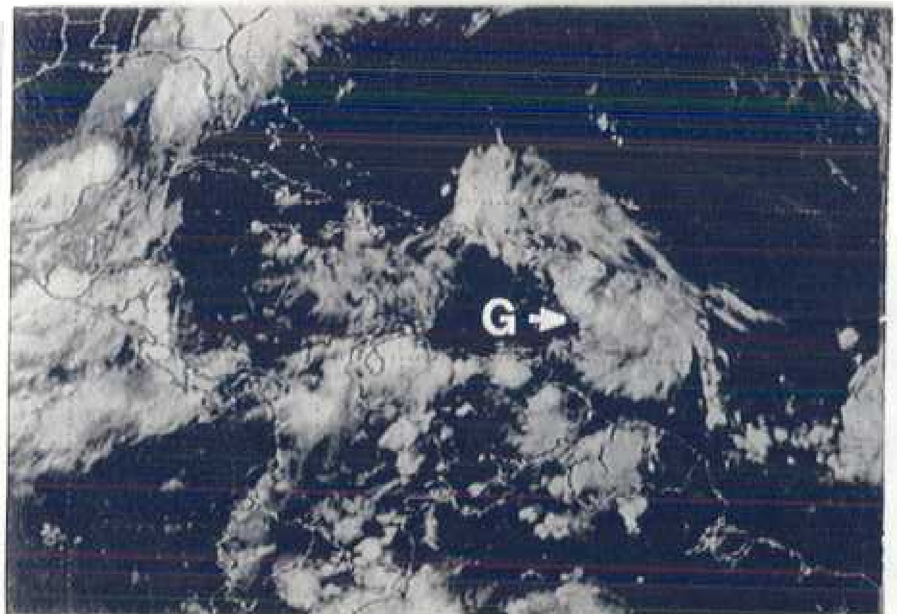
k) 0001 September 1988



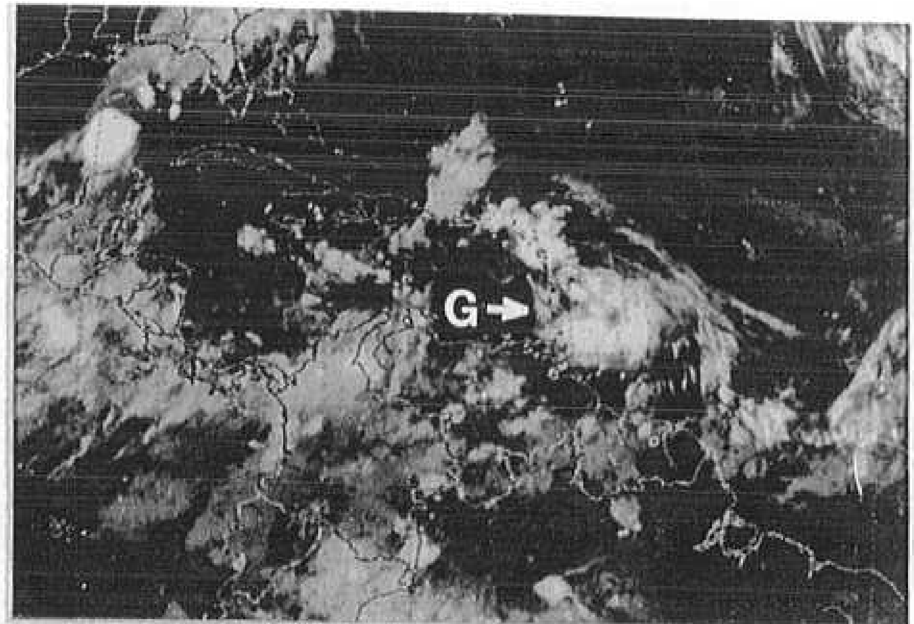
l) 1201 8 September 1988



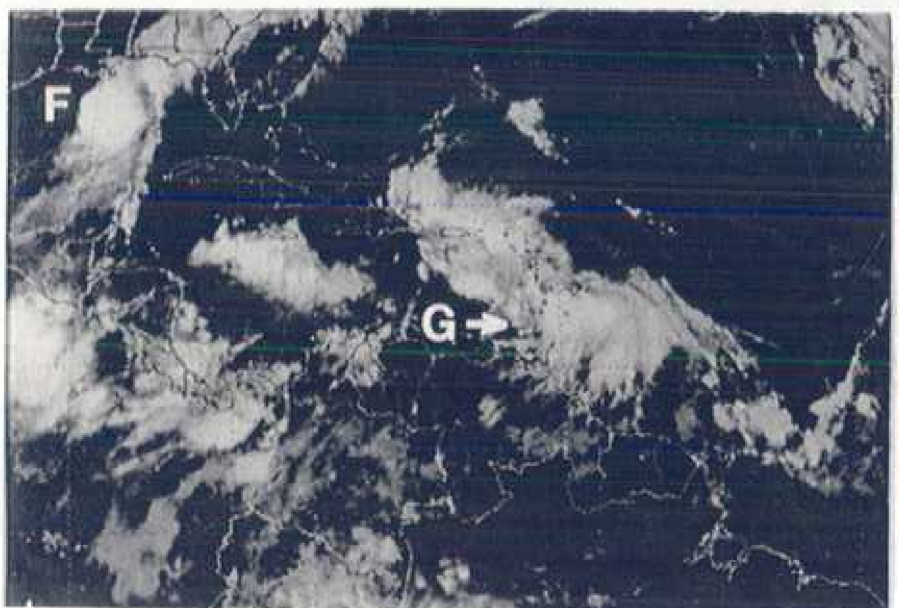
m) 1701 8 September 1988



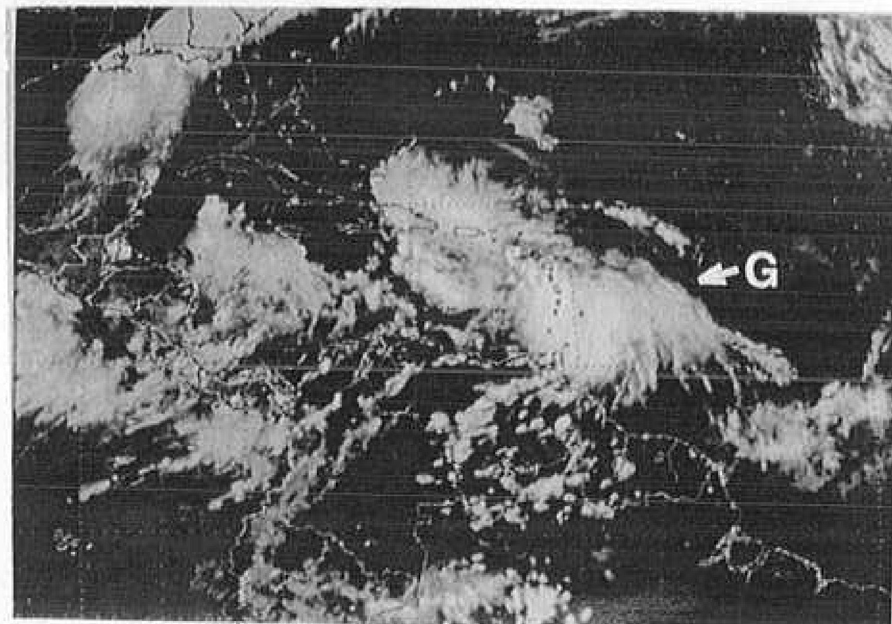
n) 0001 9 September 1988



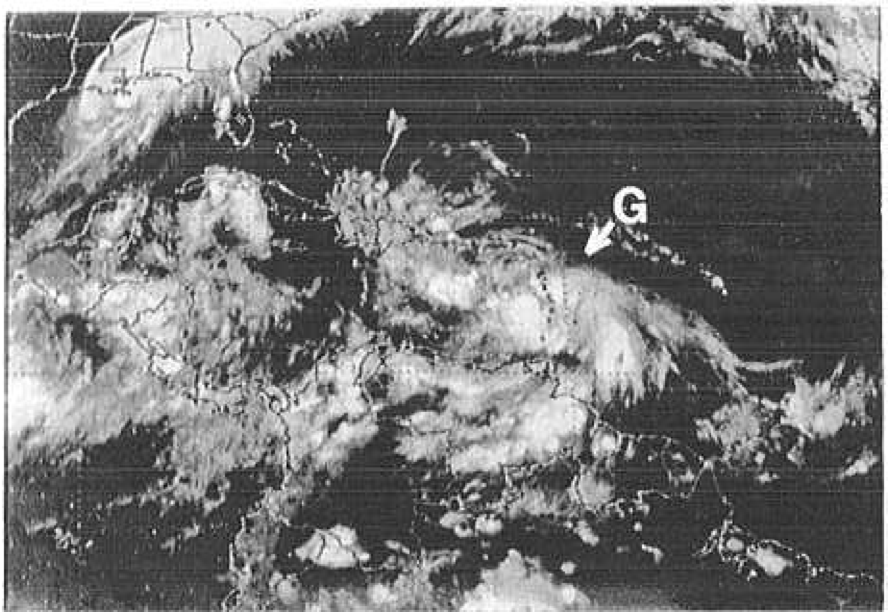
o) 0601 9 September 1988



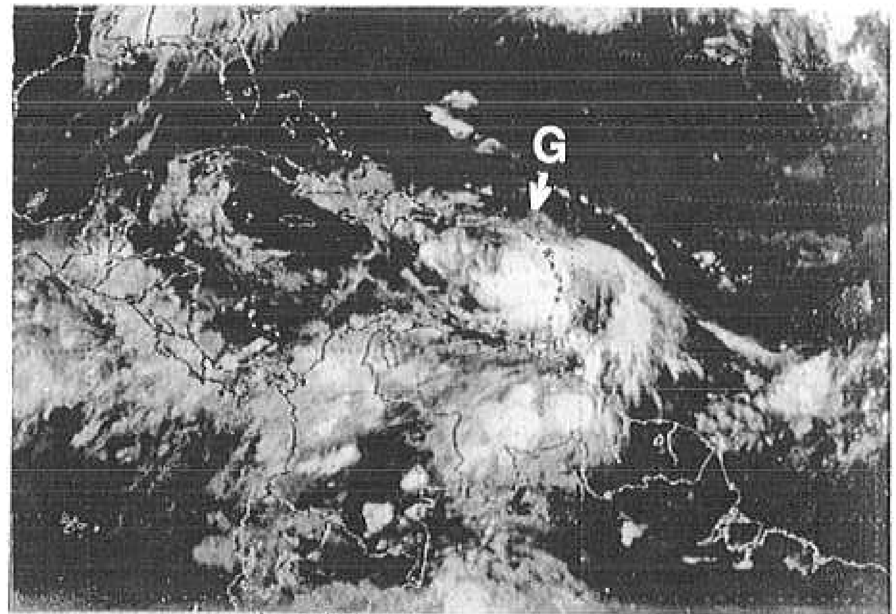
p) 1303 9 September 1988



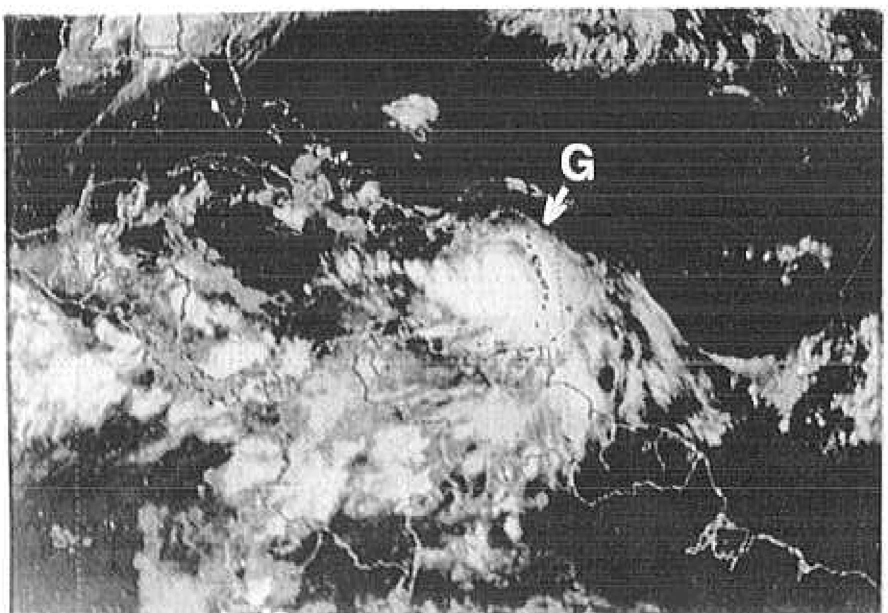
q) 1801 9 September 1988



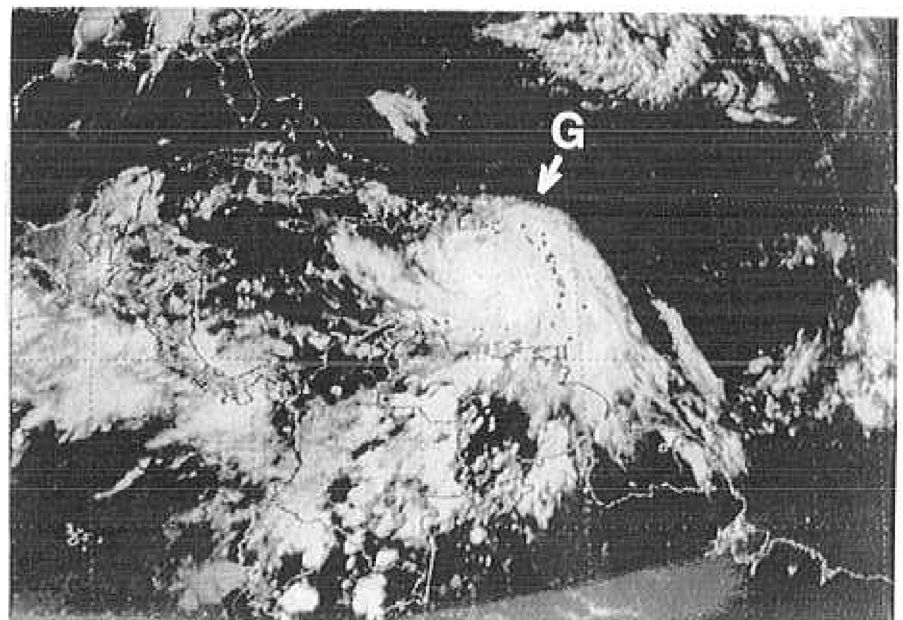
r) 0001 10 September 1988



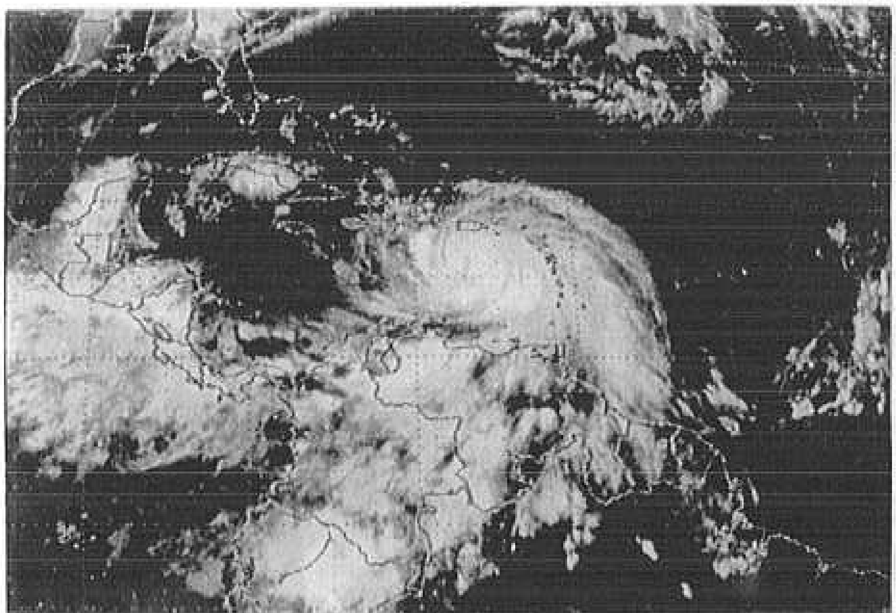
s) 0601 10 September 1988



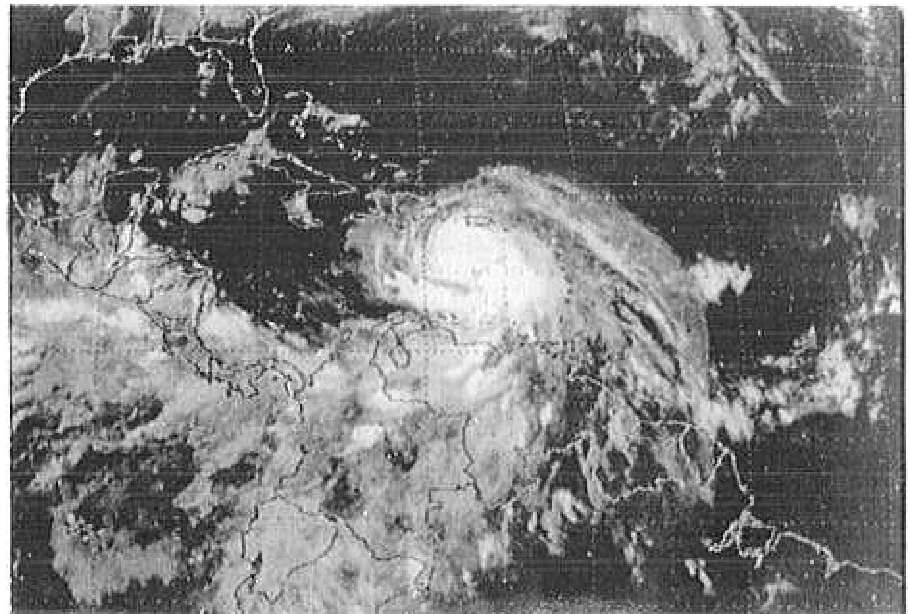
t) 1201 10 September 1988



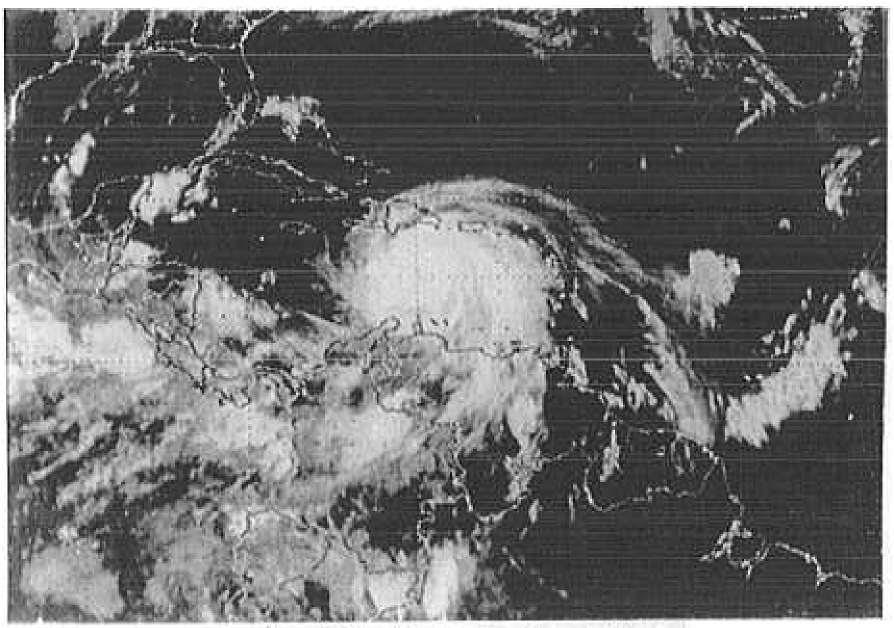
u) 1801 10 September 1988



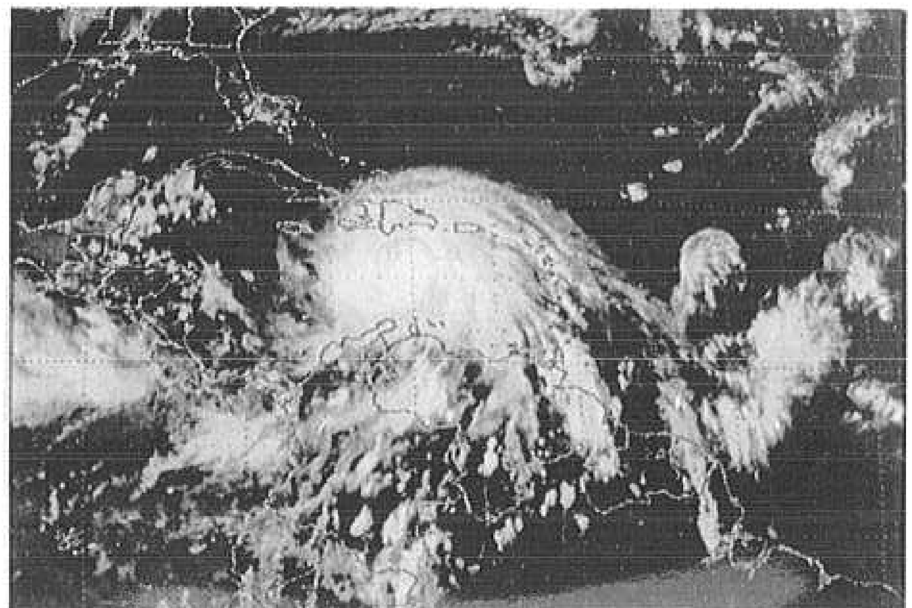
v) 0001 11 September 1988



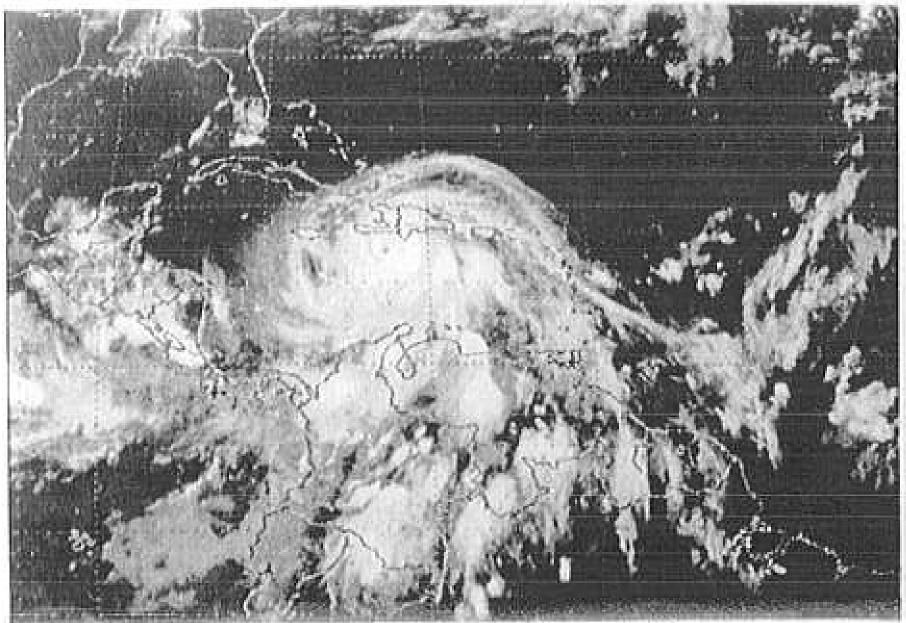
w) 0601 11 September 1988



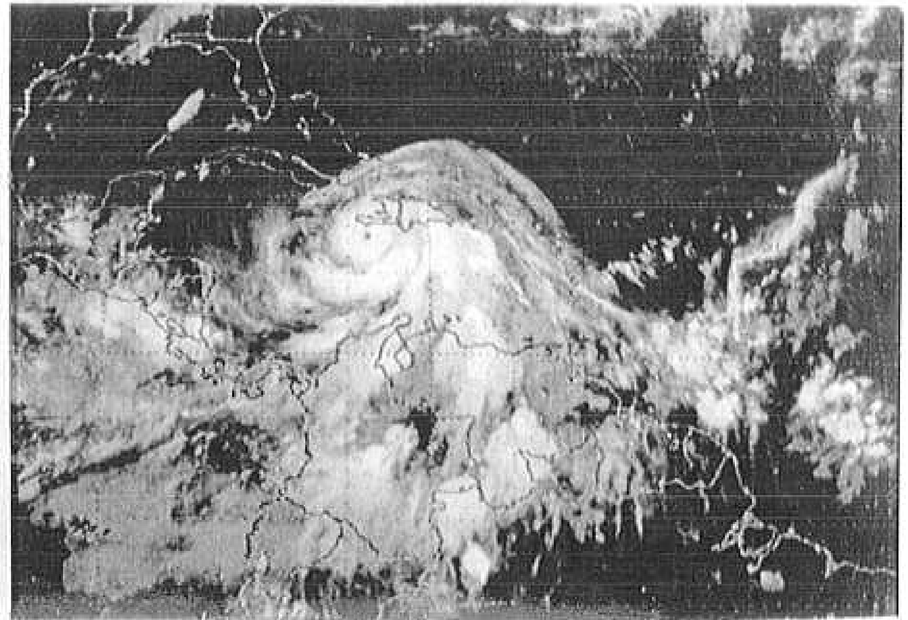
x) 1201 11 September 1988



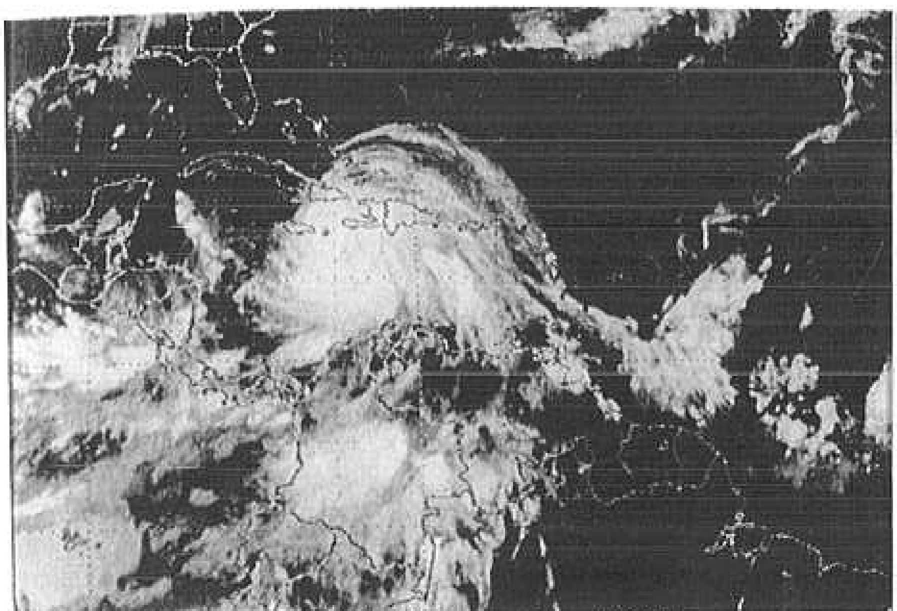
y) 1801 11 September 1988



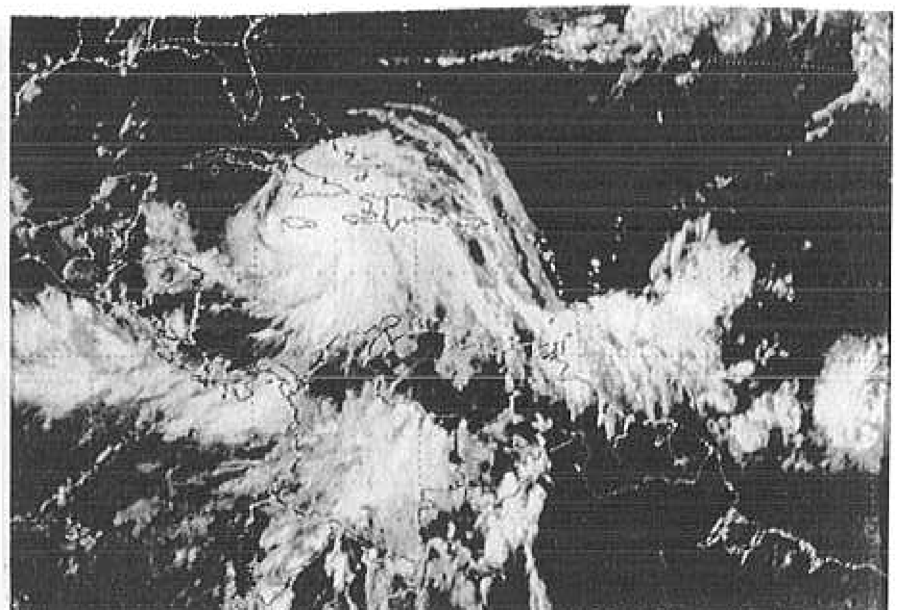
z) 0201 12 September 1988



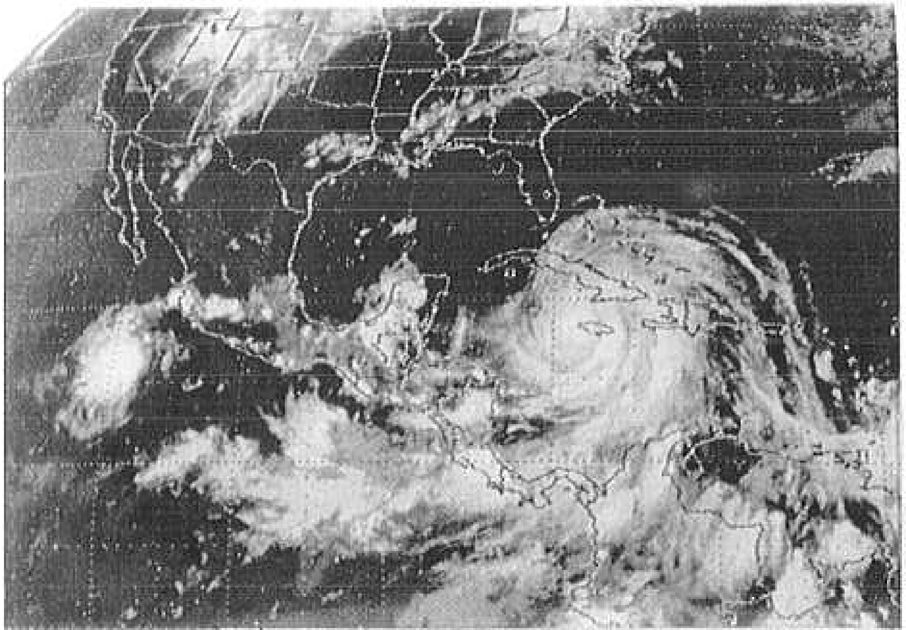
aa) 0601 12 September 1988



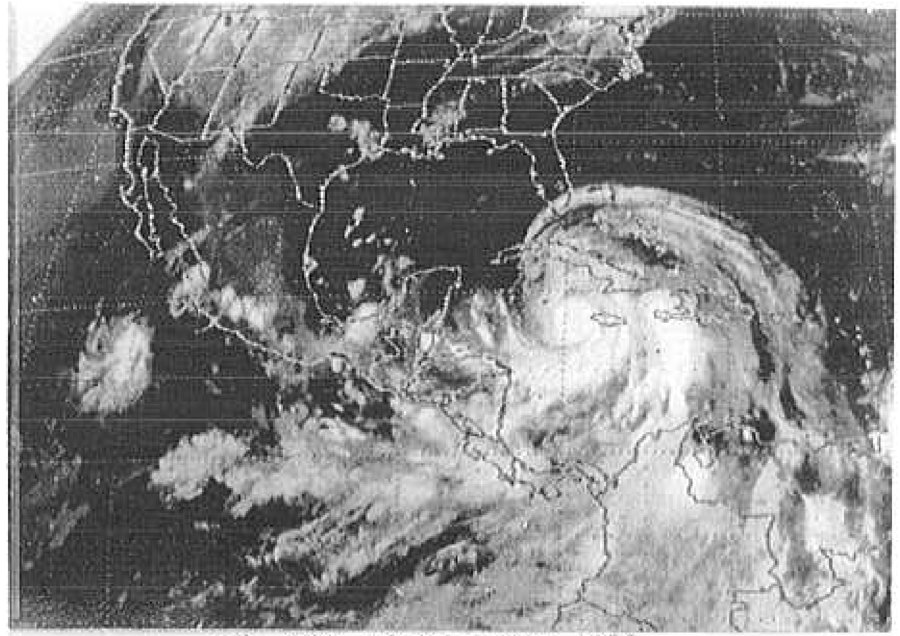
bb) 1201 12 September 1988



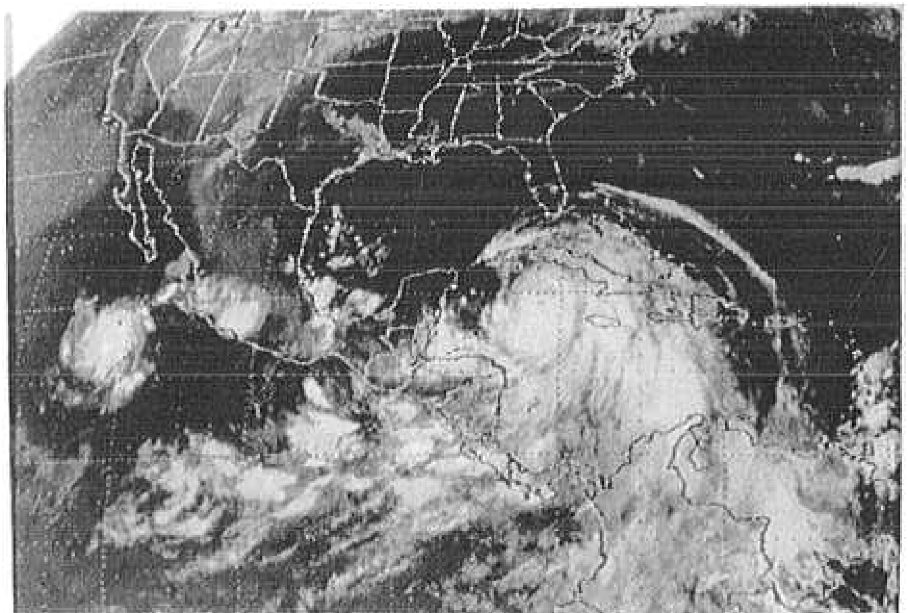
cc) 1801 12 September 1988



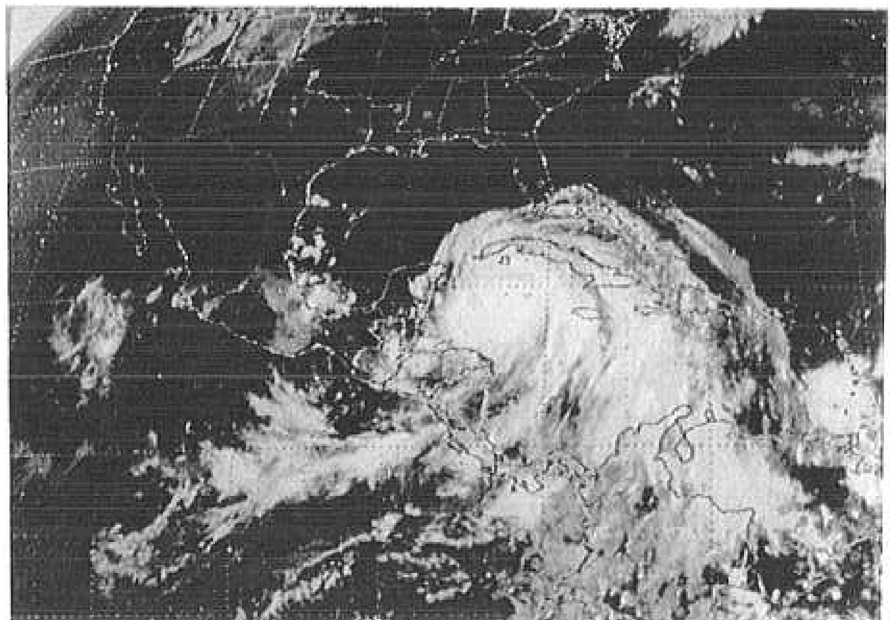
dd) 0001 13 September 1988



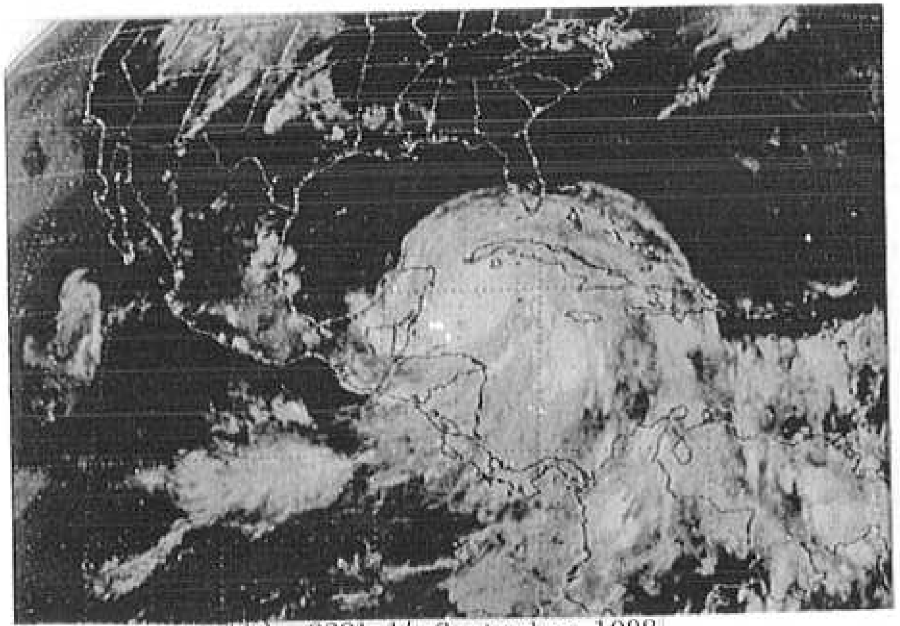
ee) 0601 13 September 1988



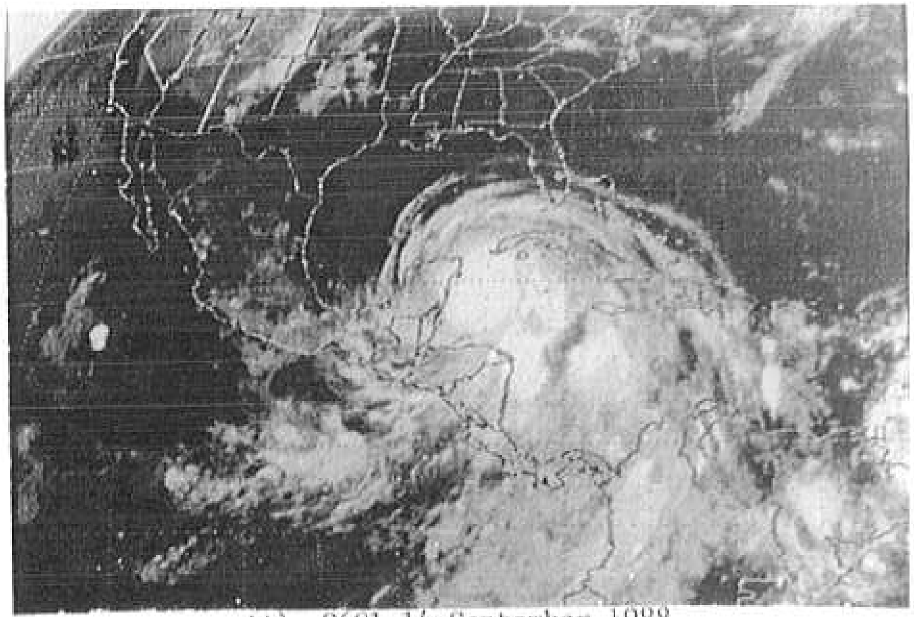
ff) 1201 13 September 1988



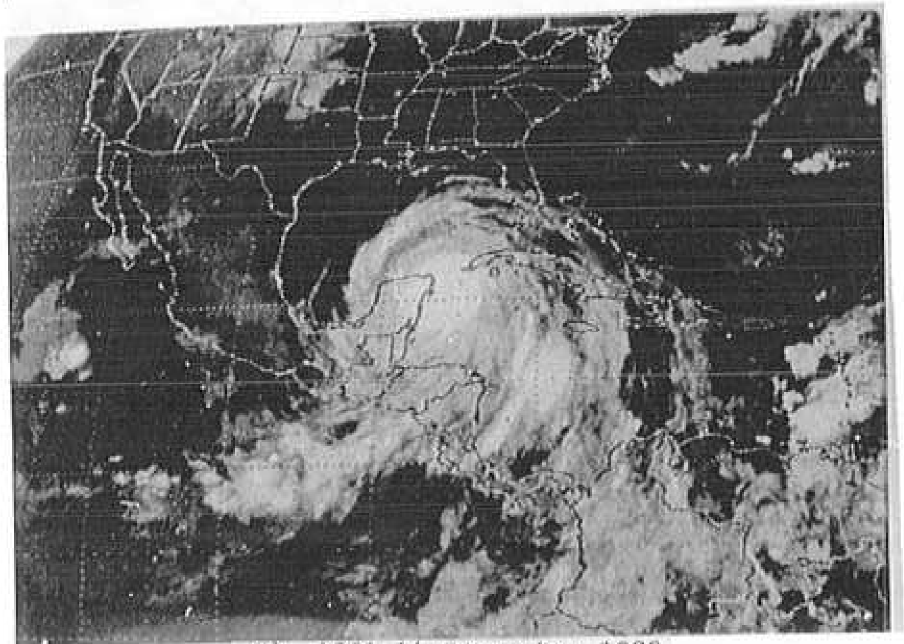
gg) 1801 13 September 1988



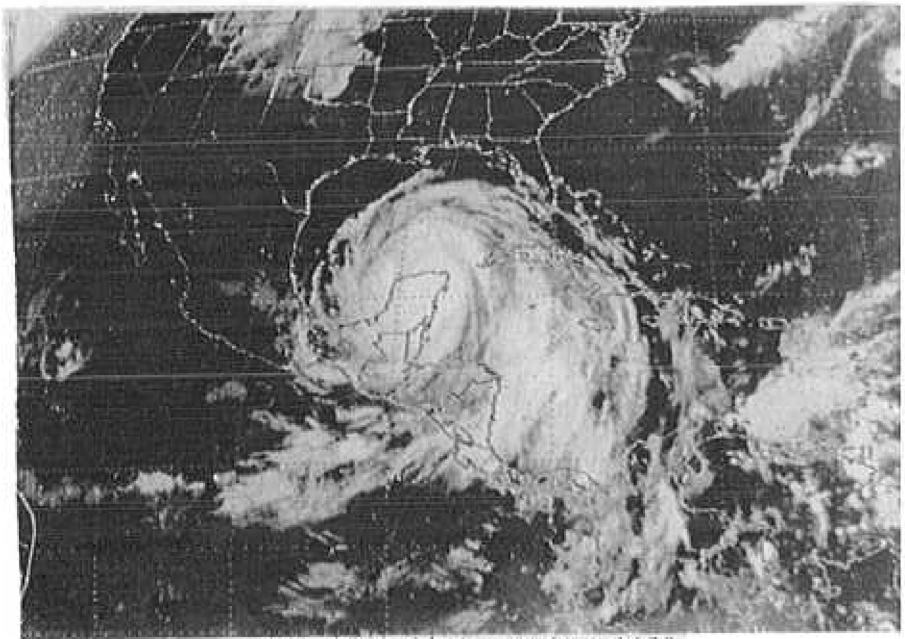
hh) 0001 14 September 1988



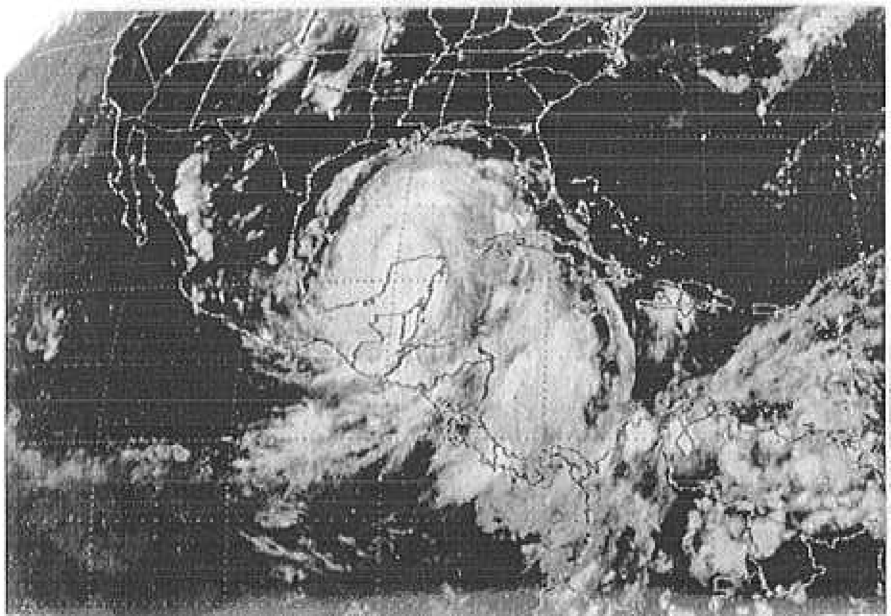
ii) 0601 14 September 1988



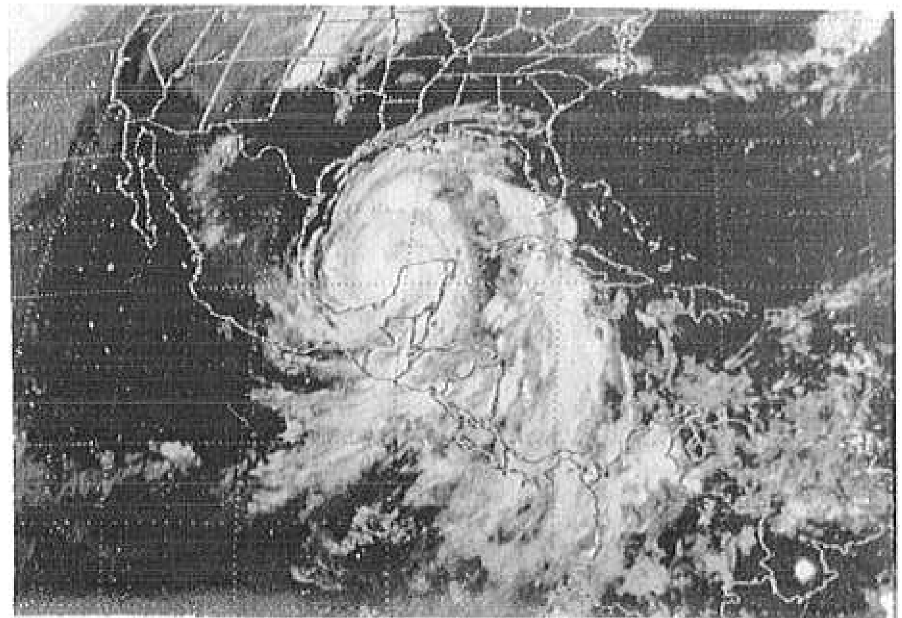
jj) 1201 14 September 1988



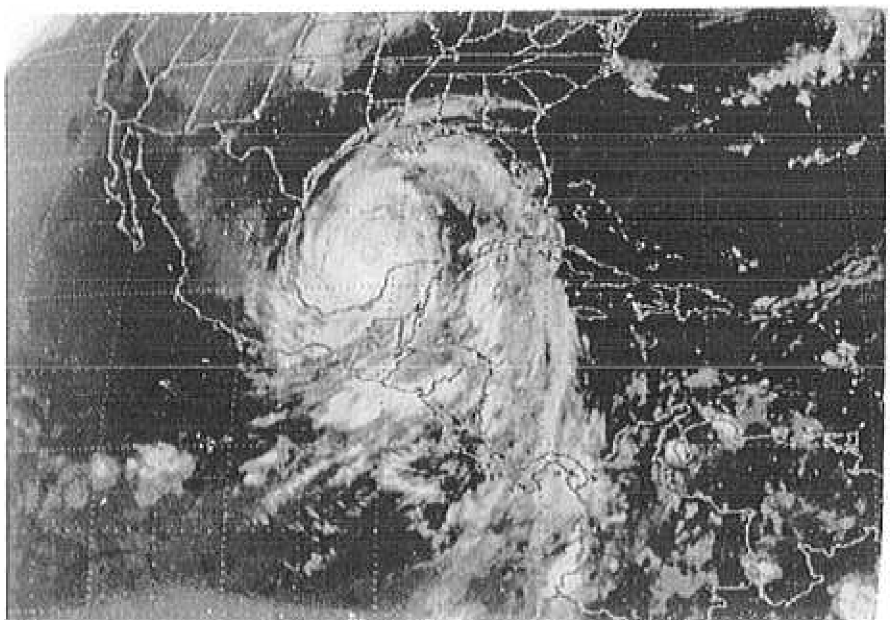
kk) 1801 14 September 1988



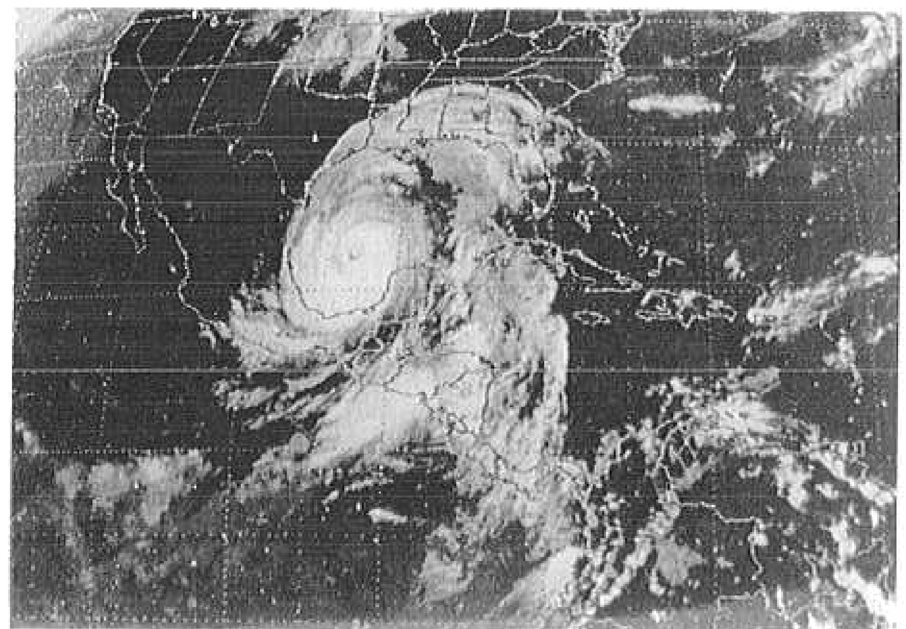
ll) 0001 15 September 1988



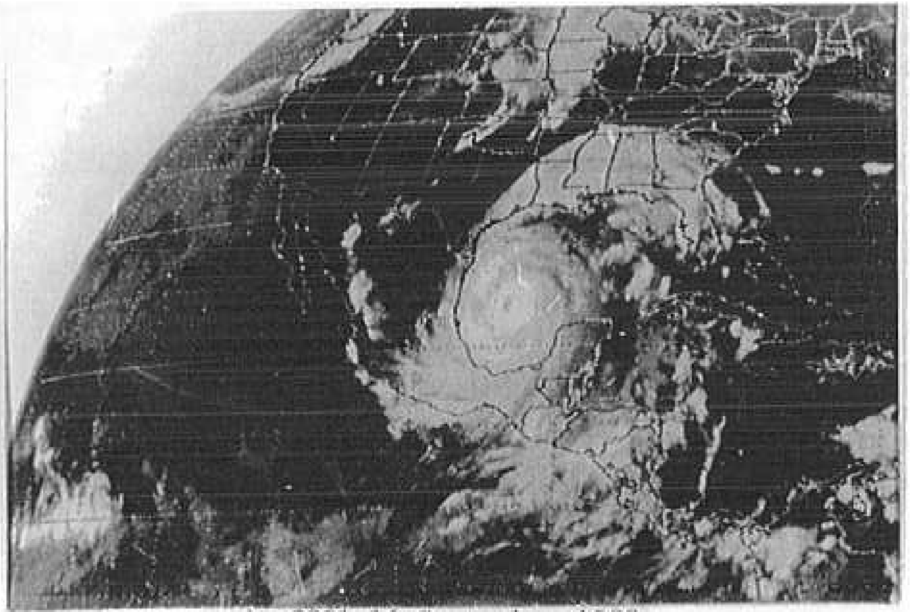
mm) 0701 15 September 1988

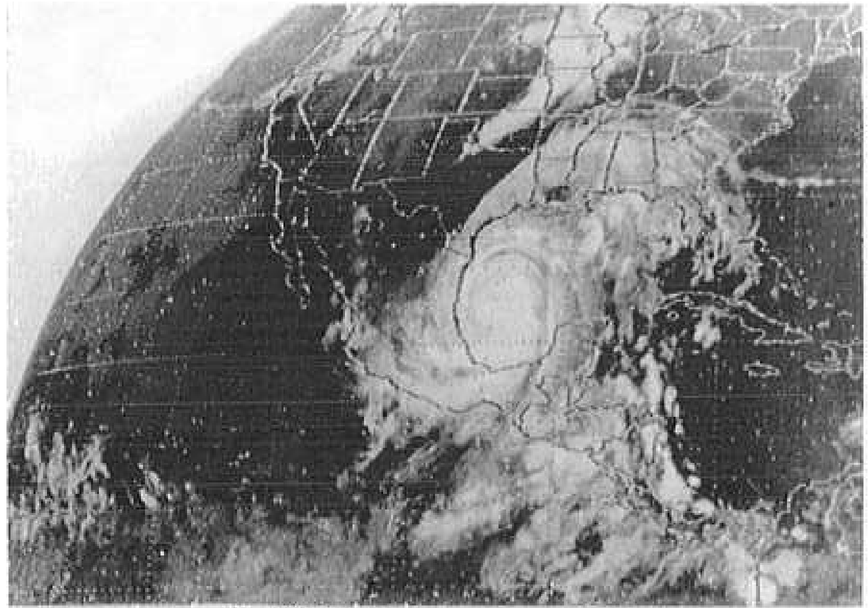


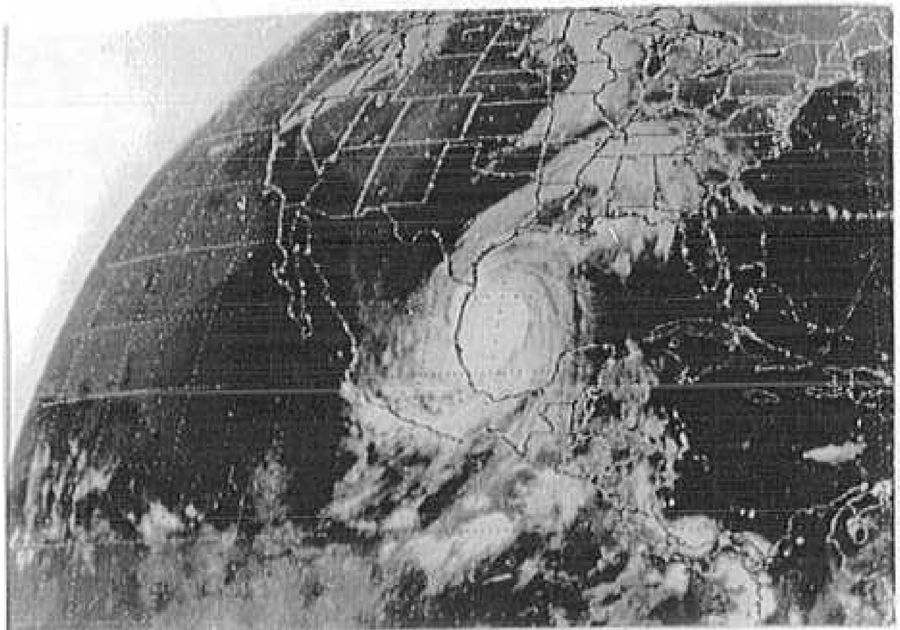
nn) 1201 15 September 1988

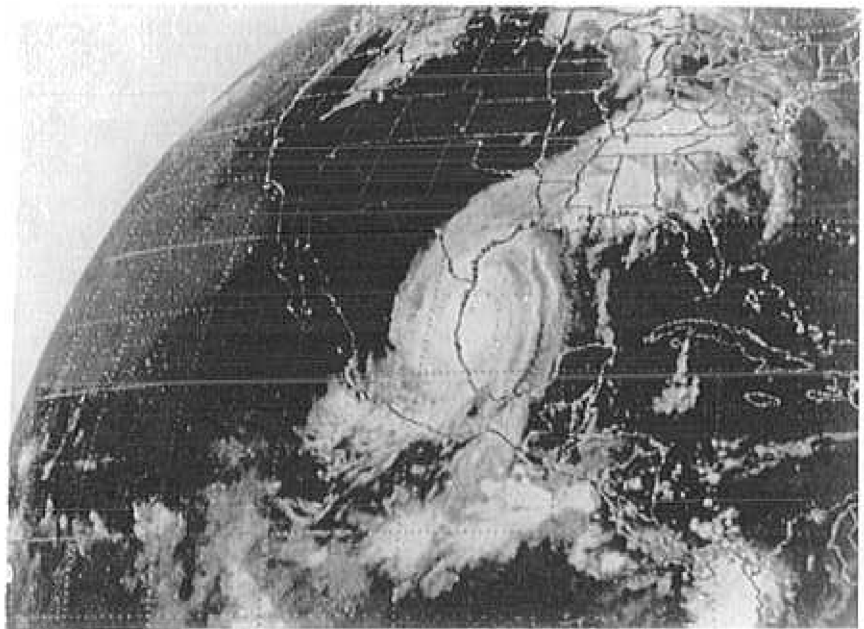


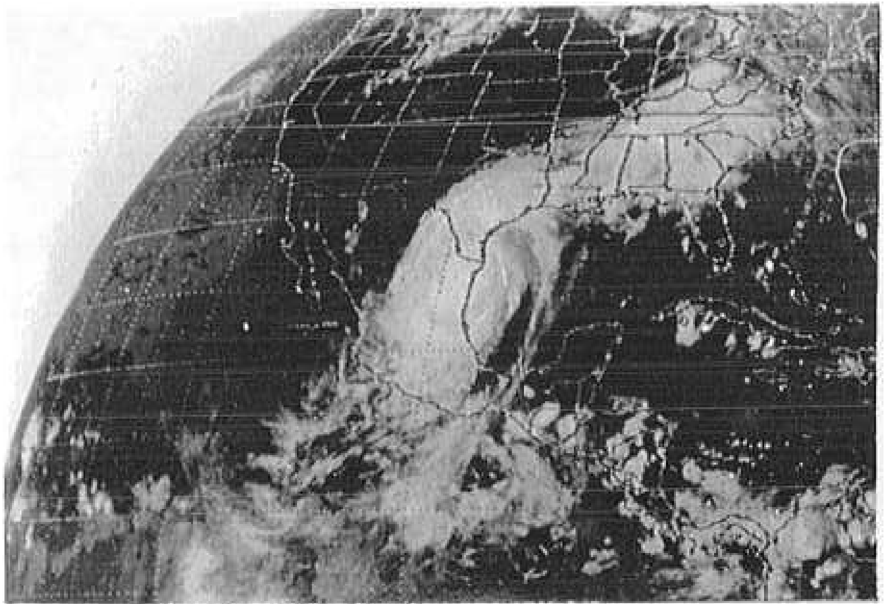
oo) 1801 15 September 1988


pp) 0001 16 September 1988

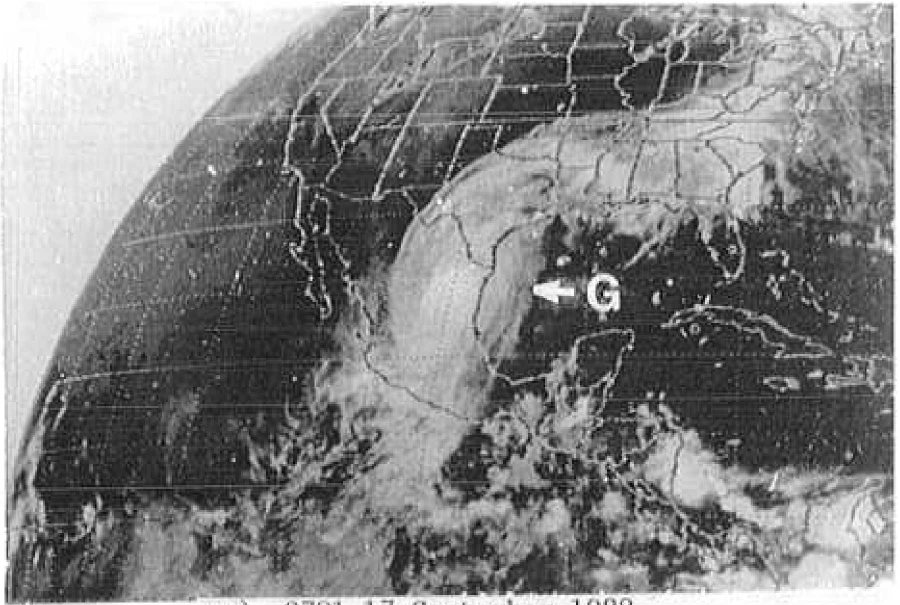

qq) 0601 16 September 1988


rr) 1101 16 September 1988

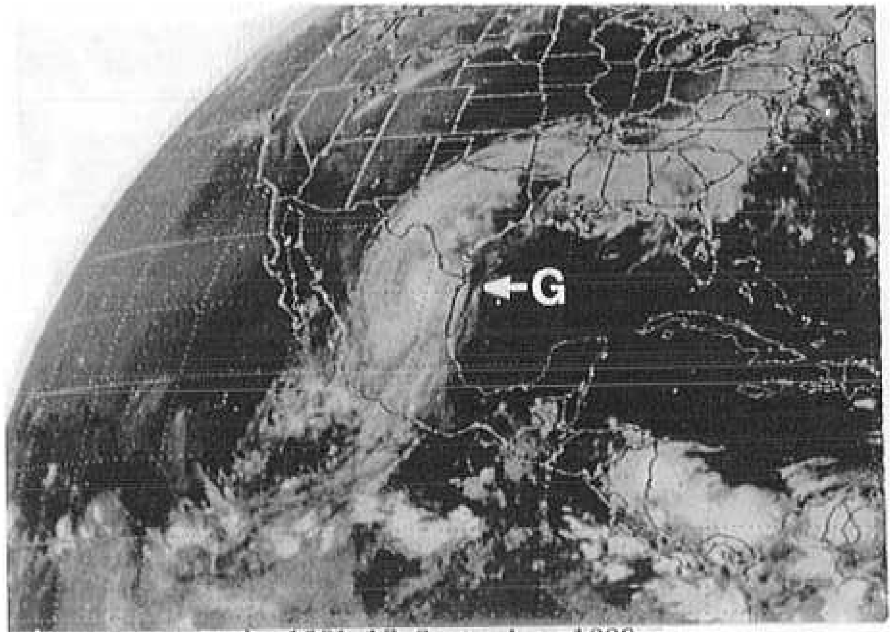

ss) 1801 16 September 1988



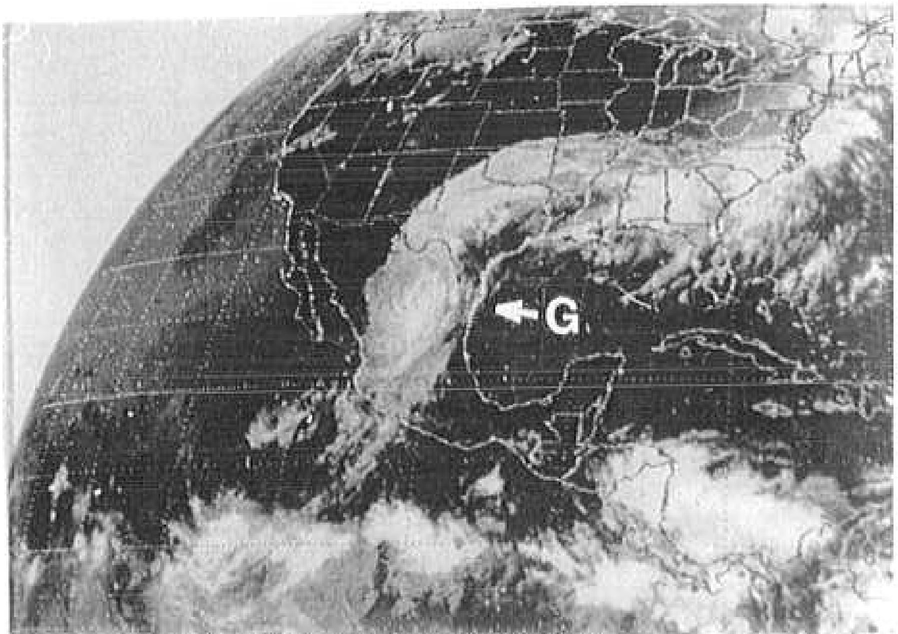
tt) 0001 17 September 1988



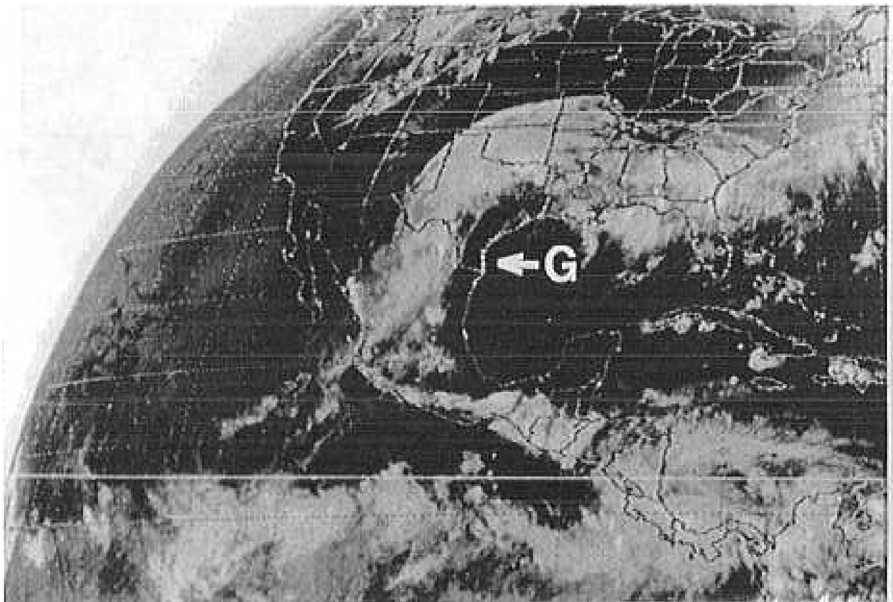
uu) 0701 17 September 1988



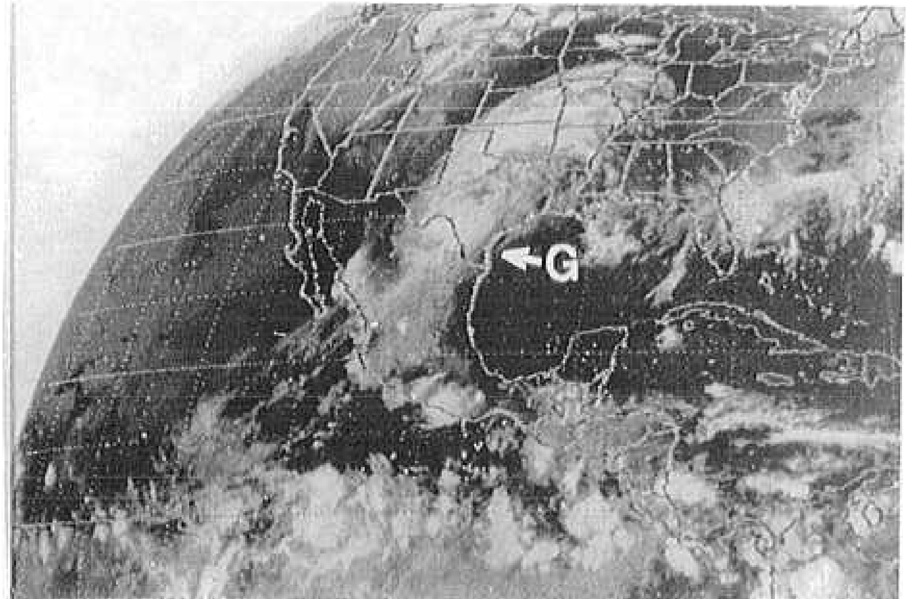
vv) 1201 17 September 1988



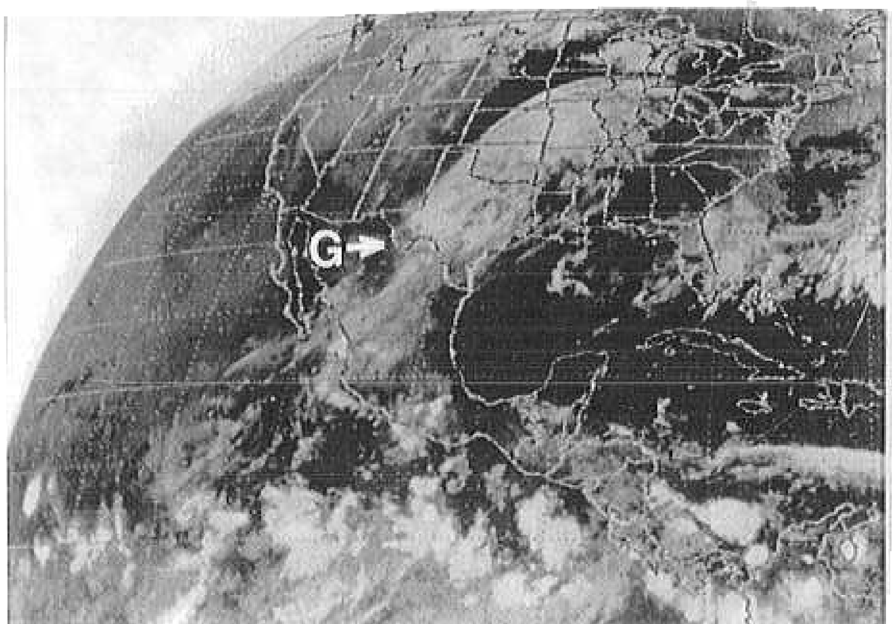
ww) 1801 17 September 1988



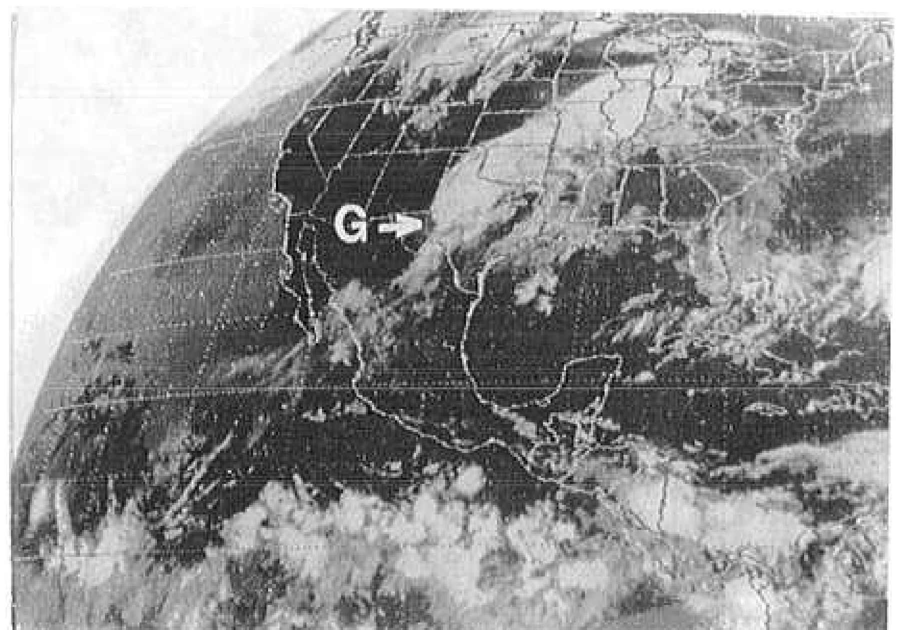
xx) 0001 18 September 1988



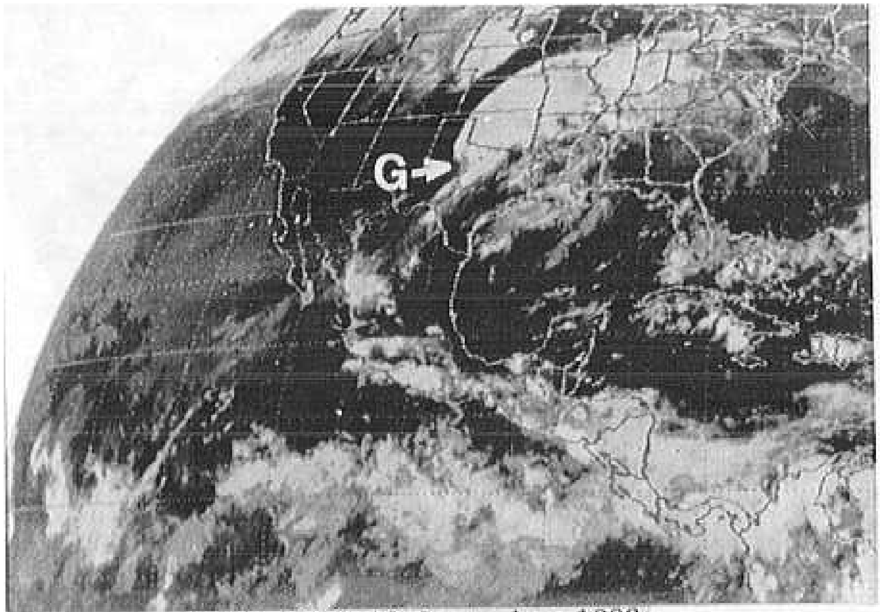
yy) 0701 18 September 1988



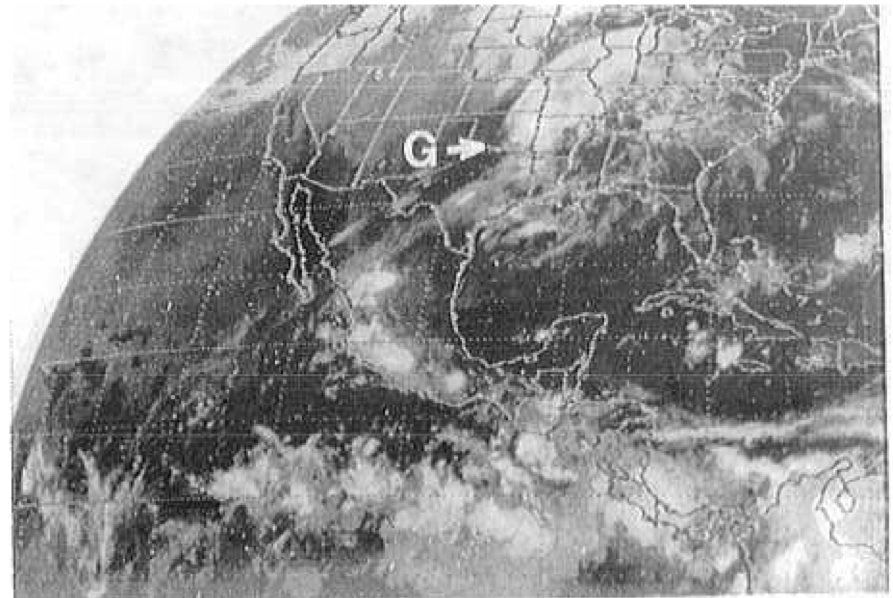
zz) 1201 18 September 1988



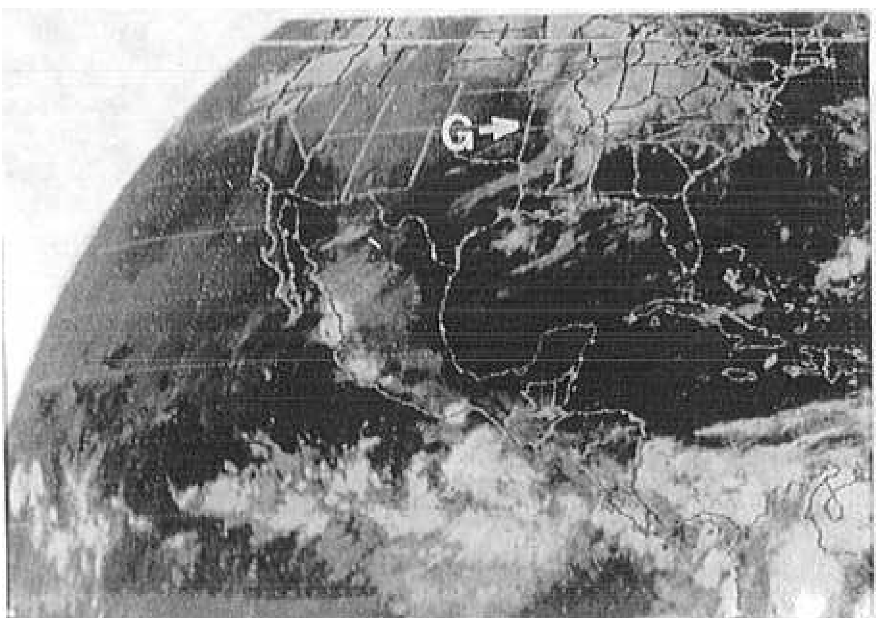
aaa) 1801 18 September 1988



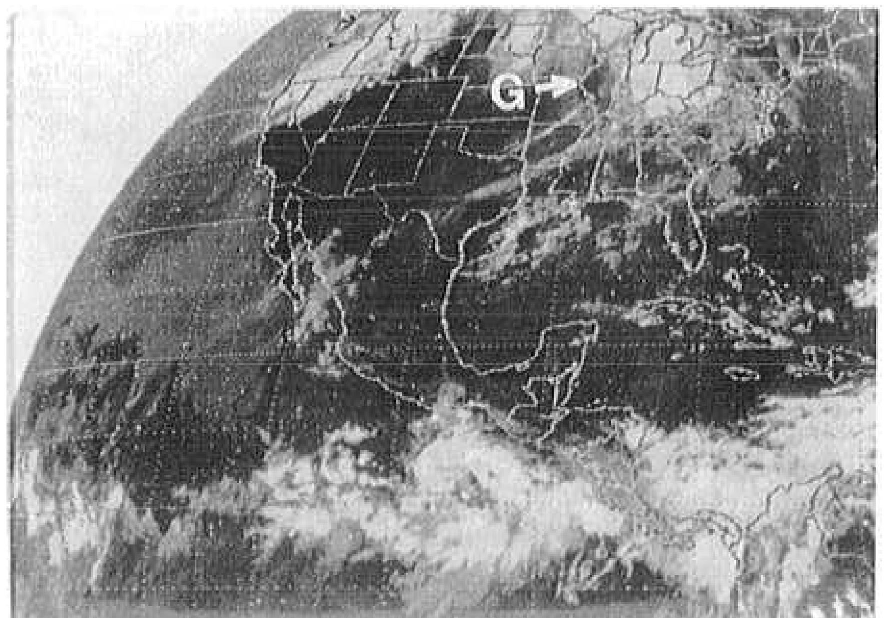
bbb) 0001 19 September 1988



ccc) 0601 19 September 1988



ddd) 1201 19 September 1988



eee) 1801 19 September 1988

This velocity was maintained approximately throughout the storm's evolution until landfall occurred over northeast Mexico.

From September 3-6, the area of cloudiness near wave 38 initially increased and then became isolated as the ITCZ became less distinct (e.g., Fig. 6e). A low-level center was again identified along the wave by 1200 UTC (henceforth, all times are UTC) September 5 (Fig. 6f). Using 1200 September 6 imagery, analysts associated the low-level circulation with a cluster of thunderstorms (Fig. 6h). Applying the Dvorak (1984) technique for estimating tropical cyclone intensity from satellite imagery, the analysts made their first "classification" of this system, formally documenting that the system had rudimentary tropical cyclone characteristics.

During the following 48 hours, significant changes in the weather pattern occurred over the central and eastern Atlantic Ocean (Figs. 6i through 6m). ITCZ convection reformed into a broad u-shaped band extending from near the coast of Africa at Dakar (15°N) southwestward to near 4°N 35°W and then northwestward to about 500 miles east of the Lesser Antilles. Convection associated with wave 38 increased and became elongated from southeast to northwest. The unnamed tropical storm developed to the east-northeast of the wave near the ITCZ, just offshore from the coast of Africa (see "U" in Fig. 6l) and merged with a developing mid-latitude storm system.

Convection in the southeastern part of wave 38 became more concentrated by 1800 September 8 (e.g., Fig. 6m) and some cyclonic turning at low- to mid-levels was noted. The organization of convection became increasingly banded (e.g., "b" in Fig. 6m). A more organized outflow at upper levels was detected and the NHC upgraded the system to a tropical depression.

The depression began separating from the ITCZ and approached the Lesser Antilles on September 9 (Figs. 6n through 6q). The depression expanded. Convection over the northern part of South America took on a cyclonic curvature in the area to the south of the circulation center (e.g, Fig. 6q). This indicated a broadening of the depression's low- to mid-level circulation. The upper-level outflow became more distinct, particularly to the south and east of the storm center. Simultaneously, convection near the storm's center became more concentrated. The system became Tropical Storm Gilbert on September 9.

To the west of Gilbert, convection also became enhanced in a broad area along and to the north of the ITCZ (e.g., Fig. 6q). Heavy rainfall occurred over Central America. Further north, Tropical Storm Florence ("F" in Fig. 6p) intensified into a hurricane and then moved inland over the U.S. central Gulf coast.

Gilbert crossed the Lesser Antilles on September 10. The satellite imagery (and data from reconnaissance aircraft) indicated rapid intensification. Strong convection near the storm's center grew from a small cluster of 100 miles diameter at 0000 (Fig. 6r) to an area of 500 miles diameter by 1800 (Fig. 6u). Convection associated with the part of wave 38 to Gilbert's northwest dissipated, probably in response to widespread subsidence associated with the intense convection in Gilbert. Using the Dvorak technique, it was estimated that the storm was nearing hurricane strength. During the evening of September 10 Gilbert became a hurricane.

Gilbert's zone of convection continued to expand as the hurricane's center passed to the south of Puerto Rico and Hispaniola on September 11 (Figs. 6v through 6y). A "banding eye" could be seen at 0000 (Fig. 6v) and "overshooting" thunderstorm tops penetrated through the tropopause. Strong convection continued over northern South America and banding of convection increased. Anticyclonic outflow aloft became prominent from the southern Bahamas to near the Equator.

By 0000 September 12, a distinct eye of 40 miles diameter had developed (Fig. 6z). Gilbert overspread the eastern tip of Jamaica during the evening (Fig. 6cc). The GOES imagery indicates some asymmetry to the convection and cirrus outflow with more cloudiness east of the eye than to the west. A close-up high resolution (1 km) visible picture of Gilbert as the hurricane approached Kingston, Jamaica at 1700 shows the eye, area of intense convection and cloud bands (Fig. 7a).

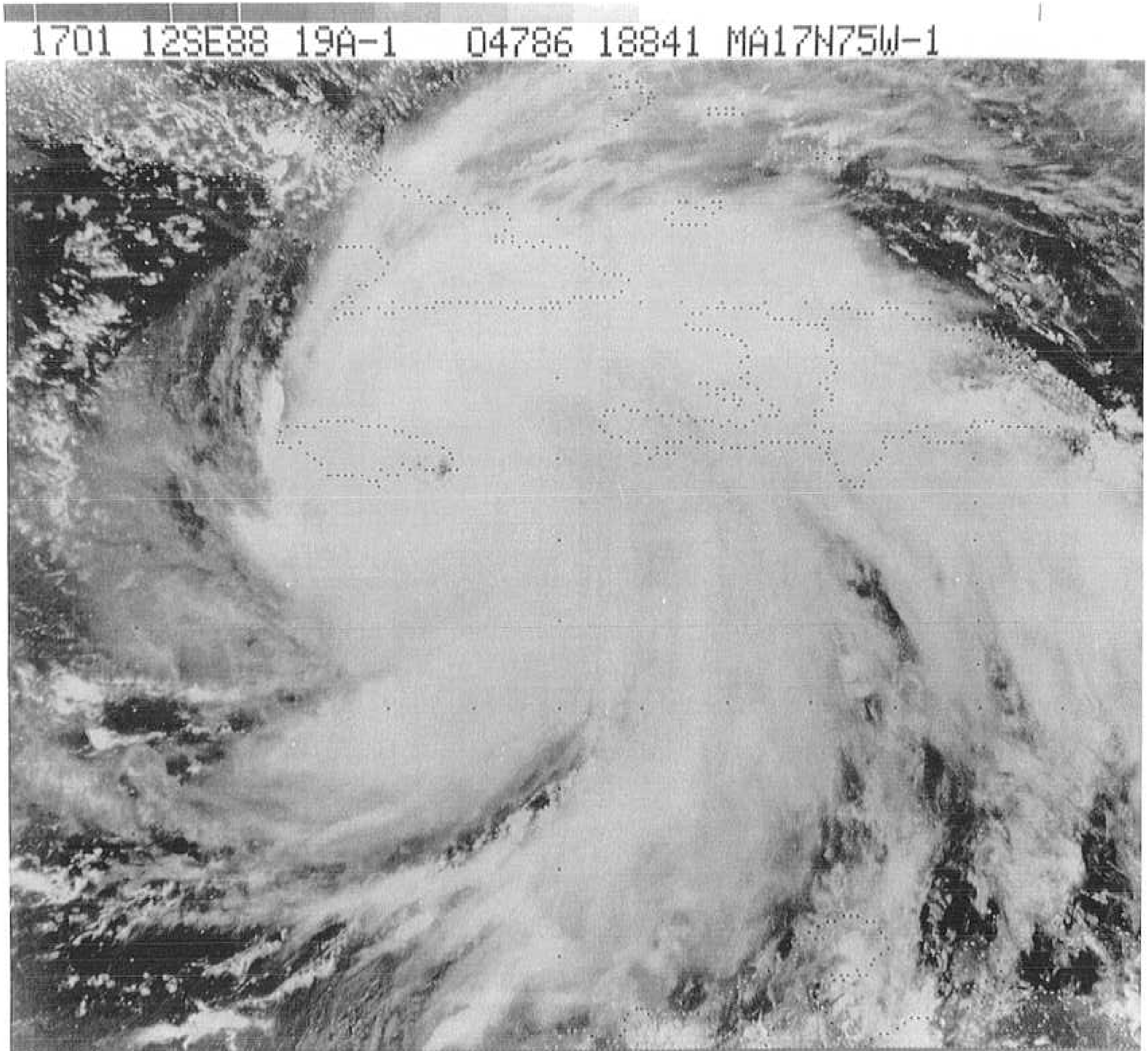
Gilbert's center moved westward across the length of Jamaica and reentered the Caribbean early on September 13. The imagery showed a somewhat smaller area of intense convection than the storm had upon landfall (cf. Figs. 6cc and 6dd), perhaps as a result of the interaction with land.

The satellite images (Figs. 6dd through 6gg) are consistent with reconnaissance aircraft data (Sec. 3.3) in indicating that Gilbert went through its most rapid deepening on September 13 and reached its peak intensity near 2152 September 13. The area of strong convection increased (cf. whitest areas in Figs. 6dd and 6gg) and the diameter of the eye decreased to an exceptionally small value of between about 5 and 10 miles. A close-up visible picture (Fig. 7b) shows the cloud structure of Gilbert about 20 min prior to the report from aircraft reconnaissance of peak intensity.

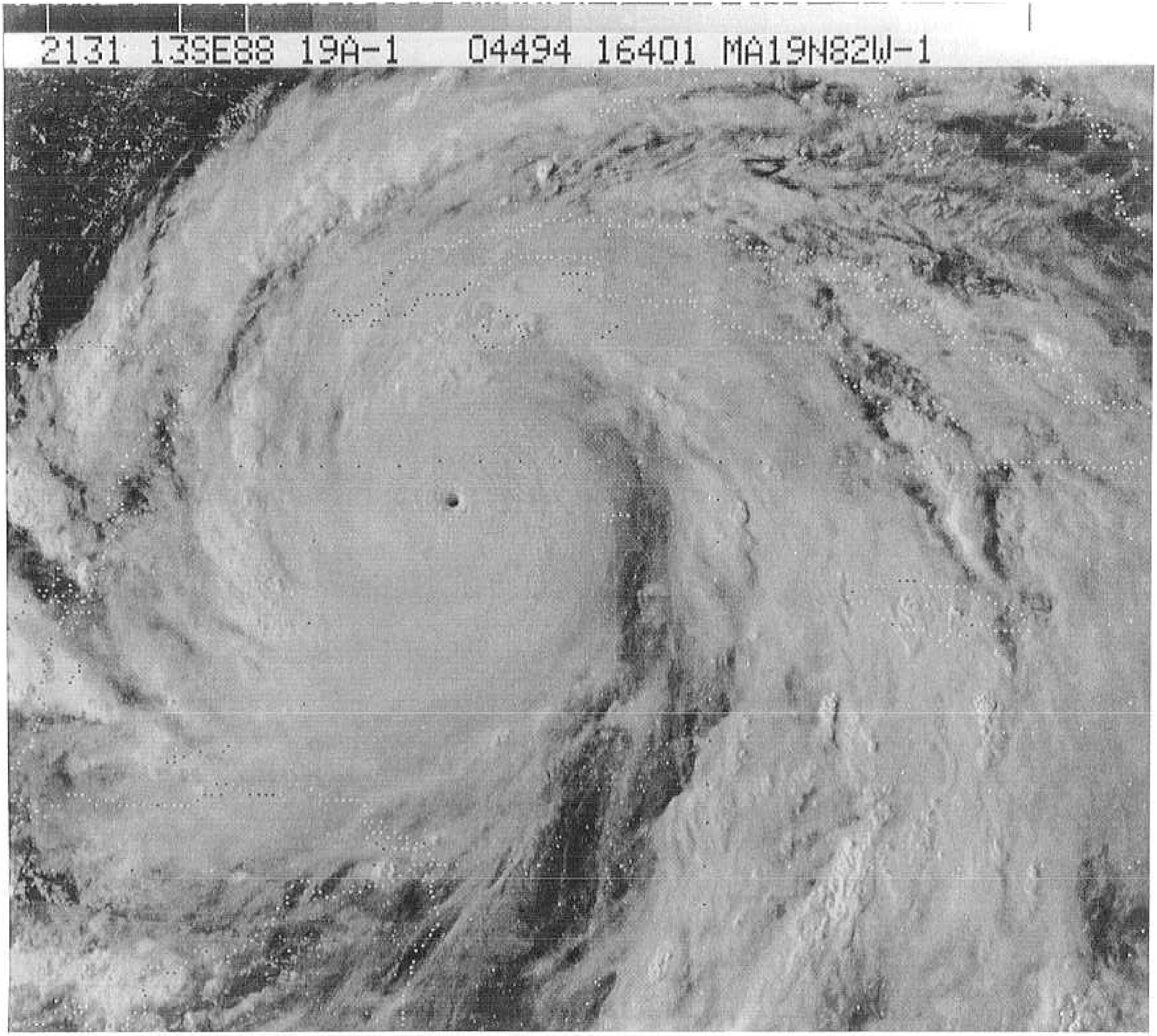
Figure 8a is a wide-area infrared view when the hurricane was near its peak intensity (a Dvorak T-number of 8.0, the highest on that scale). Gilbert's upper-level cloud and anticyclone were huge in horizontal extent, covering more than 3 million square miles from central Florida southward into the northernmost Southern Hemisphere and from Central America eastward to Puerto Rico. By contrast, the area of Gilbert's upper-level outflow greatly exceeded that from Hurricane Camille. This can be seen by comparing Gilbert's cloud in Fig. 8a with that of Camille shown in Fig. 8b, when the latter hurricane was near its peak intensity.

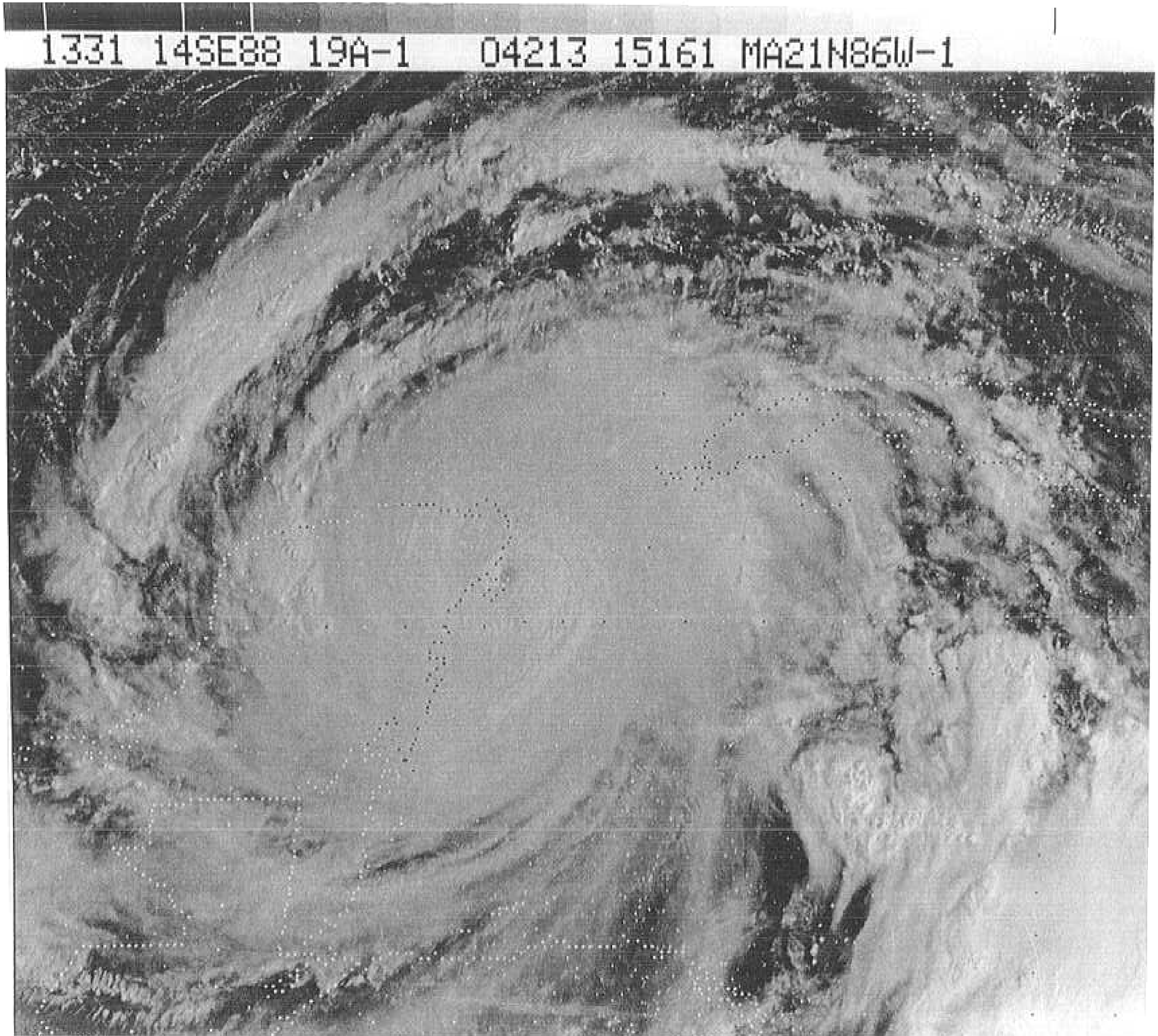
Satellite photographs (and reconnaissance reports) suggest that Gilbert's intensity remained near its maximum early on September 14 as Gilbert passed over the northern tip of Cozumel Island (Figs. 6hh through 6jj, 7c).

Fig. 7. High resolution (1 km) GOES-EAST visible satellite imagery of Hurricane Gilbert near (a) Jamaica, (b) maximum intensity, (c) Yucatan peninsula and (d) northeast Mexico.

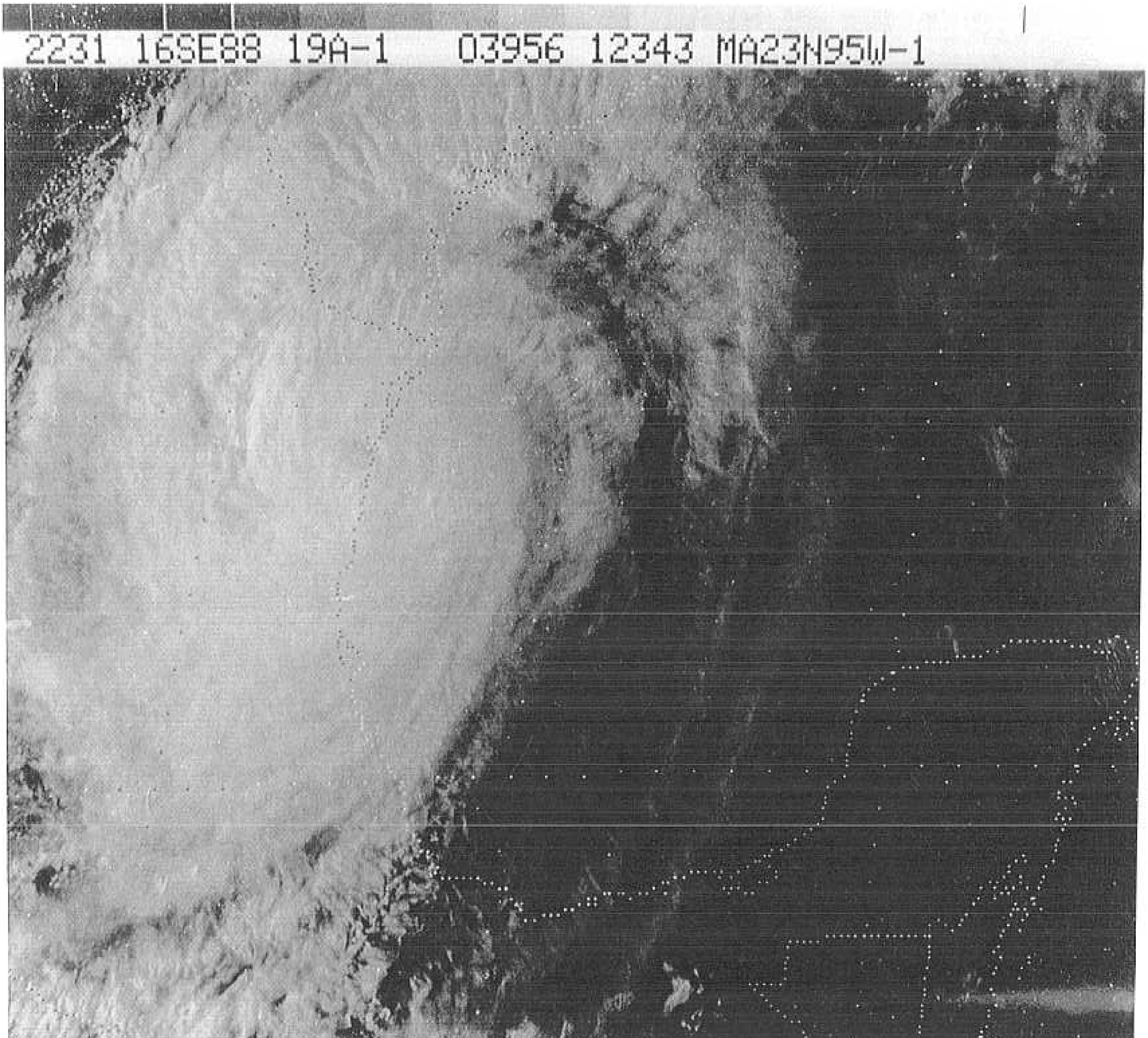


a) 1701 12 September 1988


2131 13SE88 19A-1 04494 16401 MA19N82W-1



c) 1331 14 September 1988



d) 2231 16 September 1988

(a)

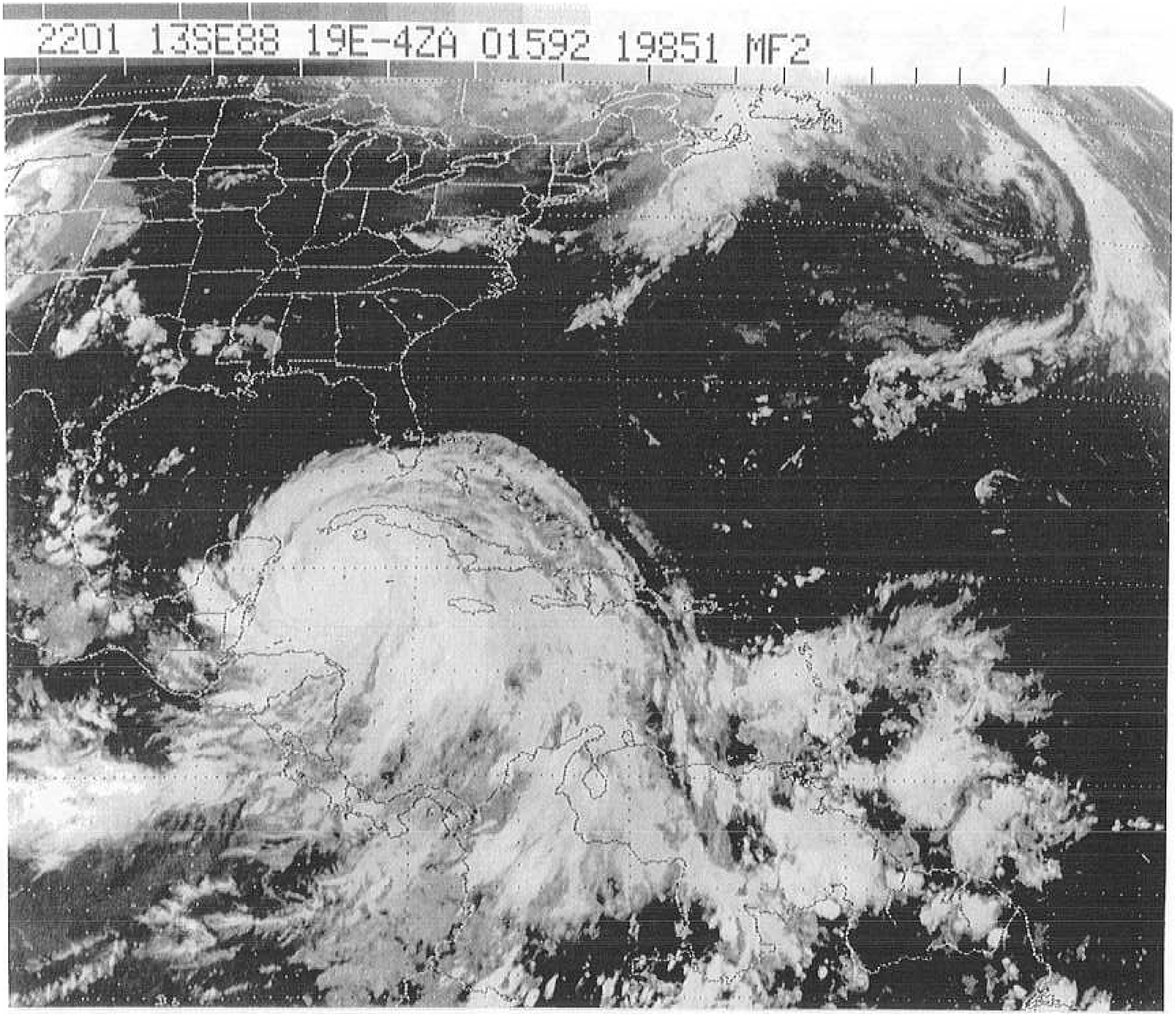
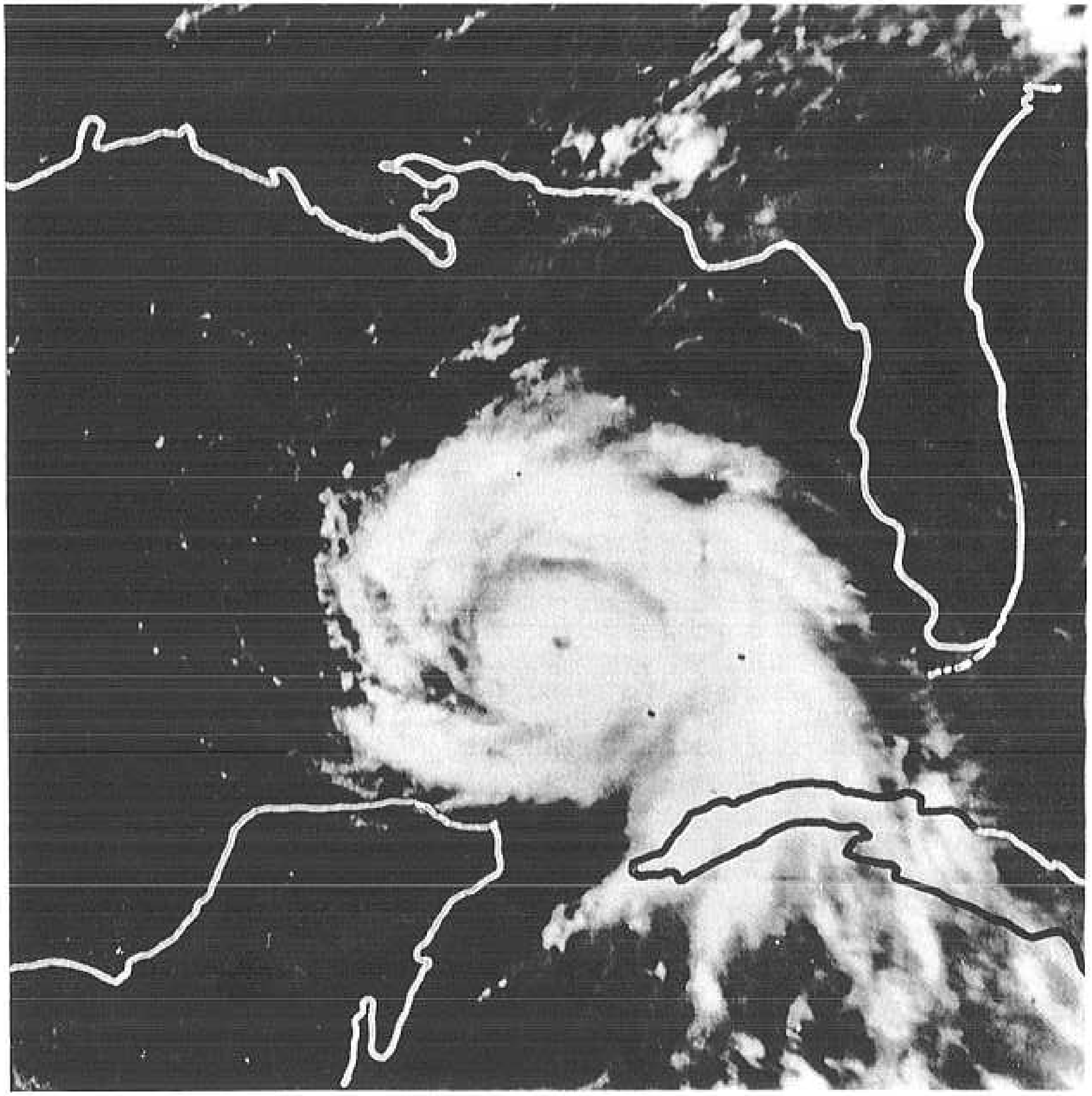


Fig. 8. (a) GOES-EAST infrared satellite image of Gilbert near peak intensity, at 2200 UTC September 13, 1988. (b) Nimbus III infrared satellite image of Hurricane Camille at 1710 UTC August 16, 1969 when Camille had a central pressure of 908 mb and maximum sustained wind of 130 kt. White outline shows coastline.

(b)



The amount of inner core convection and the cirrus shield over Gilbert decreased in size when the storm overspread the Yucatan peninsula and entered the Bay of Campeche (Figs. 6ll and 6mm). The diameter of the eye increased to more than 30 miles. Cirrus partially obscured the eye after landfall.

While over the central Gulf, Gilbert changed little in intensity as seen in the imagery (cf. Figs. 6ll and 6qq). The outer-most rainbands to the northwest of Gilbert's center spread to the central U. S. Gulf coast and then the western Gulf coast on the 15th (e.g., Fig. 6oo). The upper flow to the north of Gilbert became southwesterly as Gilbert approached a frontal system in the mid-latitude westerlies (see Sec. 3.4). This pattern elongated upper-level clouds associated with Gilbert from south to north. By 0600 September 16, the upper clouds from the hurricane and upper clouds with the front merged over the lower Mississippi valley (Fig. 6qq). Later, Gilbert would merge completely with a mid-latitude frontal system, seen in Fig. 6qq to be over the Pacific Northwest on September 16.

Satellite imagery suggests that Gilbert may have begun to re-intensify during the 18 h prior to the hurricane making landfall over northeast Mexico on the evening of September 16. The area of convection around the storm's center increased (e.g., Fig. 6rr). Just prior to landfall the eye became distinct once again (Fig. 6ss) and analysts of satellite data noted some reduction in the diameter of the eye. On the other hand, reconnaissance aircraft did not detect a significant drop in Gilbert's central pressure coinciding with the changes in cloud structure.

As Gilbert made landfall on the northeast coast of Mexico the eye gradually became obscured (Fig. 7d) and could not be identified in satellite imagery after about 0400 September 17 (not shown). Despite weakening, Gilbert's circulation interacted with the elevated terrain of northeast Mexico to generate heavy rains. The rains produced extensive flooding that was a factor in the large loss of life in the city of Monterrey, as noted in Section 2.5.3.3.

When Gilbert moved further inland on the 17th (Figs. 6tt through 6ww) and turned toward the northwest, the system elongated from south to north. Upper-level clouds spread to the north into the central United States while most low- and mid-level clouds near Gilbert's center remained to the east of the continental divide, their westward advance blocked by the higher terrain of Mexico to the west.

Much of Gilbert's convection had spread into Texas with higher clouds advancing to near the United States-Canada border by September 18 (Figs. 6xx through 6aaa). Convection near Gilbert's center appeared diffuse early on the 18th as the storm weakened to a tropical depression (Fig. 6xx). However, by late in the day the area of convection had reconsolidated and cloud tops increased (Fig. 6zz). Surface data suggest that the storm's central pressure had begun to fall. This occurred as the system began to take on the characteristics of an extratropical (mid-latitude) system.

Upper-level clouds from Gilbert were still distinct on 19 September when the system merged with a front over the Great Lakes (Figs. 6bbb through 6eee). However, the system sheared apart in the vertical. Upper-level clouds accelerated northeastward away from the remnant low-level circulation (cf, Figs. 6ddd and 9hh). Even so, Gilbert produced rain from Texas through Oklahoma, Kansas, Missouri and Illinois. Much of that region experienced an otherwise exceptionally dry summer.

3.2 Surface Weather Maps

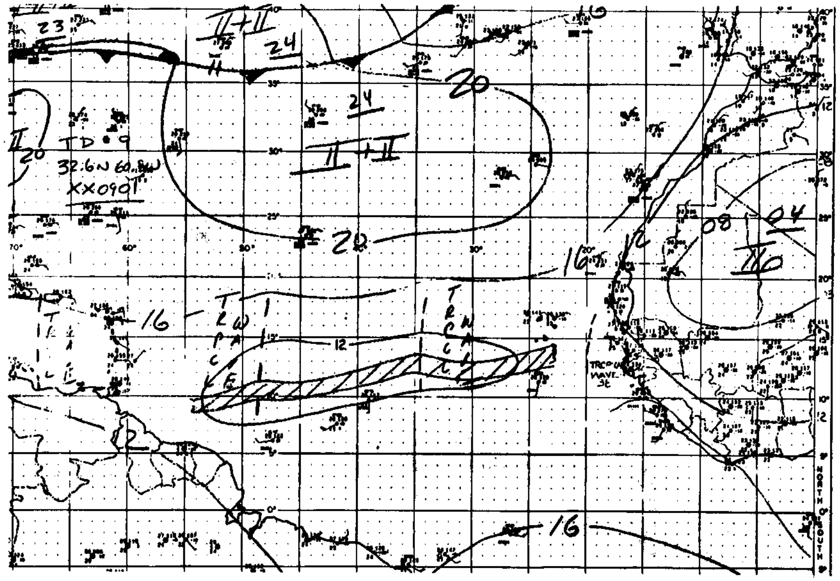
The previous section described the large extent and extreme intensity of Hurricane Gilbert as estimated from satellite imagery. In situ surface observations of a storm are rare but, when available, indicate more precisely the low-level intensity of a tropical cyclone and the characteristics of the storm's environment. Unlike satellite imagery, these surface observations provide "ground truth". This section describes the large-scale surface weather pattern from September 3-20, 1988 as seen in 12-hourly surface weather maps, and highlights interesting observations near Gilbert. The maps were prepared operationally by the NHC and subsequently modified to be consistent with data not available at the time of the original analyses (Fig. 9).

The large-scale pattern coinciding with wave 38's passage into the Atlantic on September 3, 1988 was not unusual (Fig. 9a). A broad low with a minimum pressure of about 1004 mb covered western Africa. A subtropical high, the "Bermuda High", with a central pressure near 1024 mb extended from west to east across the Atlantic along about 30°N. The high lay to the north of a monsoon trough associated with ITCZ convection. As wave 38 passed over the coastline of Africa and to the south of the Cape Verde Islands, the surface pressure near the axis of the wave was 1010-1012 mb.

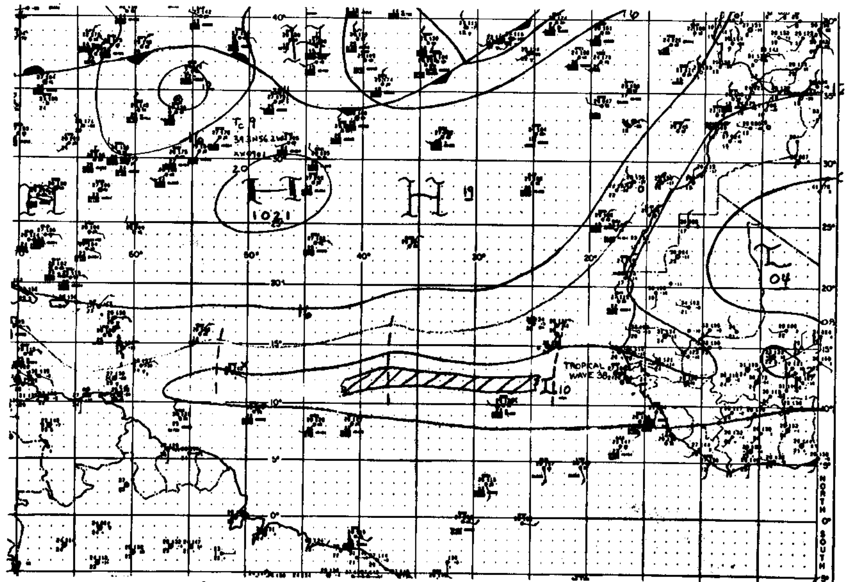
There were few surface observations within several hundred miles of the system for four to five days after wave 38 passed the Cape Verde Islands. The position of the wave was estimated from satellite imagery and extrapolation during that period. This was not an unusual circumstance. Surface observations over the tropical Atlantic are rare and typically limited to island observations and ship reports that are distant from storms. Nearby ship reports, though infrequent, provide the NHC with crucial and reliable observations of a tropical cyclone. It is a point of some irony that the ship reports which alert or help confirm to the NHC that a storm is developing are also often the basis for the NHC to advise or warn ships away from a storm, by critical necessity eliminating their valuable input to the analysis of the storm.

The large-scale pattern changed while wave 38 moved westward across the Atlantic (Figs. 9a through 9l). The subtropical high weakened initially to a pressure of about 1019 mb as mid-latitude frontal features and Tropical Storm Ernesto passed eastward along 35-40°N. The central pressure in the high then rose quickly to near 1028 mb following these systems on September 7 (e.g., 9j).

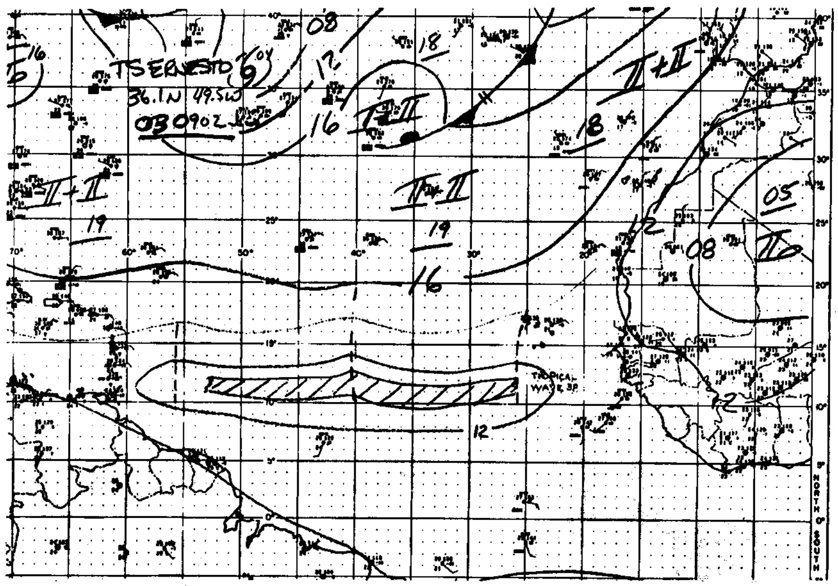
Fig. 9. Large-scale surface analyses from September 3-20, 1988, using conventional notation. Times are UTC.



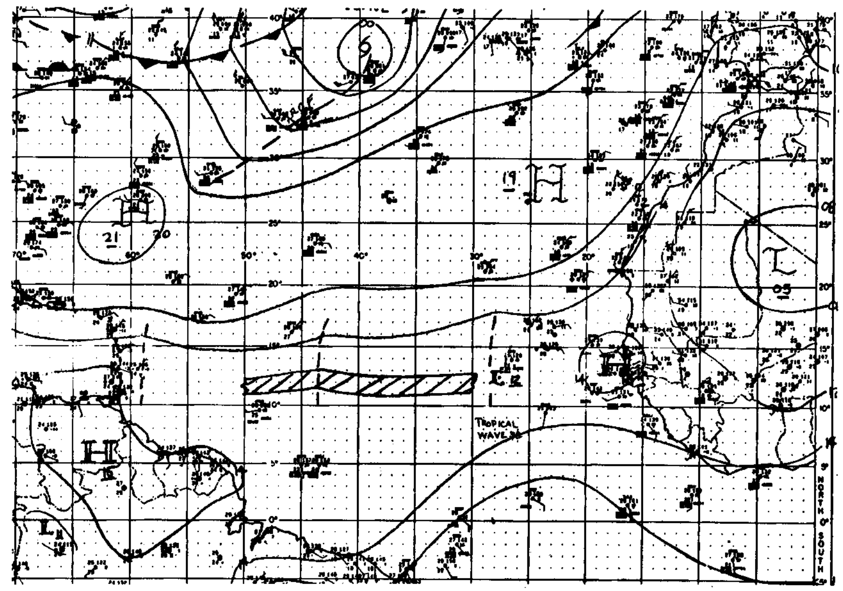
a) 0000 3 September 1988



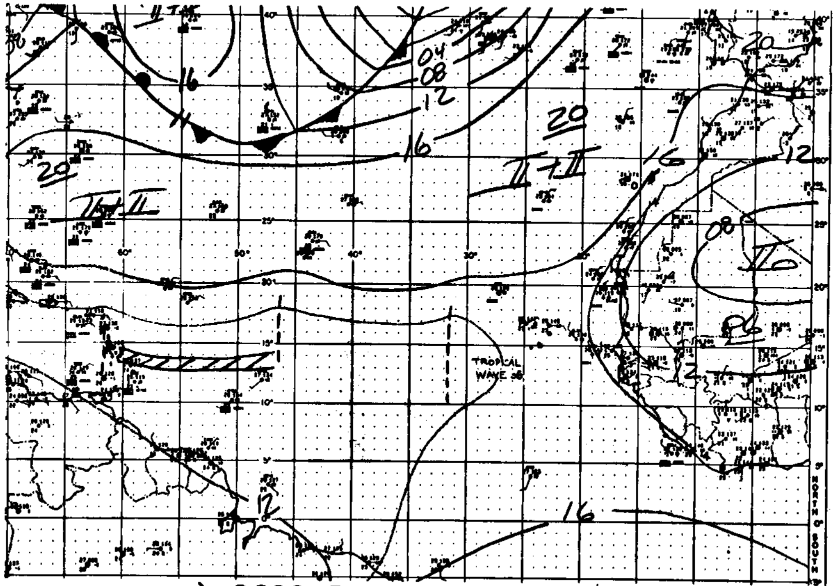
b) 1200 3 September 1988



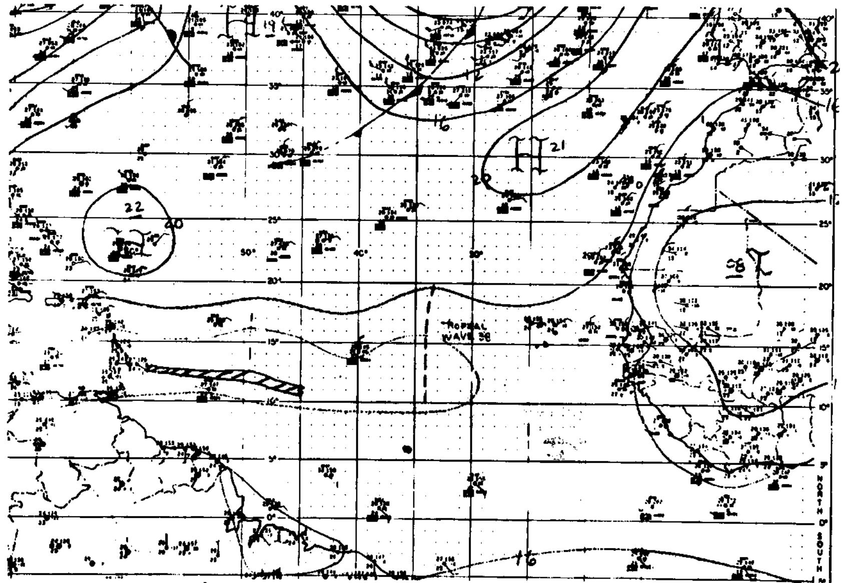
c) 0000 4 September 1988



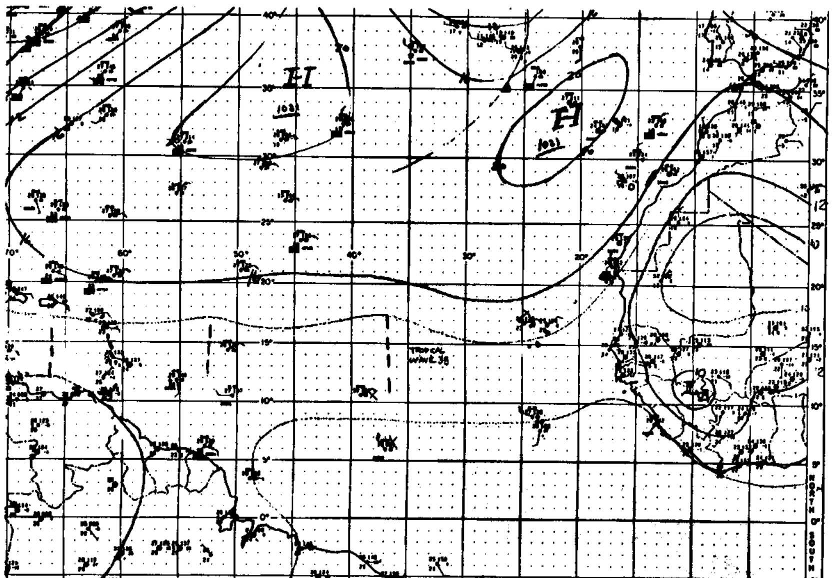
d) 1200 4 September 1988



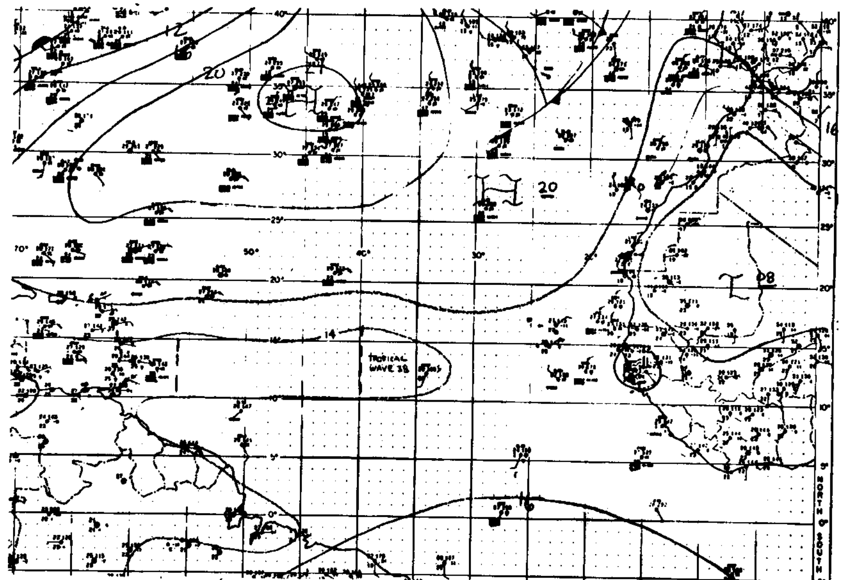
e) 0000 5 September 1988



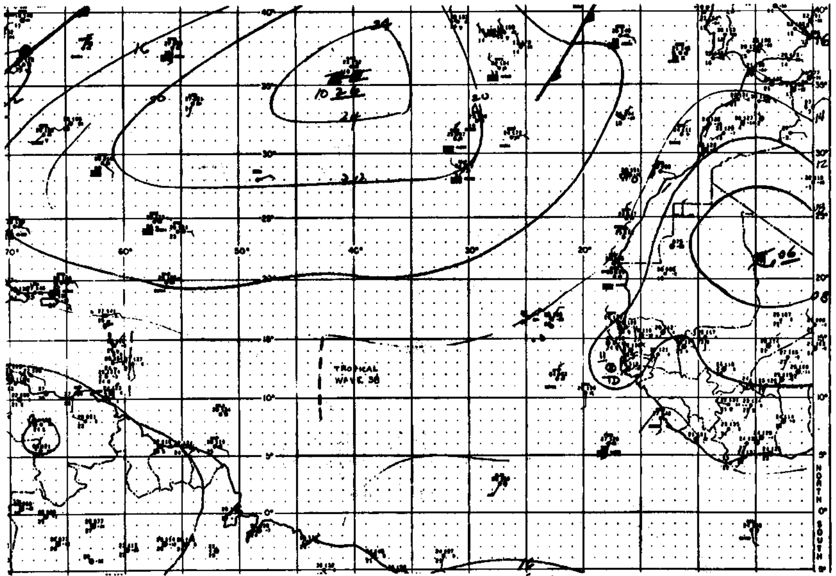
f) 1200 5 September 1988



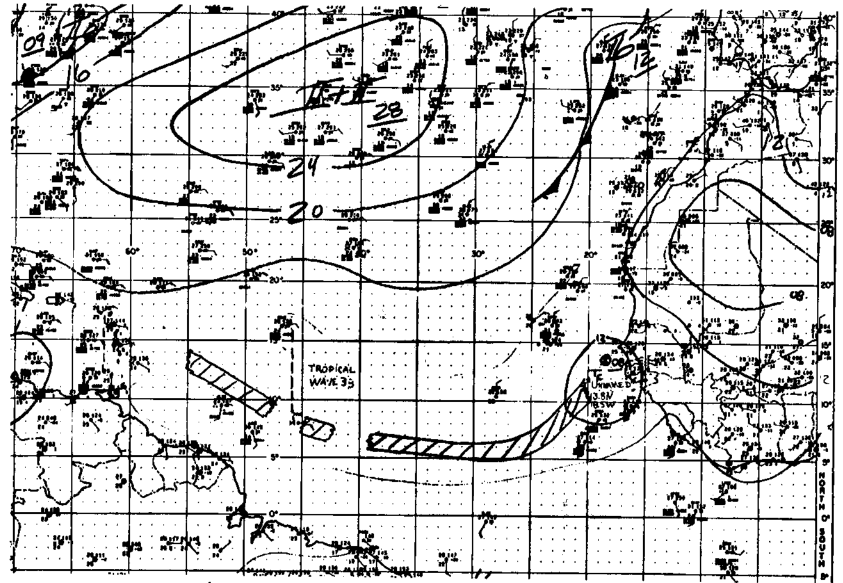
g) 0000 6 September 1988



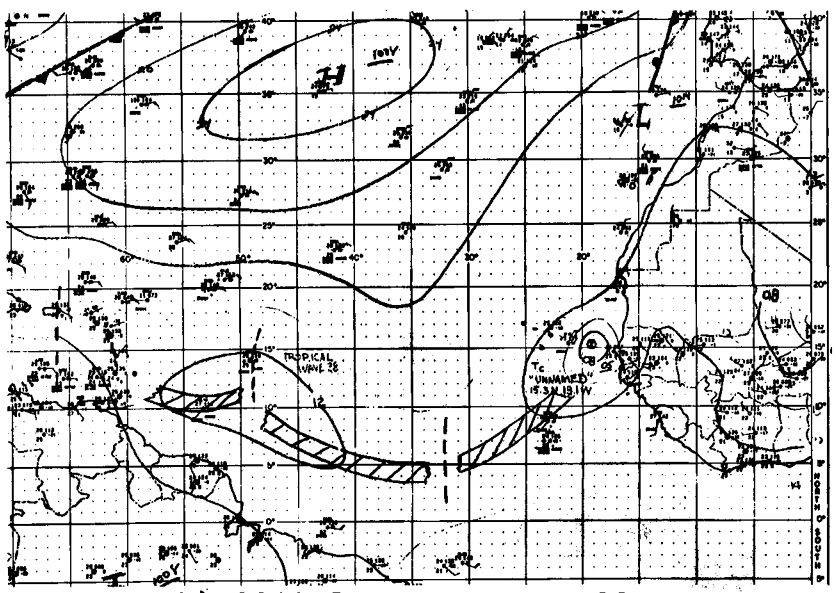
h) 1200 6 September 1988



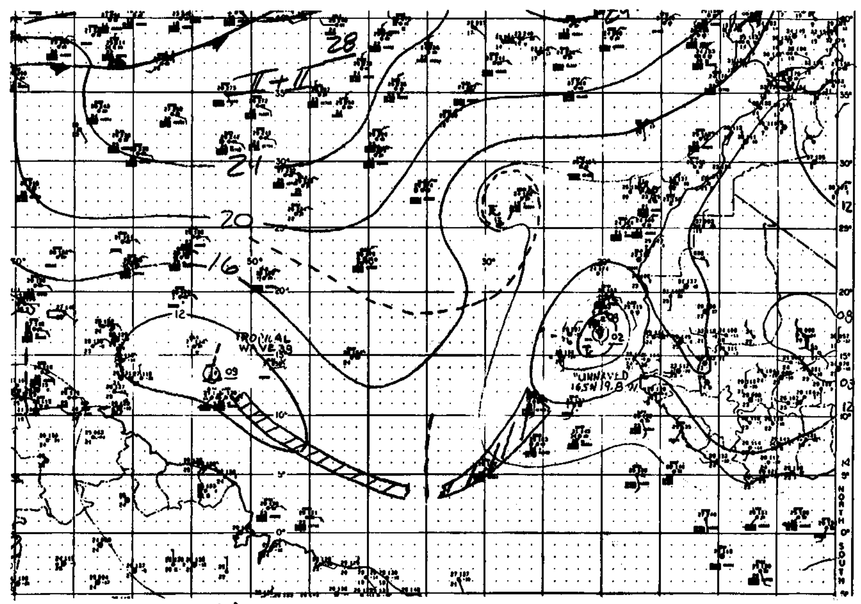
i) 0000 7 September 1988



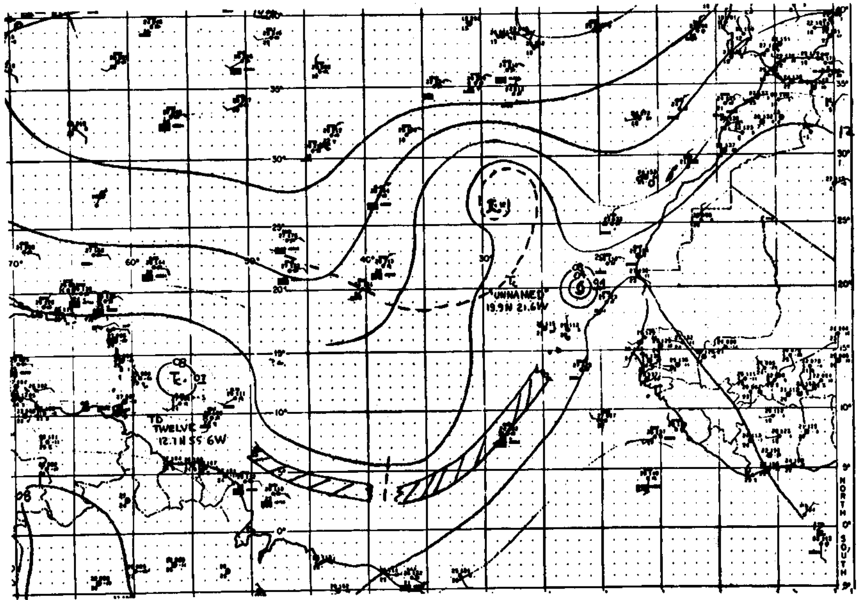
j) 1200 7 September 1988



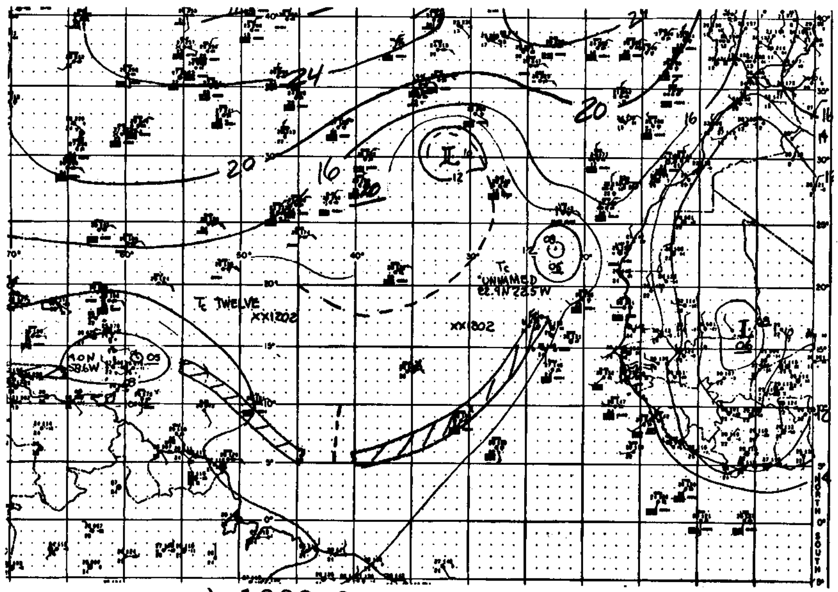
k) 0000 8 September 1988



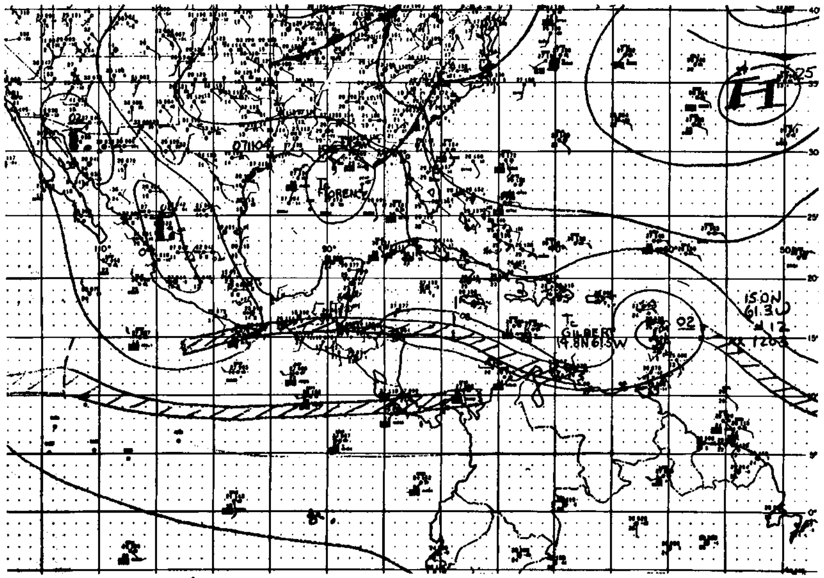
l) 1200 8 September 1988



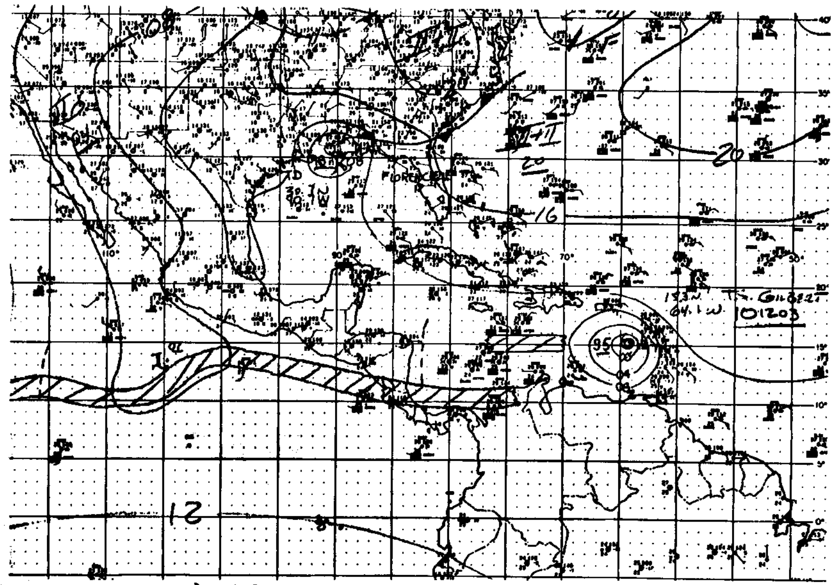
m) 0000 9 September 1988



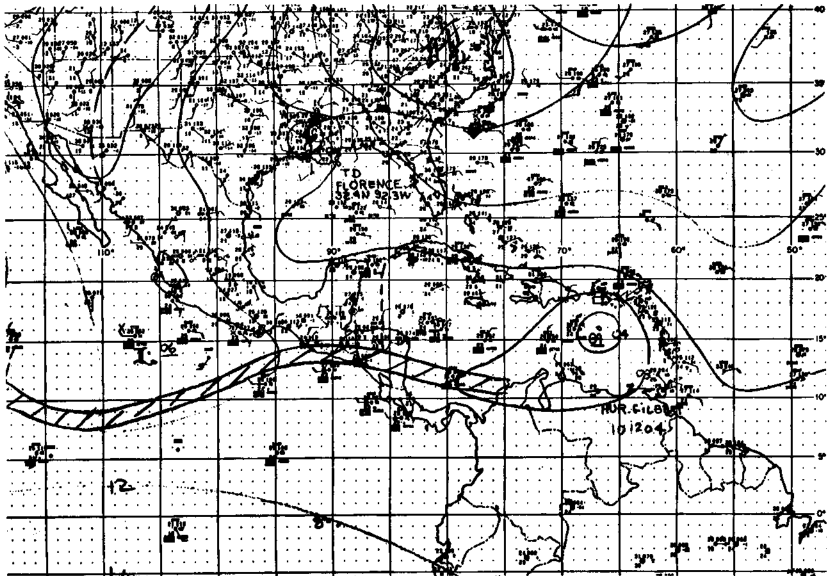
n) 1200 9 September 1988



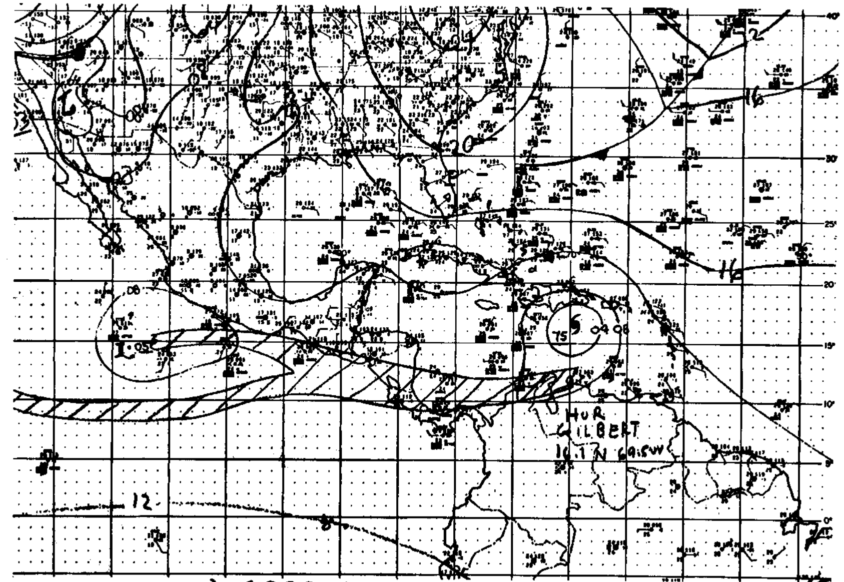
o) 0000 10 September 1988



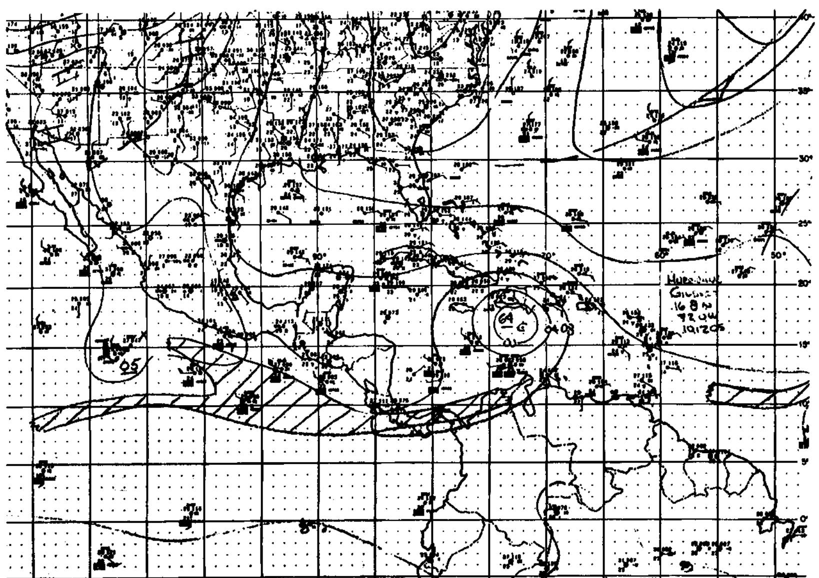
p) 1200 10 September 1988



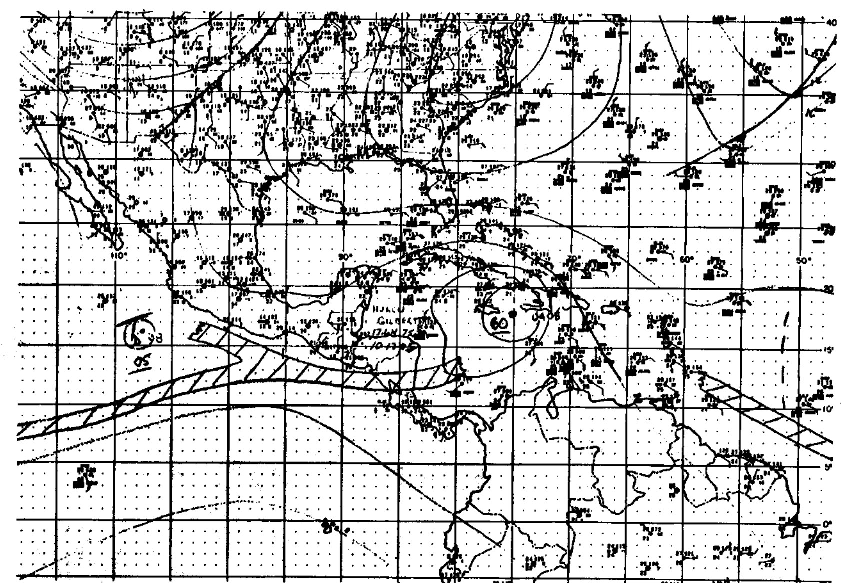
q) 0000 11 September 1988



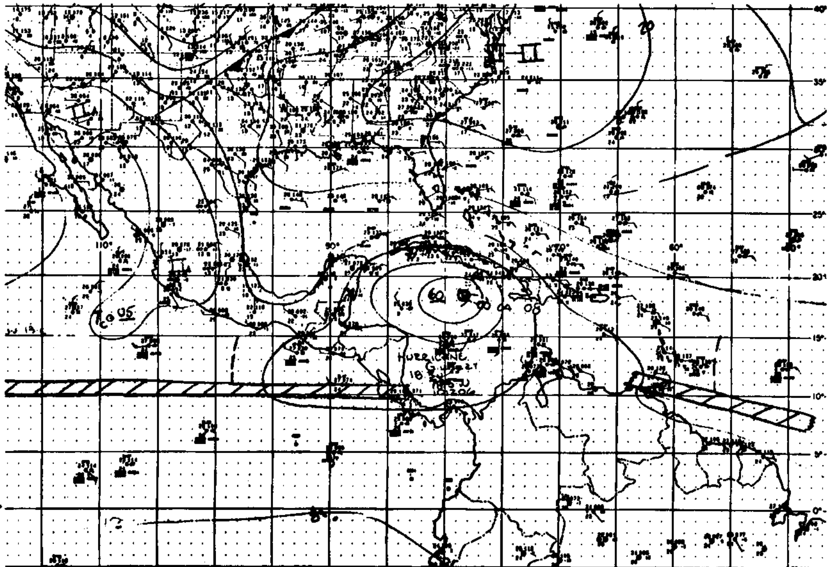
r) 1200 11 September 1988



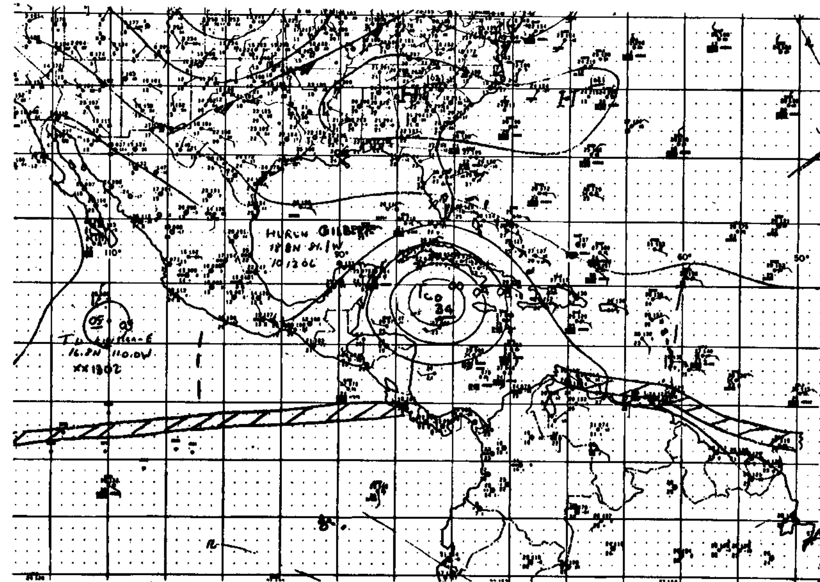
s) 0000 12 September 1988



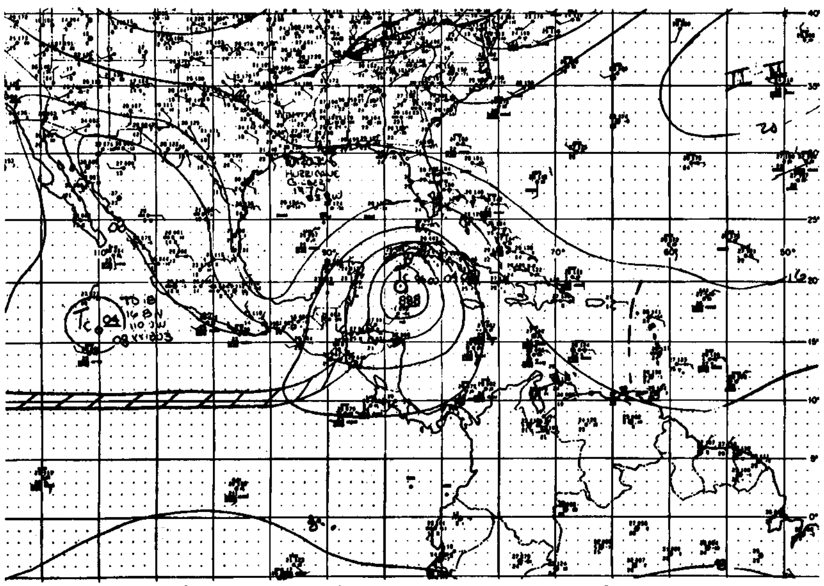
t) 1200 12 September 1988



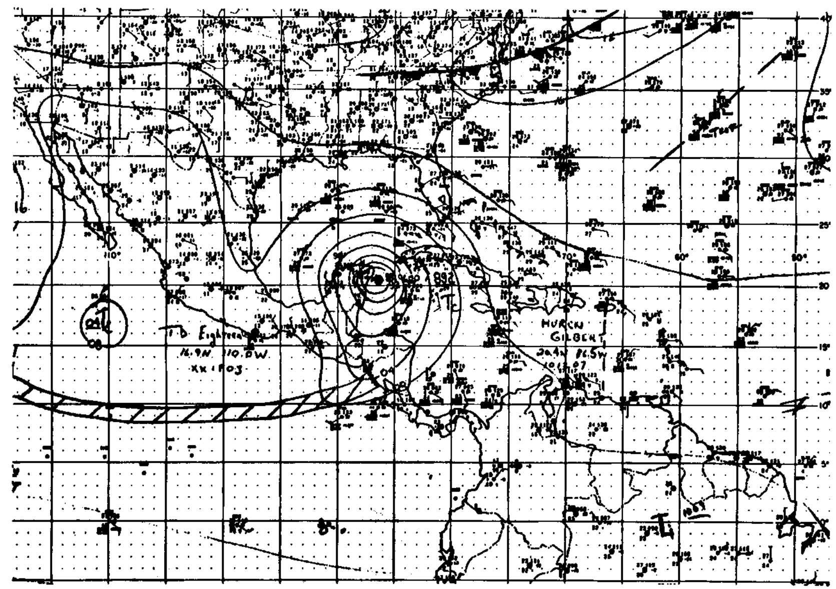
u) 0000 13 September 1988



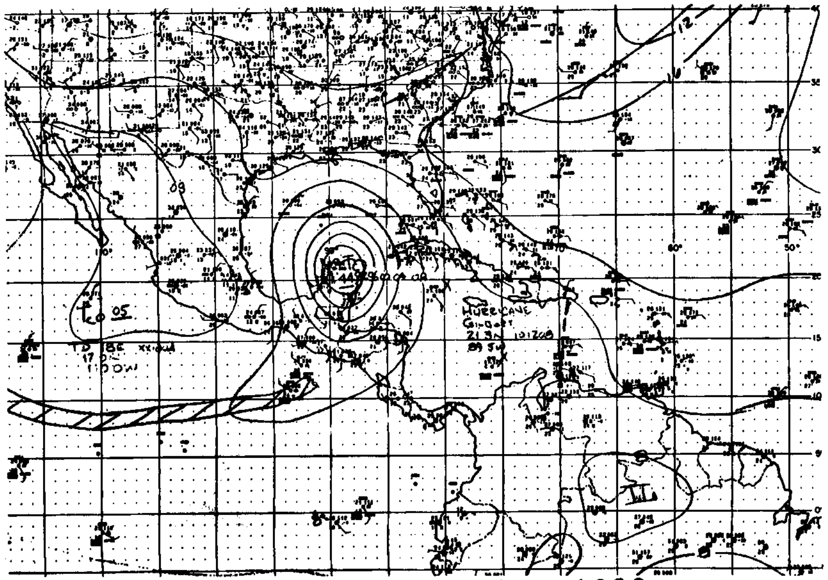
v) 1200 13 September 1988



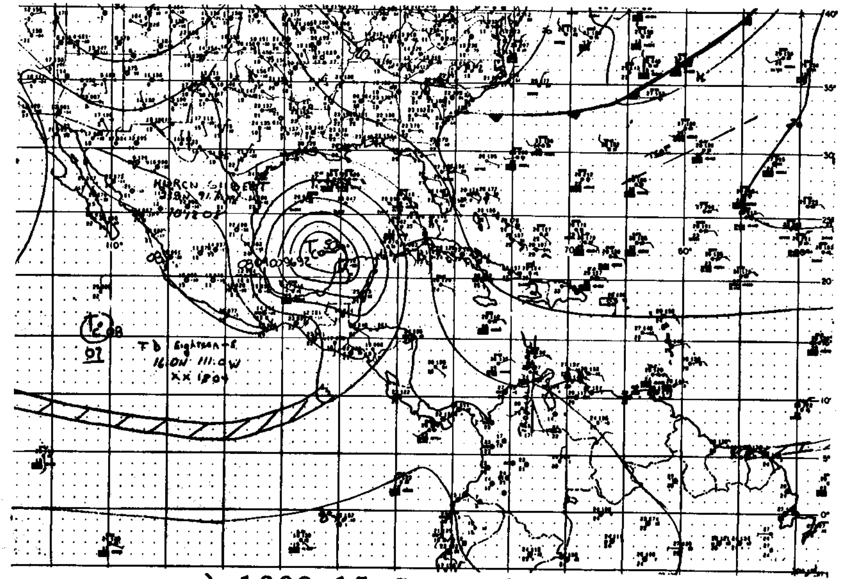
w) 0000 14 September 1988



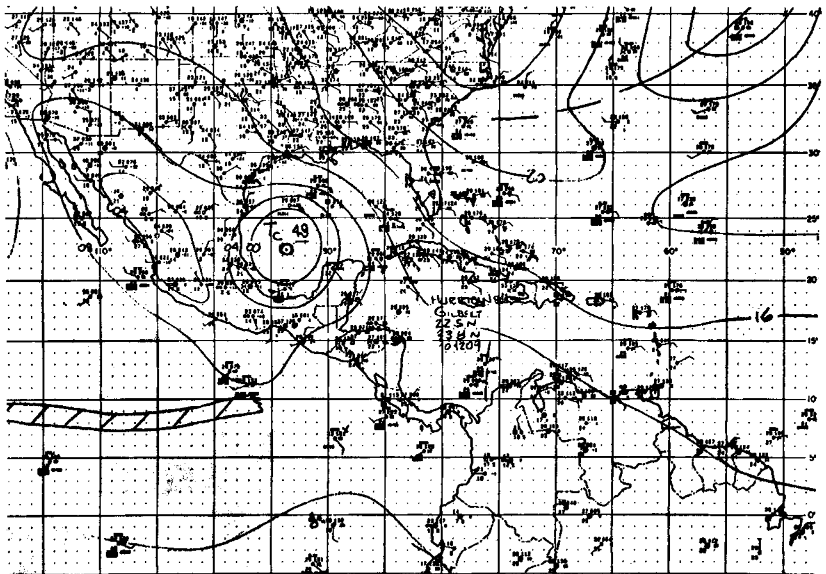
x) 1200 14 September 1988



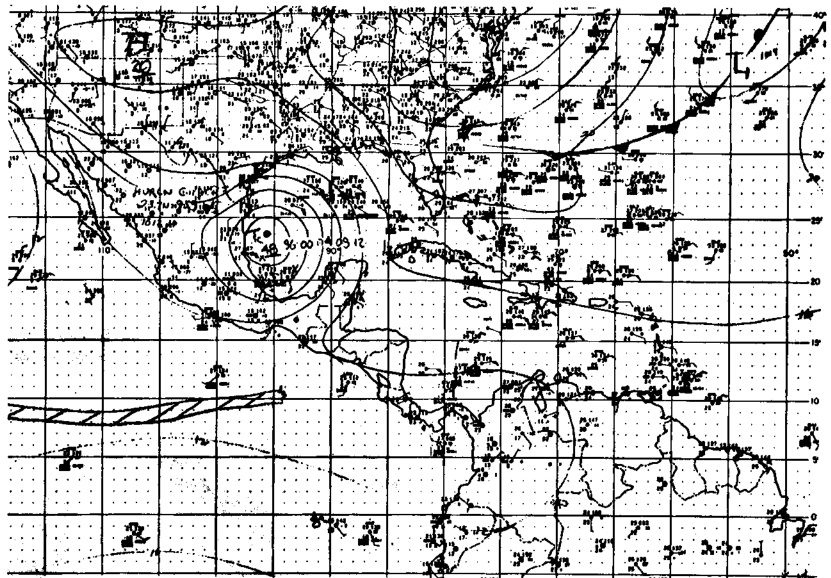
y) 0000 15 September 1988



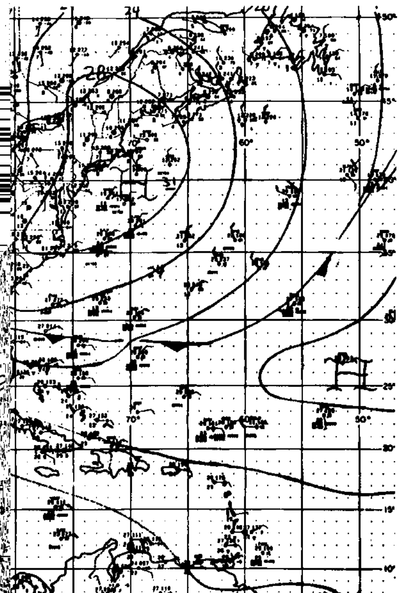
z) 1200 15 September 1988



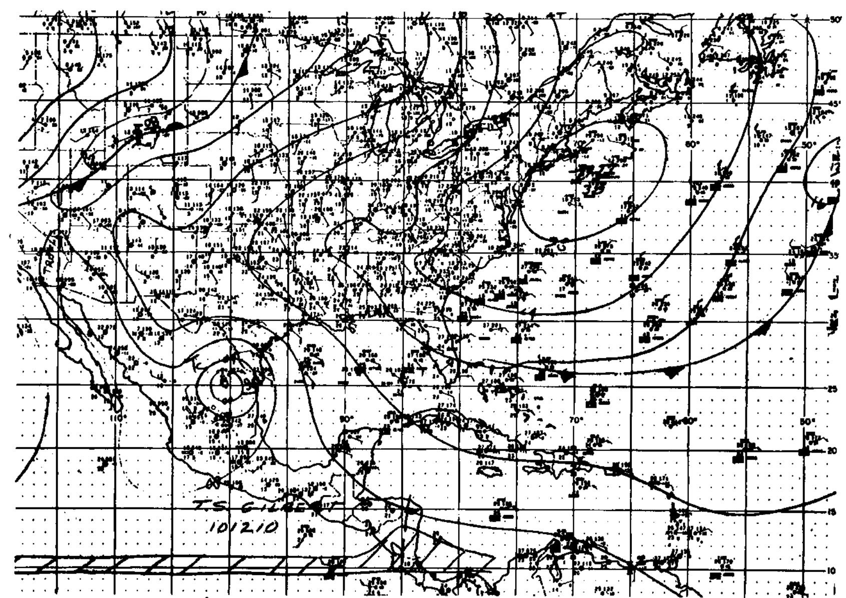
aa) 0000 16 September 1988



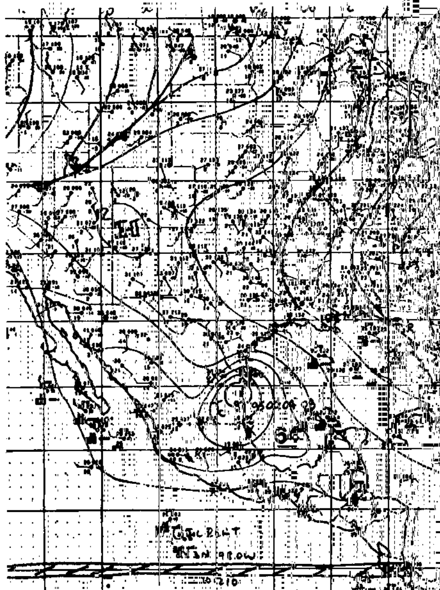
bb) 1200 16 September 1988



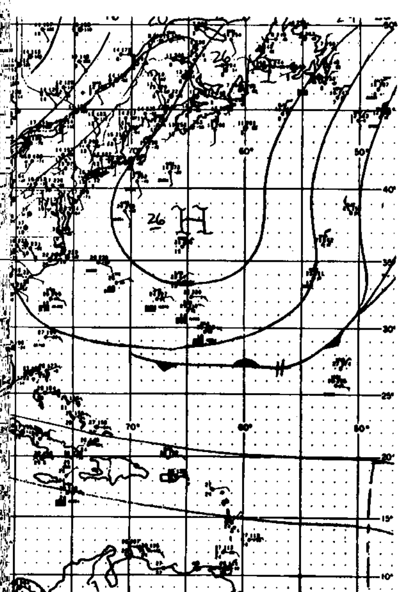
tember 1988



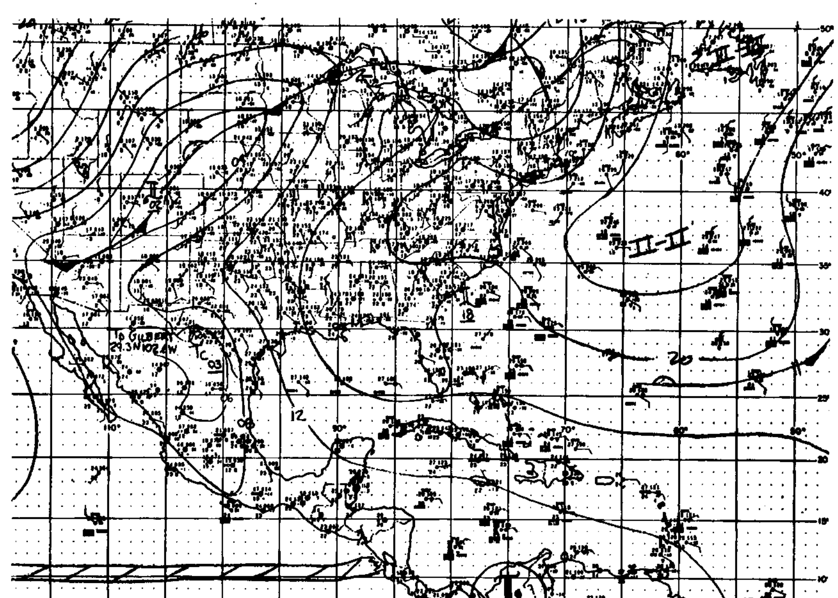
dd) 1200 17 September 1988



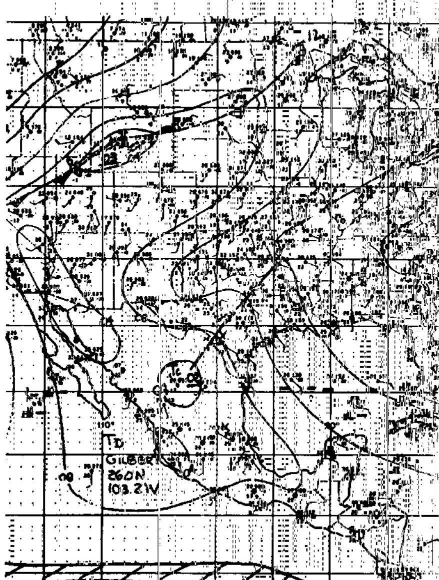
cc) 0000 17 Sep



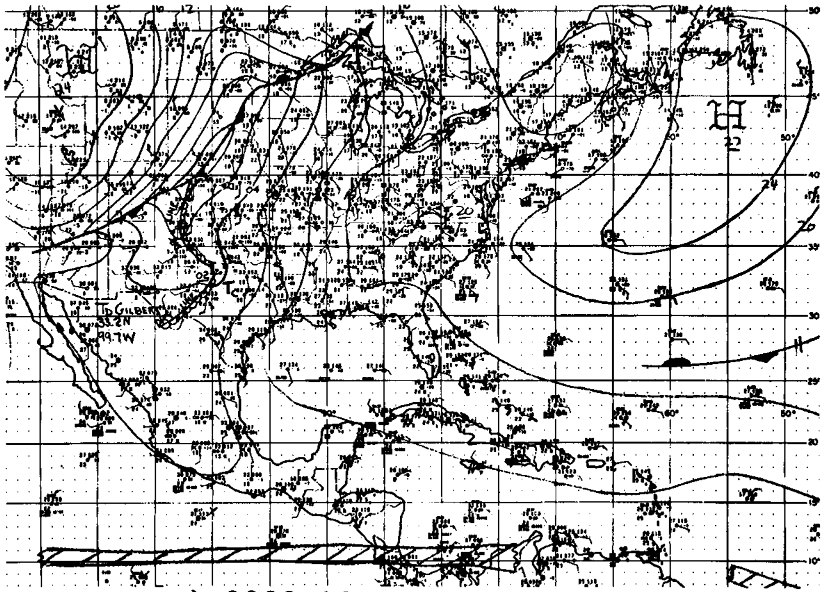
tember 1988



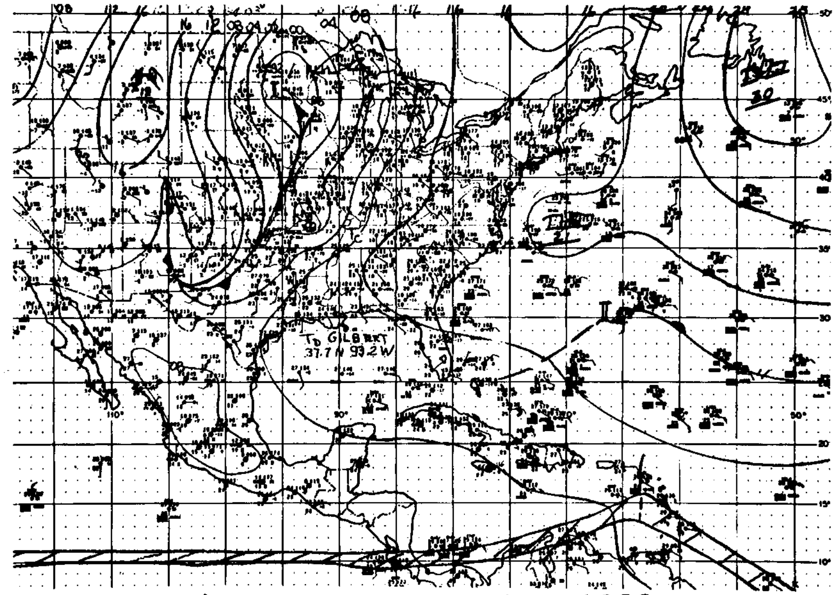
ff) 1200 18 September 1988



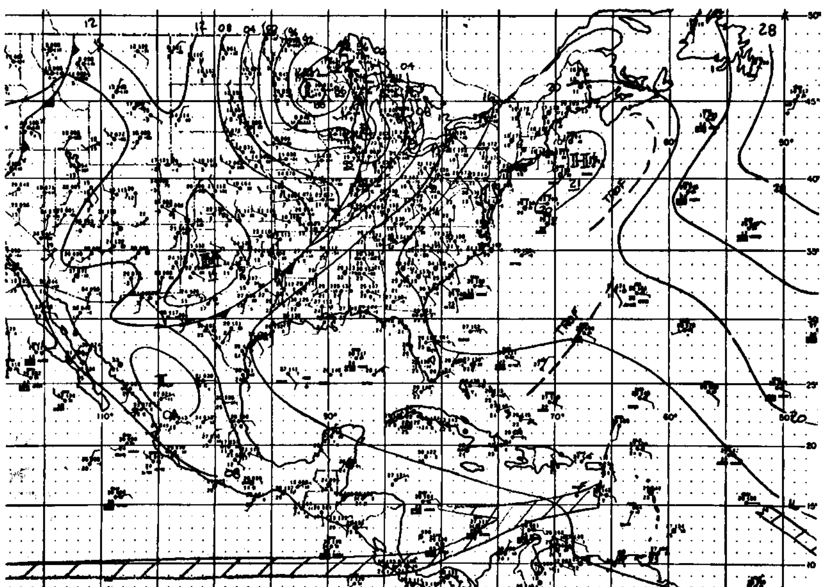
ee) 0000 18 Sep



gg) 0000 19 September 1988



hh) 1200 19 September 1988



ii) 0000 20 September 1988

As the high built over the central Atlantic, a ridge of the high developed southward to low latitudes along 35-40°W. The southward development of the ridge relocated the ITCZ southward to near 4°N along 35-40°W and led to the u-shaped configuration of the ITCZ seen in both the surface analyses (Figs. 9k through 9n) and satellite imagery (e.g., Fig. 6k) of September 8 and 9.

By September 9 wave 38 had become part of a section of the ITCZ that extended from west-northwestward to east-southeast. This configuration likely increased the low-level wind speeds and convergence between the ITCZ and the strengthened ridge to the north, possibly creating an environment more favorable for tropical cyclone formation.

To the west of Gilbert, the ITCZ had an unusual structure at 0000 September 10 (Fig. 9o). The ITCZ consisted of two parallel east to west bands of cloud (not shown) and convergent low-level flow. Winds were southerly immediately south of each band. Westerly winds occurred between the bands. The westerly winds created an upslope flow of moist eastern Pacific air over the western part of Central America. Heavy rain occurred there. Northerly winds occurred to the north of the northern band.

A few surface observations of the high winds and low pressure near Gilbert's center were made as Gilbert intensified to hurricane strength over the Caribbean. A ship to the east of the center reported 57 mph winds at 1200 September 10. On September 12, sustained winds of 121 mph with gusts to 147 mph and a pressure of 965 mb were observed near Kingston, Jamaica. Grand Cayman reported a gust to 157 mph and a pressure of 976.5 mb on the following day. Progresso, Mexico reported a surface pressure of 968.4 mb at 0000 September 15 (Fig. 9y). These observations represent most of the extreme wind and pressure records available from conventional surface stations. The eye of Gilbert passed over Kingston and the surface pressure observation from that site provided a rare reliable measure of the central pressure of Gilbert from a surface site.

Figure 9x presents another opportunity to note the size of the region at the ground that was influenced by Gilbert (cf, Fig. 5). One measure of a storm's size and strength is the average distance from the storm's center to the outermost closed isobar. The 1008 mb contour was chosen as the estimated outermost isobar for Gilbert at 1200 September 14. The average radius of the 1008 mb isobar was then about 550 miles. The average radius of the 1000 mb contour was about 250-300 miles. In contrast, Camille and the 1935 Keys' storms had much smaller contour radii. The radius of the 1000 mb contour is estimated to have been 50-100 miles for Camille and about 50 miles for the Keys' storm.

Analyses of the airflow in the low levels (Fig. 10a) and at upper levels (Fig. 10b) at the time of Gilbert's peak intensity show the broad area of Gilbert's influence. The storm had a large and distinctly cyclonic (counterclockwise) flow in the low levels then.

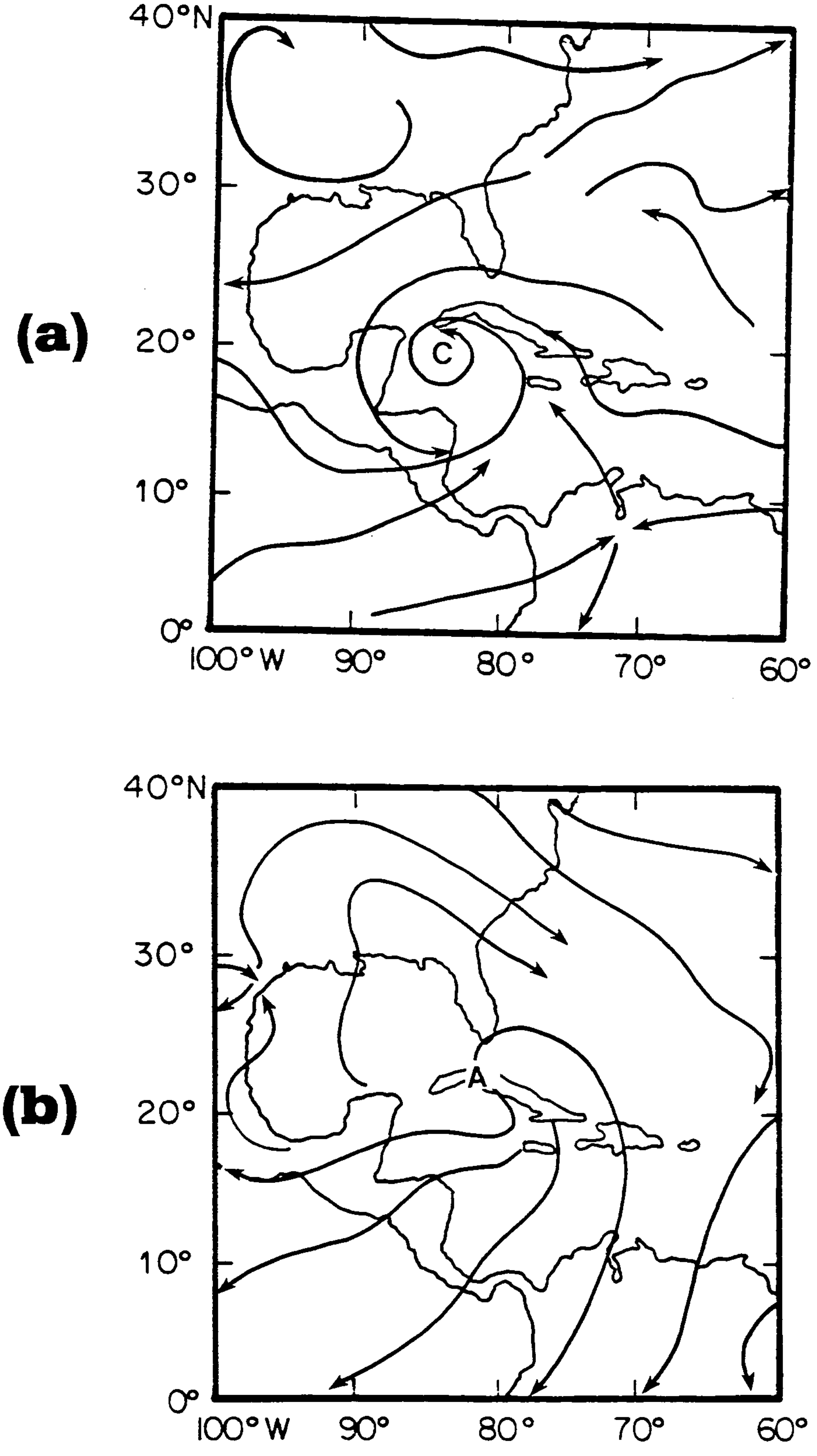


Fig. 10. NHC streamline analyses at 0000 UTC September 14, 1988 at (a) low levels and (b) 200 mb.

The westerly winds responsible for the heavy rains over Central America are evident from Fig. 10a. An anticyclonic outflow center was located over the hurricane at upper levels at that time. This feature, in combination with a broad mid-latitude high located over the southeast United States, produced the widespread outflow of upper cloud seen in the infrared imagery of Fig. 6.

When Gilbert moved into the Gulf of Mexico (e.g., Fig. 9bb) the process of separating from the ITCZ became complete. Otherwise, the outer part of Gilbert's pressure pattern changed little until the storm made landfall in northeast Mexico (Fig. 9cc). The area enclosed by each isobar rapidly diminished thereafter.

Gilbert remained distinct in the surface analyses for three days after making landfall (Figs. 9cc through 9hh). The analyses show that Gilbert's central pressure initially rose rapidly to about 1003 mb when the system approached the Rio Grande River by 1200 September 18 (Fig. 9ff). Dry westerly winds blowing into the center of the storm occurred across a large part of western Texas when the storm moved toward Oklahoma.

As Gilbert turned to the north its central pressure actually decreased as the system continued to lose its tropical character and interacted with a mid-latitude frontal system. The pressure dropped to about 999 mb on 1200 September 19 (Fig. 9hh). The wind field near the pressure minimum still showed signs of a closed circulation then.

The remnant low-level pressure and circulation center of Gilbert merged with the frontal system over northern Lake Michigan shortly after 0000 September 20 (Fig. 9ii). The central pressure of the remnant low-level center was then about 995 mb.

3.3 Inner Core Structure As Deduced From Reconnaissance Aircraft Data

For more than 40 years U.S. reconnaissance and research aircraft have penetrated Atlantic tropical cyclones to determine the location, intensity and inner structure of these storms. In Hurricane Gilbert, flights were conducted by the U.S. Air Force and the National Oceanic and Atmospheric Administration (NOAA). These flights provided the NHC with a variety of observations of great accuracy, resolution, reliability and importance.

For example, near 0000 September 14 when the lowest pressure available from conventional surface sites was 995 mb (Fig. 9w), the report from a reconnaissance aircraft was 888 mb, more than 100 mb lower than the pressure at the surface site! Note that twelve hours later the surface analysis has an "88" contour as the isobar of lowest pressure analyzed (Fig. 9x). That contour represented 988 mb, not the 888 mb pressure present at Gilbert's center. From the aircraft data we know that a more detailed surface map would require upwards of 20 additional contours to be drawn between the storm center and the (9)88 mb line in Fig. 9x!

Table 6 shows some of the information reported from the NOAA aircraft when Gilbert's sea-level pressure reached its minimum reported value of 888 mb. In addition to providing surface pressure reports in the eye of the storm, the flight crew commonly sends the storm's location, wind velocity and some characteristics of the hurricane eye.

The data in Table 6 came from one leg of a figure-4 pattern flown by the aircraft at an altitude of about 10,000 ft. Instrumentation on the plane measured a wind of 186 mph with a gust to 199 mph at flight level during that penetration of the storm. A 173 mph surface wind was calculated. The report of 885 mb shown on the form was later revised to 888 mb (Willoughby et al., 1989). Although the lowest pressure obtained from reconnaissance aircraft data was 888 mb, an analysis of the data (Fig. 11) indicates that the 888 mb report occurred during a period when Gilbert's central pressure had been falling steadily at a rate of about 6 mb per hour. Therefore, it is likely that the absolute minimum central pressure attained by Gilbert was lower than 888 mb.

Figure 12a shows a profile of the flight-level wind speed and "D-value" along a west-to-east passage through Gilbert's eye near 2100 September 13. (D-value is a measure of the departure, in the vertical, of a constant pressure surface from its "standard" altitude. It is used to estimate the minimum sea-level pressure of a storm when a direct measurement by a dropsonde released from the aircraft is not available. The 888 mb minimum pressure was derived from a D-value calculation.) The wind speed profile shows two sharp peaks in wind speed at a radius of about 10 miles on either side of a minumum in speed. The minimum is in the hurricane eye. The peaks correspond to the regions of high wind in the western and eastern portions of the hurricane eyewall.

Figure 12b shows a profile about 10 hours later just prior to Gilbert's landfall at Cozumel. The absolute peaks in wind speed in the eyewall were not as high as earlier but the area of hurricane force winds had increased to extend outward more than 100 miles from the eye. Note also the set of secondary peaks in wind speed at a radius of about 40 miles.

The NOAA aircraft also carry weather radars capable of displaying rainfall distribution in real-time, as in Fig. 13. The figure shows the horizontal distribution of rainfall. Dark regions indicate the heaviest rain. The winds measured along the flight track are also shown superimposed on the radar picture. The narrow ring at the center of the picture is the eyewall with its intense rainfall and very strong winds. The white area within the eyewall is the relatively rain free and calm eye. In Gilbert, the eye had an exceptionally small diameter, about 5-10 miles, during the hurricane's maximum intensity.

Two radar panels, one from near Gilbert's peak intensity and the other as the storm approached Cozumel are shown in Fig. 14. The tiny circular bands near the center of each panel represent the

Table 6. Flight data sheet for NOAA aircraft penetration of Hurricane Gilbert at hurricane's peak intensity.

DATE	SCHEDULED FIX TIME	AIRCRAFT NUMBER	ARWO
13 Sep 88		NOAA 43	Masters

MANOP HEADING (PRECEDENCE INMEDIATE)

MISSION IDENTIFIER AND OBSERVATION NUMBER NOAA 3 1212 A Gilbert

(ABBREVIATED) DETAILED VORTEX DATA MESSAGE OB #12

A	13 / 2152 Z	DATE AND TIME OF FIX
B	19 DEG 31 MIN (N) S	LATITUDE OF VORTEX FIX [1]
	83 DEG 19 MIN E (W)	LONGITUDE OF VORTEX FIX [1]
C	700 MB 2091 M	MINIMUM HEIGHT AT STANDARD LEVEL
D	150 KT	ESTIMATE OF MAXIMUM SURFACE WIND OBSERVED
E	360 DEG 5 NM	BEARING AND RANGE FROM CENTER OF MAXIMUM SURFACE WIND
F	085 DEG 162 KT	MAXIMUM FLIGHT LEVEL WIND NEAR CENTER
G	360 DEG 5 NM	BEARING AND RANGE FROM CENTER OF MAXIMUM FLIGHT LEVEL WIND
H	— MB	MINIMUM SEA LEVEL PRESSURE COMPUTED FROM DROPSONDE OR EXTRAPOLATED FROM WITHIN 1500 FT OF SEA SURFACE
I	14 C/ 3180 M	MAXIMUM FLIGHT LEVEL TEMP/PRESSURE ALTITUDE OUTSIDE EYE [2]
J	26 C/ 3813 M	MAXIMUM FLIGHT LEVEL TEMP/PRESSURE ALTITUDE INSIDE EYE [2]
K	Neg 02 C/ Noss C	DEWPOINT TEMP/SEA SURFACE TEMP INSIDE EYE
L	Closed wall	EYE CHARACTER: Closed wall, poorly defined, open SW, etc.
M	C 08	EYE SHAPE/ORIENTATION/DIAMETER. Code eye shape as: C – Circular; CO – Concentric; E – Elliptical. Transmit orientation of major axis in tens of degrees, i.e., 01–010 to 190; 17–170 to 350. Transmit diameter in nautical miles. *Examples:* C8– Circular eye 8 miles in diameter. E09/15/5 – Elliptical eye, major axis 090–270, length of major axis 15 NM, length of minor axis 5 NM. CO8–14–Concentric eye, diameter inner eye 8 NM, outer eye 14 NM.
N	19 DEG 31 MIN (N) S	CONFIRMATION OF FIX: Coordinates and Time
	83 DEG 19 MIN E (W)	
	13 / 2152 Z	
O	12345 / 7	FIX DETERMINE BY/FIX LEVEL FIX DETERMINED BY: 1 – Penetration; 2 – Radar; 3 – Wind; 4 – Pressure; 5 – Temperature. FIX LEVEL (Indicate surface center if visible; indicate both surface and flight level centers only when same): 0 – Surface; 1 – 1500 ft; 8 – 850 mb; 7 – 700 mb; 5 – 500 mb; 4 – 400 mb; 3 300 mb; 2 – 200 mb; 9 – Other.
P	4 / 3 NM	NAVIGATION FIX ACCURACY/METEOROLOGICAL ACCURACY
Q		REMARKS

① Peak wnd 173 kts 19° 37'N 83° 19'W at 2151Z
② 35 kt updraft in N eyewall at 2151 z
③ 30 kt downdraft in S eyewall at 21542
④ Sfc wnd est from microwave radiometer
⑤ Est SLP 885 mb, extrap from 700 mb (JORDAN'S equation)

INSTRUCTIONS: Items A through G (and H when extrapolated) are transmitted from the aircraft immediately following the fix. The remainder of the message is transmitted as soon as available for scheduled fixes and at the ARWO's discretion for unscheduled (intermediate) fixes.

1 CHECK SUM REQUIRED IN WESTPAC.

2 ABSOLUTE ALTITUDE ALSO REQUIRED IN WESTPAC.

AWS FORM JULY 80 82 PREVIOUS EDITION WILL BE USED ABBREVIATED/VORTEX DATA MESSAGE

U.S. GOVERNMENT PRINTING OFFICE: 1987 – 784-004/40628

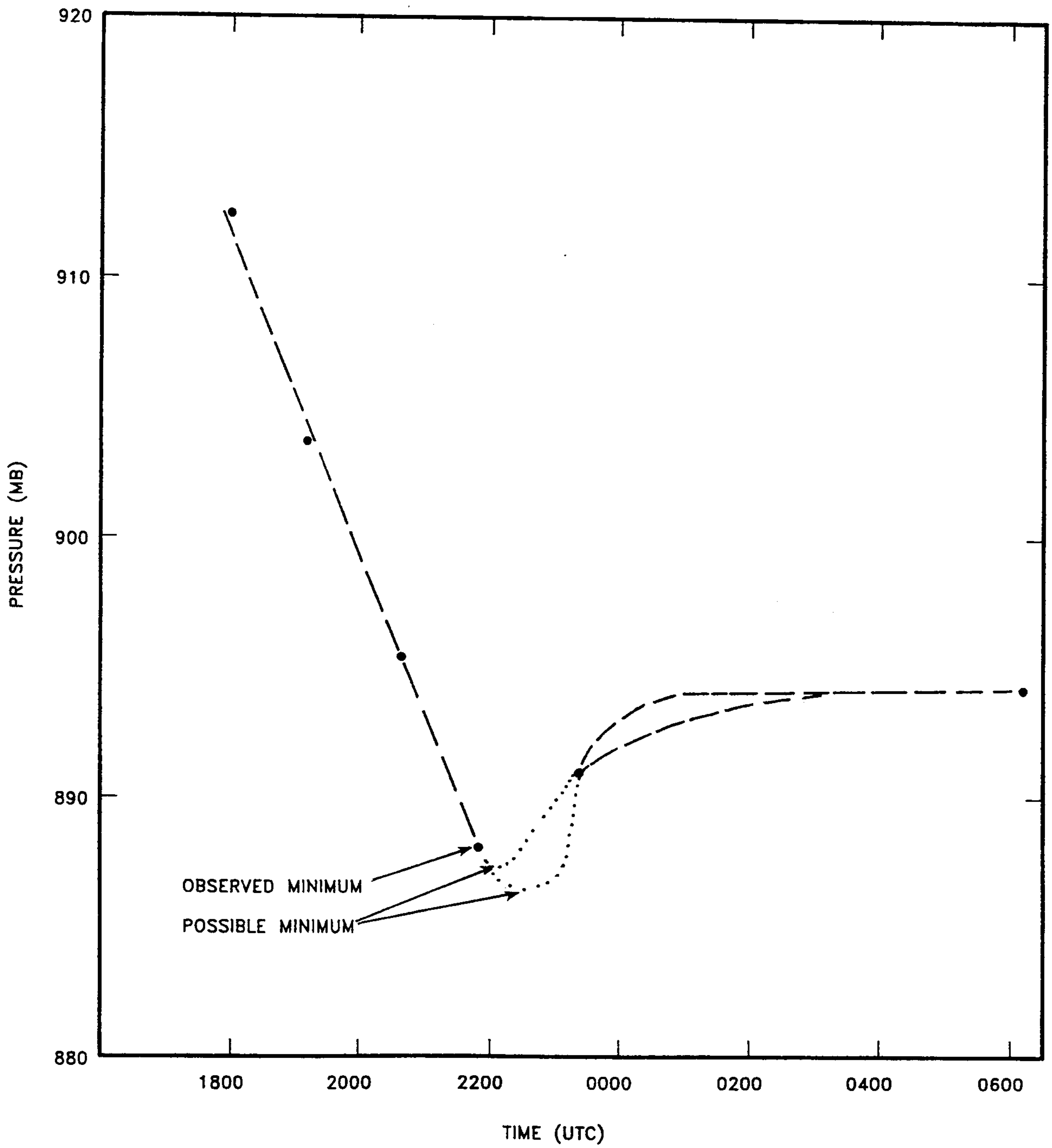


Fig. 11. Hurricane Gilbert central pressure data from 1800 UTC September 13 to 0600 UTC September 14, 1988. Large dots are observations from reconnaissance aircraft. The reported minimum pressure was 888 mb. The actual minimum pressure was probably somewhat lower, occurring between observations. The dotted lines show two of the possible pressure curves which would yield a lower minimum central pressure.

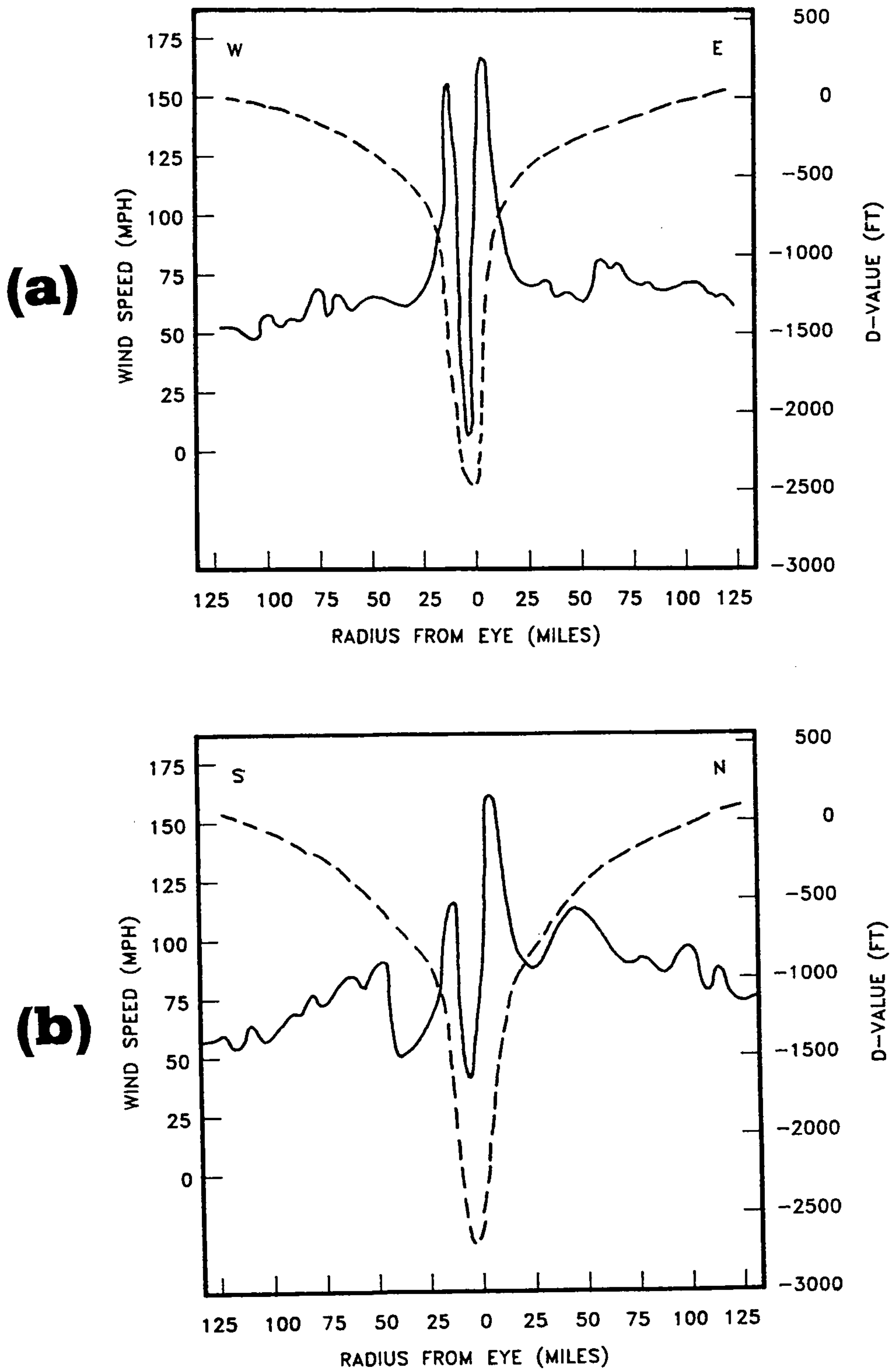


Fig. 12. Profiles of wind speed (kt) and D-value (m; see text) derived from data collected during NOAA aircraft transits through Hurricane Gilbert. (a) Plot near Gilbert's peak intensity. (b) Plot about 10 hours after Gilbert reached peak intensity, shortly before landfall on the Yucatan peninsula. Profiles provided by NOAA /Atlantic Oceanographic and Meteorological Laboratory (AOML) Hurricane Research Division (HRD).

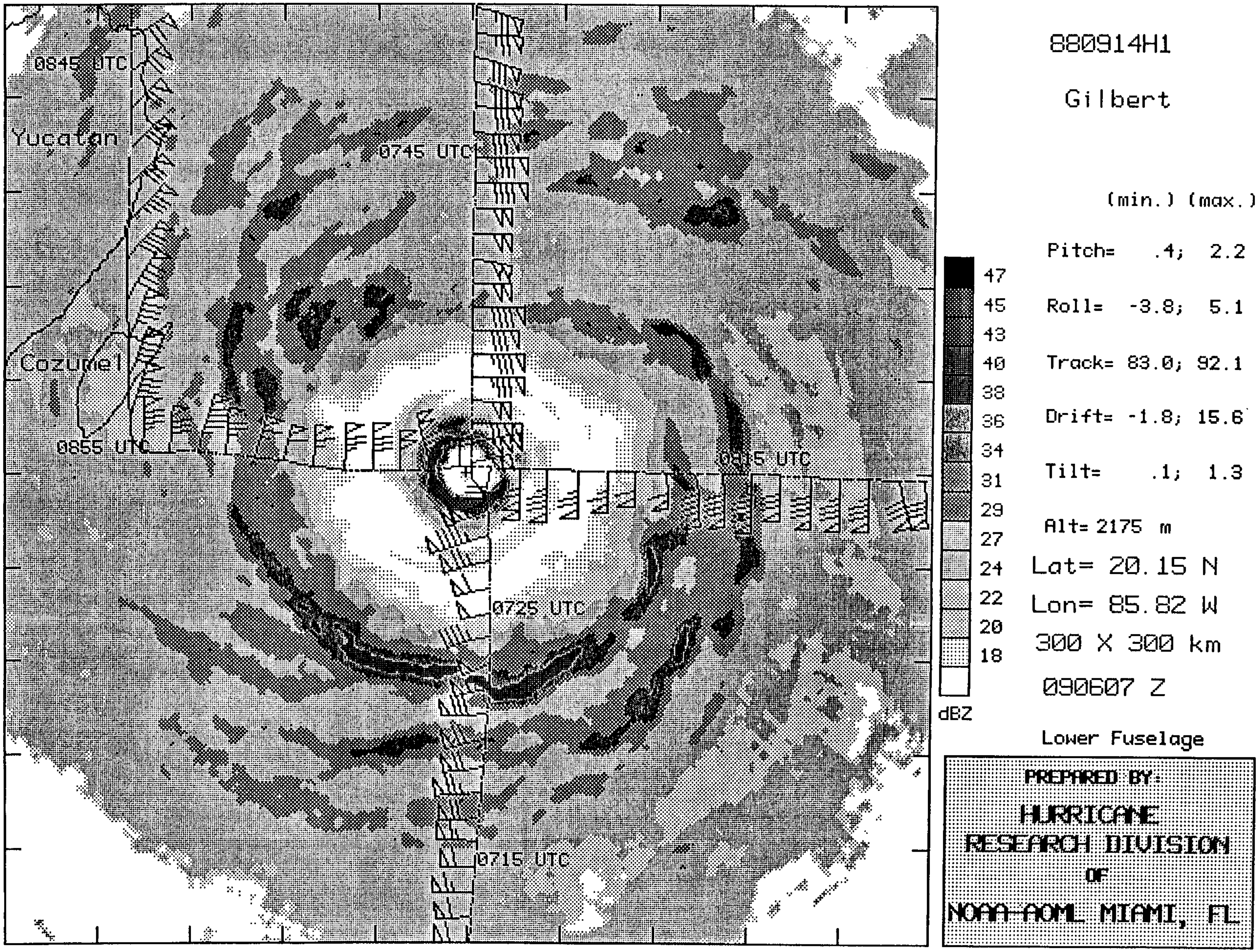


Fig. 13. Radar reflectivity (similar to rainfall intensity) of Hurricane Gilbert near 0733 UTC, with flight-level winds from about 0715-0925 UTC September 14, 1988 superimposed. Variations in reflectivity factor (dBZ) denoted by shades of gray. Storm-relative aircraft flight track depicted by solid black line. Flight-level winds plotted at 1-min intervals, with a flag for 50 kt, full barb for 10 kt, and half barb for 5 kt. The hurricane's location (latitude and longitude) is listed on right-hand side and indicated by small black "+" symbol in the center of the image. Domain size is 300 km x 300 km. Yucatan peninsula and Cozumel outlined by the solid lines. Figure provided by NOAA-AOML HRD.

eyewall at those times. As Gilbert crossed the Yucatan peninsula the eyewall became permanently fragmented. Note in Fig. 14 that the eyewall is enclosed within an outer circular band of heavy rain. The outer circular band is approximately colocated with the secondary maximum in wind speed seen in Fig. 12a.

The track of the eye as derived from the radar data has been drawn on Fig. 14. This track contains numerous small-scale undulations indicative of the "trochoidal" motion often observed of major hurricanes.

Vertical cross sections of radar data through the hurricane show tall spires of intense rain within the eyewall (Fig. 15). These stand out prominently near the center of the picture. Note that the vertical scale in the figure is exaggerated.

3.4 Deep-Layer Mean Analyses

The forward motion of a hurricane has been compared to the downstream motion of a float in a river. The path of a small storm may resemble that of a block of wood following the stream's every meander. The track of a big storm, on the other hand, may resemble the track of a large bouyant log which by its momentum seemingly ignores minor bends in the river and instead crashes ahead, forging its own course.

While the interaction between a hurricane and the surrounding atmosphere is far more complex than the analogy suggests, the concept of environmental "steering" is useful. One fairly accurate measure of environmental steering is the deep-layer mean (DLM) wind flow computed by arithmetically averaging the wind at ten different levels through the depth of the troposphere (Fig. 16). The DLM has proven useful in both diagnostic studies of storm motion and as input for computer simulations that produce forecasts of storm track (e.g., Neumann, 1988). In general, tropical cyclones tend to move approximately with the DLM wind (Elsberry et al., 1985).

During Gilbert's passage through the Caribbean and Gulf of Mexico, the storm was visible in the DLM as an area of low pressure (actually, low "geopotential height") and cyclonic flow (e.g., Fig. 16a). A very large region of high pressure and anticyclonic flow (the Bermuda High), persisted to the north of the storm. Gilbert remained embedded in an east to east-southeasterly flow on the south side of the high from September 10-17 and moved steadily toward the west-northwest through that period.

Although Gilbert followed a steady course, the configuration of the DLM pattern evolved significantly. When Gilbert was yet a tropical storm on September 10 (Fig. 16a), the "longwave" or large-scale pattern over the continental United States and western Atlantic was in the process of change. The DLM large-scale ridge of high pressure moved westward ("retrograded") from its position over the west-central Atlantic to a position extending from the

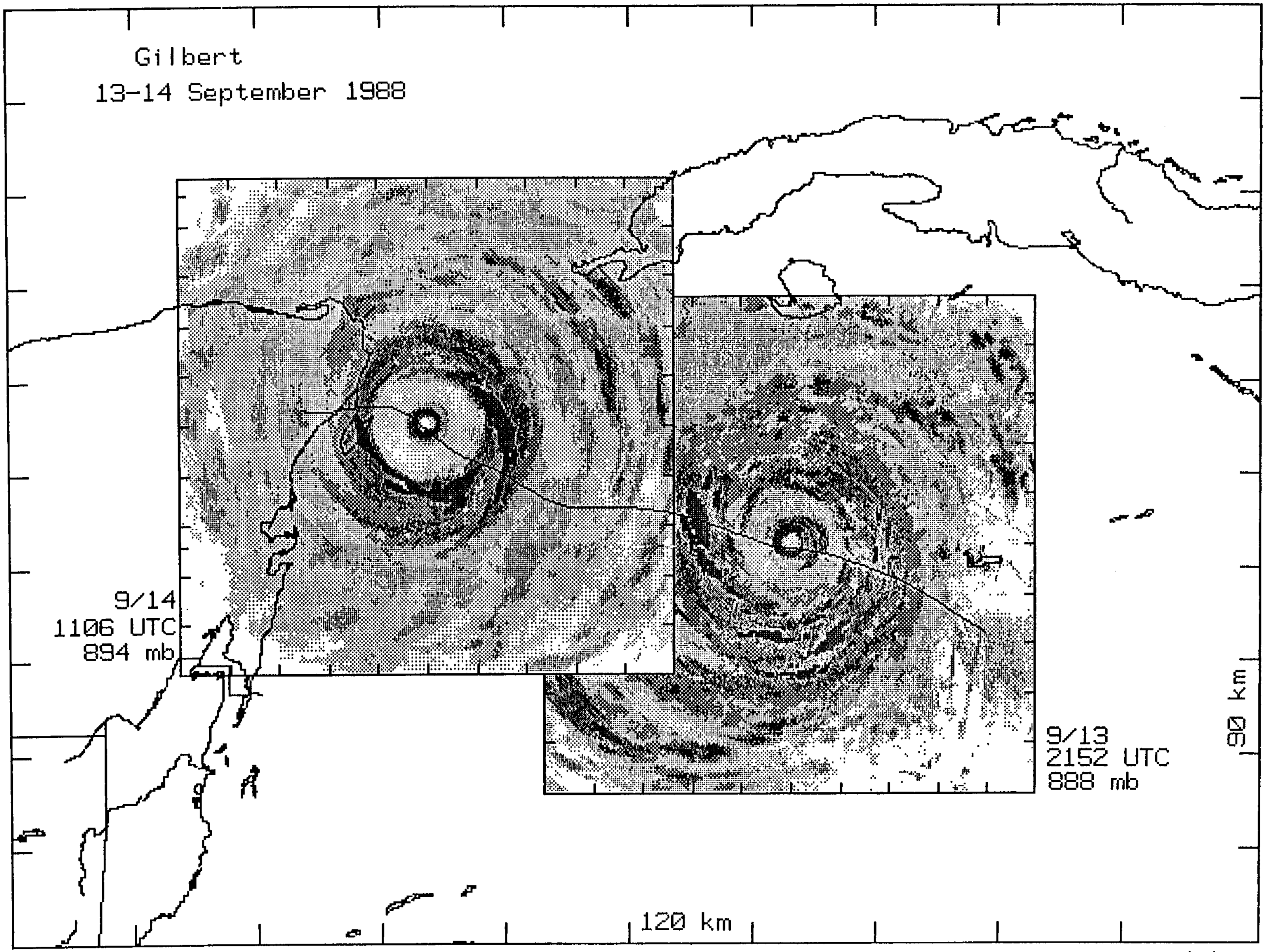


Fig. 14. Radar reflectivity pattern of Hurricane Gilbert near 1106 UTC September 14, and reflectivity pattern at 2152 UTC September 13, 1988. Light (dark) stippling represents light (heavy) rainfall. Figure provided by NOAA-AOML HRD.

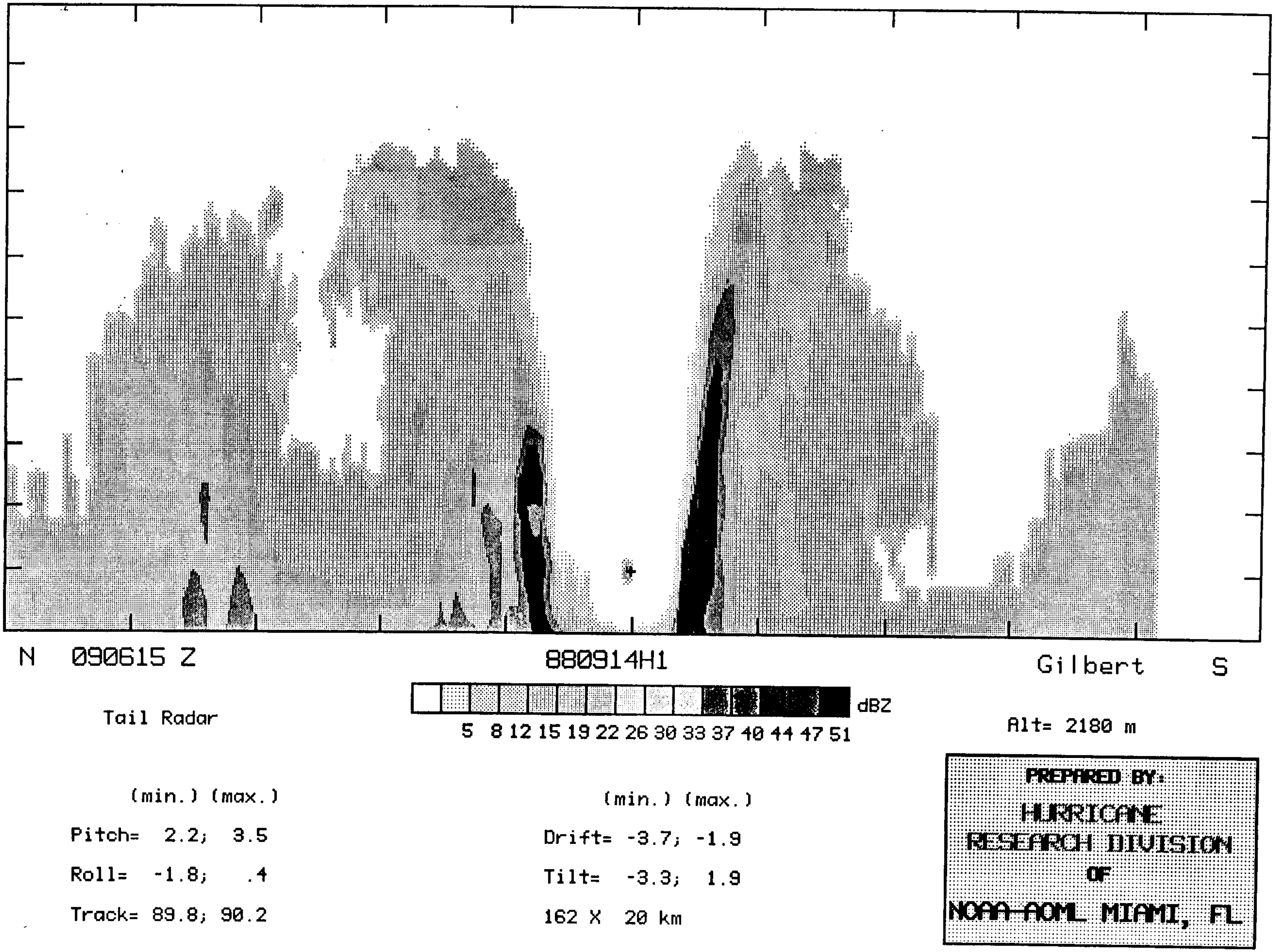
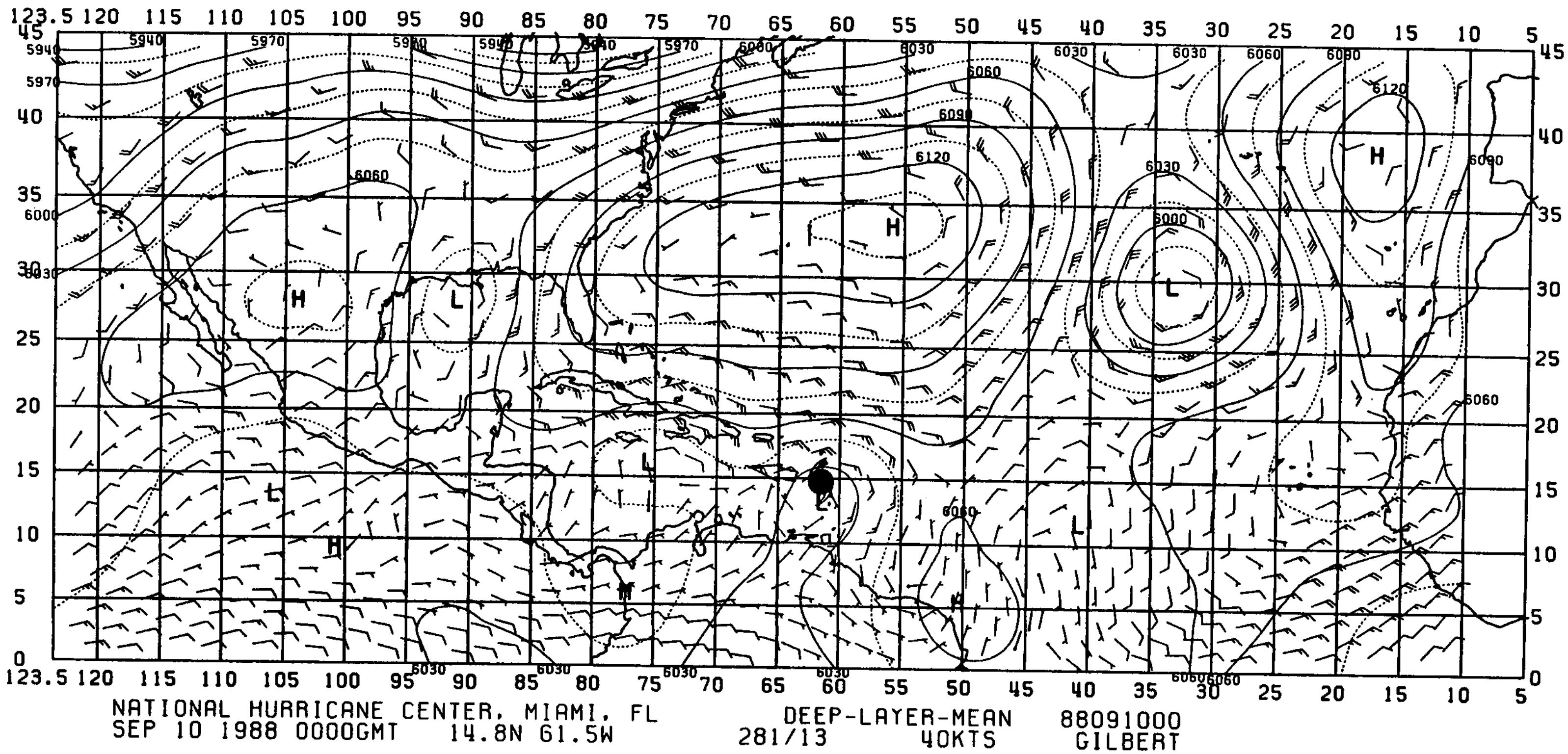
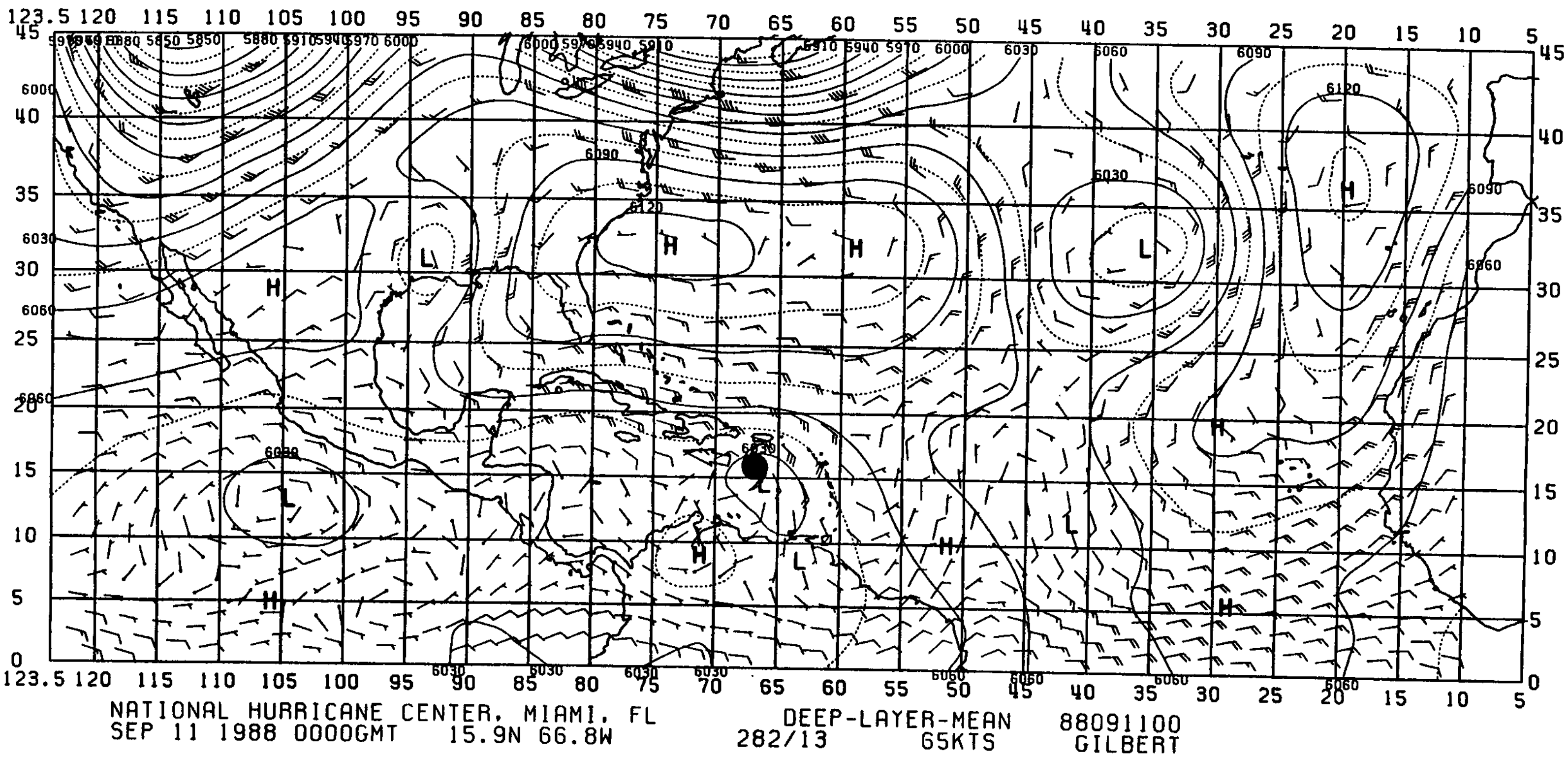


Fig. 15. North-south vertical cross section of radar reflectivity through Hurricane Gilbert at 0906 UTC September 14, 1988. Light (dark) stippling indicates light (heavy) rainfall. Tall cores of intense precipitation near center of figure show part of eyewall. Reflectivity void at center indicates eye of storm. Figure provided by NOAA-AOML HRD.

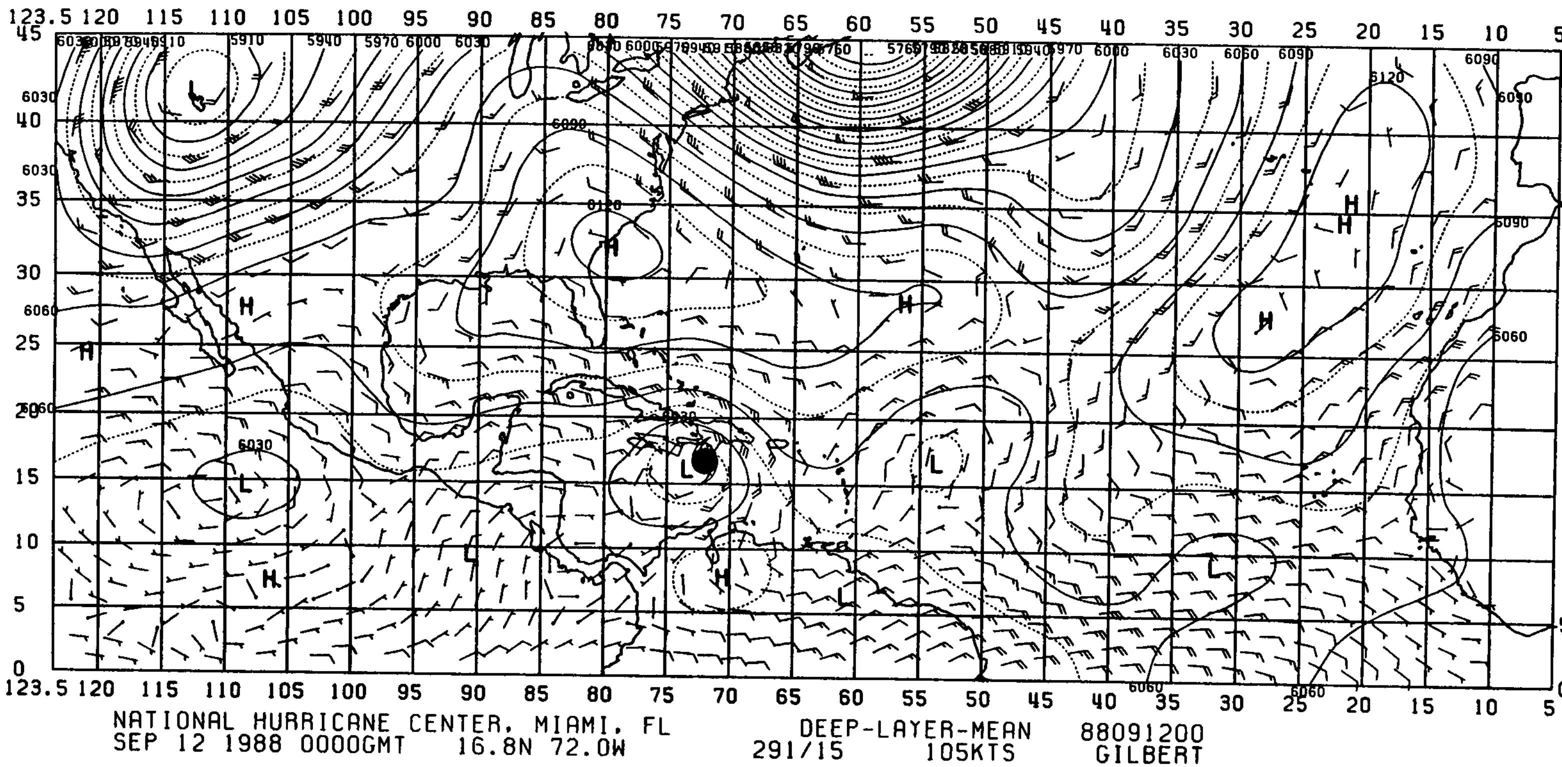
Fig. 16. NHC deep-layer mean analyses of geopotential height and wind data near Gilbert from September 10-17, 1988. Hurricane symbol (shaded circle) shows location of Gilbert's center. Height contours labeled in meters. Flag for 50 kt, full barb for 10 kt, half or oblique barb for 5 kt, solitary mast for 3 kt and open circle for calm wind.


NATIONAL HURRICANE CENTER, MIAMI, FL
DEEP-LAYER-MEAN
88091000
SEP 10 1988 0000GMT
14.8N 61.5W
281/13
40KTS
GILBERT

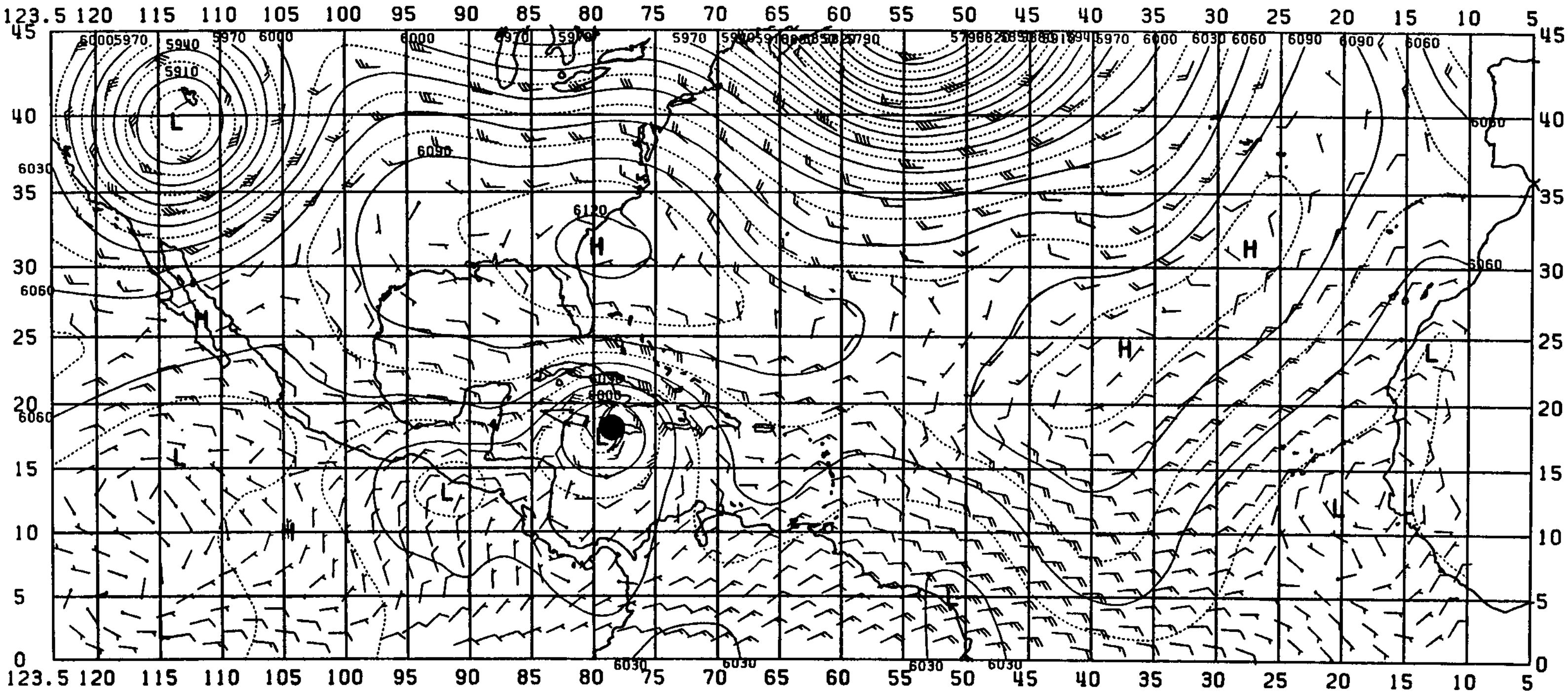
(a)


NATIONAL HURRICANE CENTER, MIAMI, FL
SEP 11 1988 0000GMT
15.9N 66.8W
DEEP-LAYER-MEAN
282/13
65KTS
88091100
GILBERT

(b)

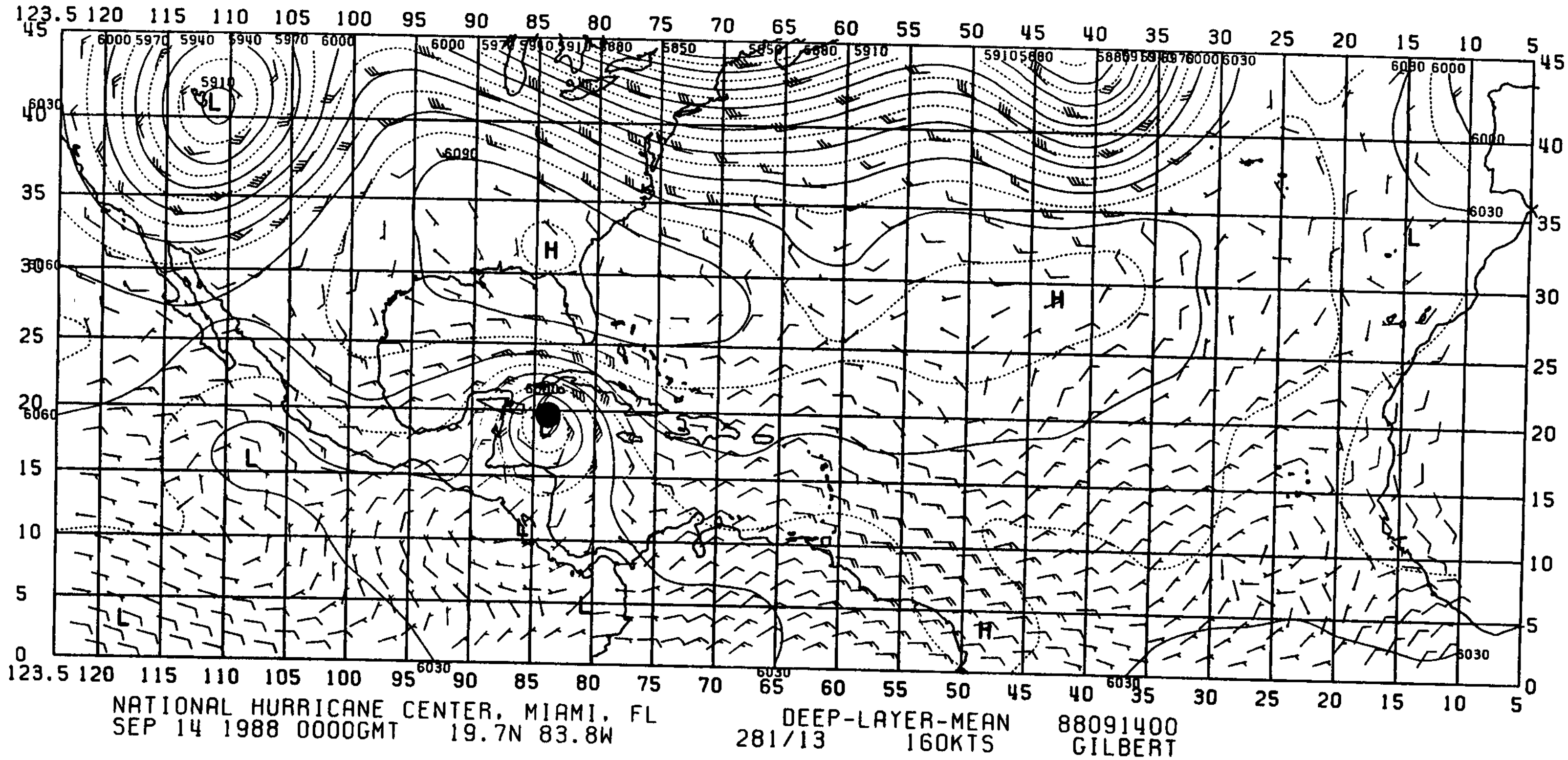

NATIONAL HURRICANE CENTER, MIAMI, FL
DEEP-LAYER-MEAN
88091200
SEP 12 1988 0000GMT
16.8N 72.0W
291/15
105KTS
GILBERT

(c)

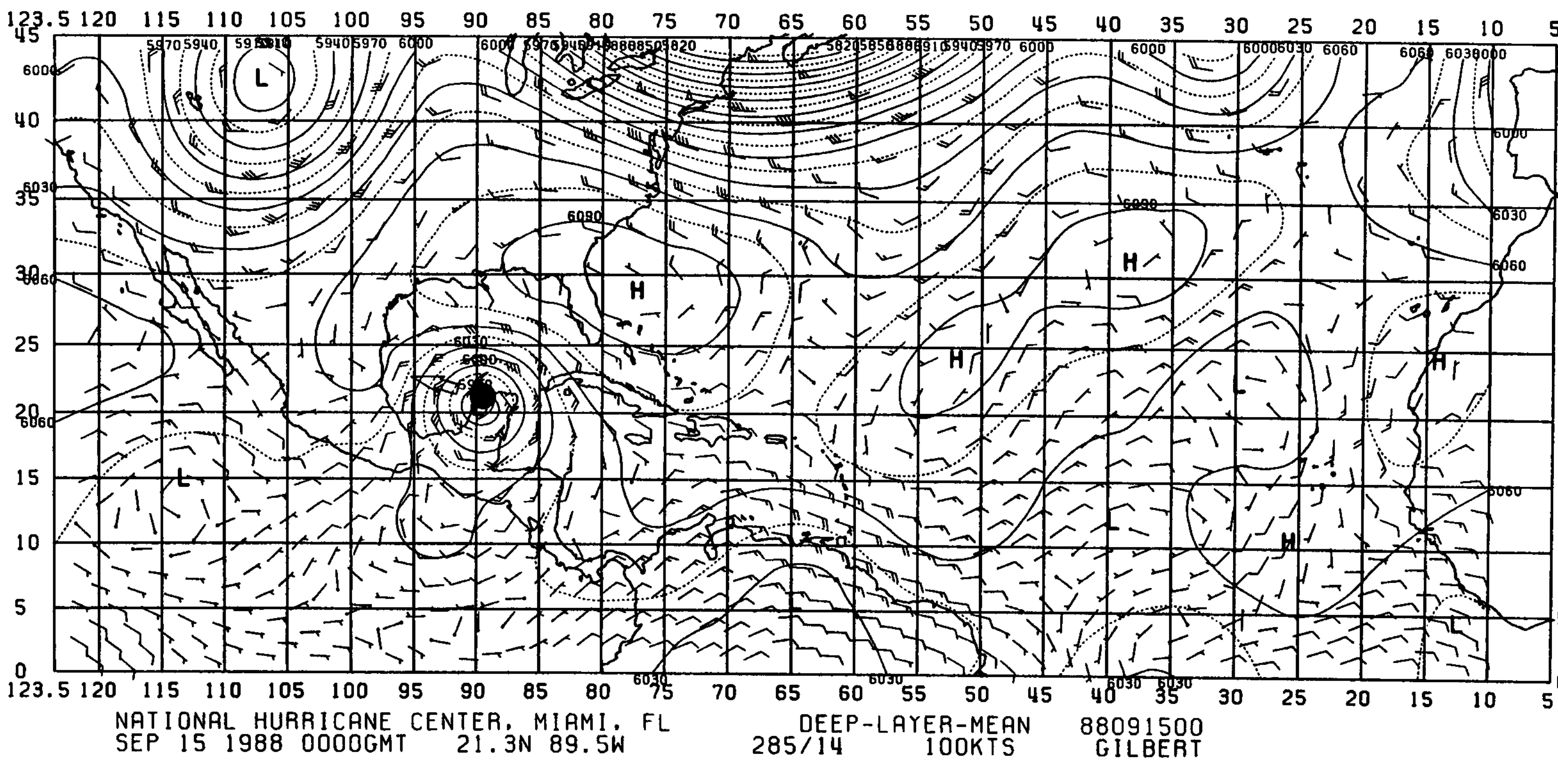


NATIONAL HURRICANE CENTER, MIAMI, FL   DEEP-LAYER-MEAN   88091300
SEP 13 1988 0000GMT   18.2N 78.5W   283/14   110KTS   GILBERT

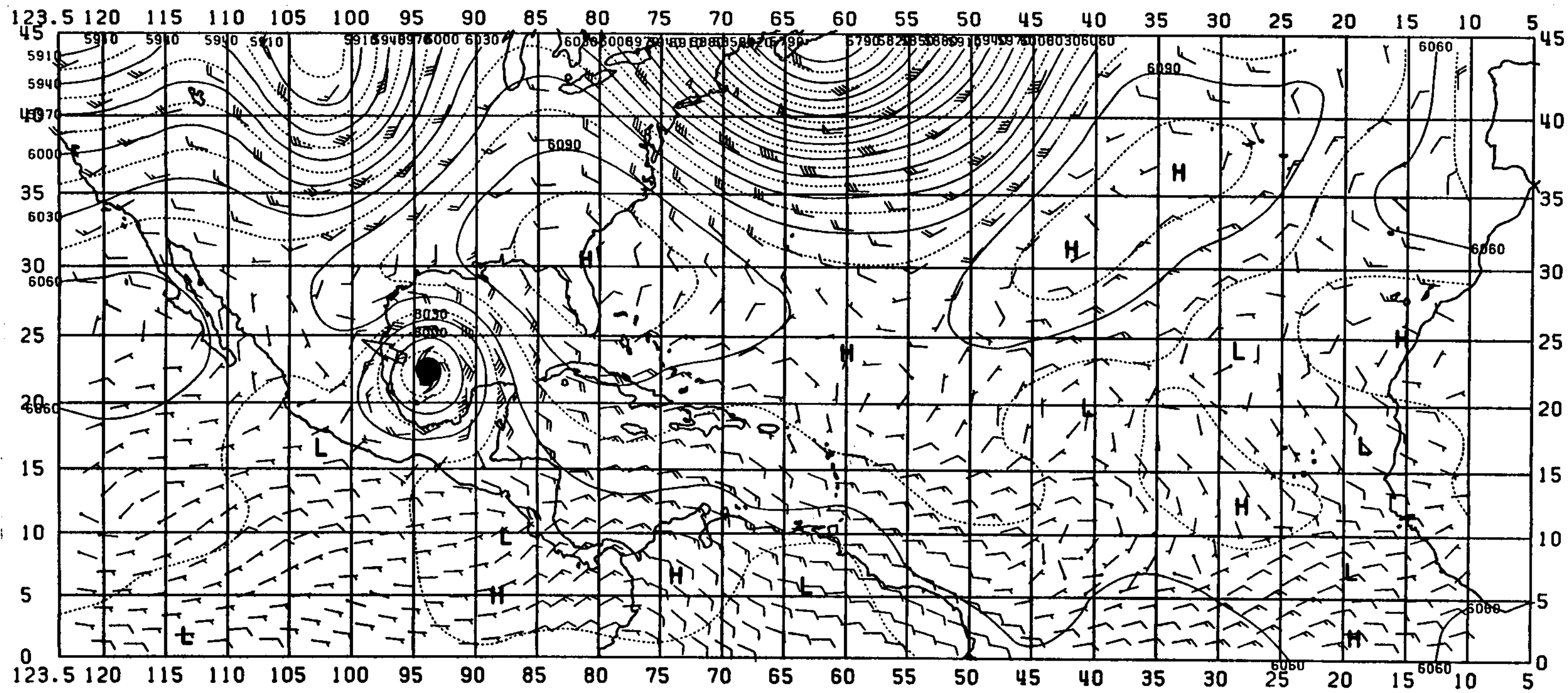
(d)


NATIONAL HURRICANE CENTER, MIAMI, FL
SEP 14 1988 0000GMT 19.7N 83.8W
DEEP-LAYER-MEAN 88091400
281/13 160KTS GILBERT

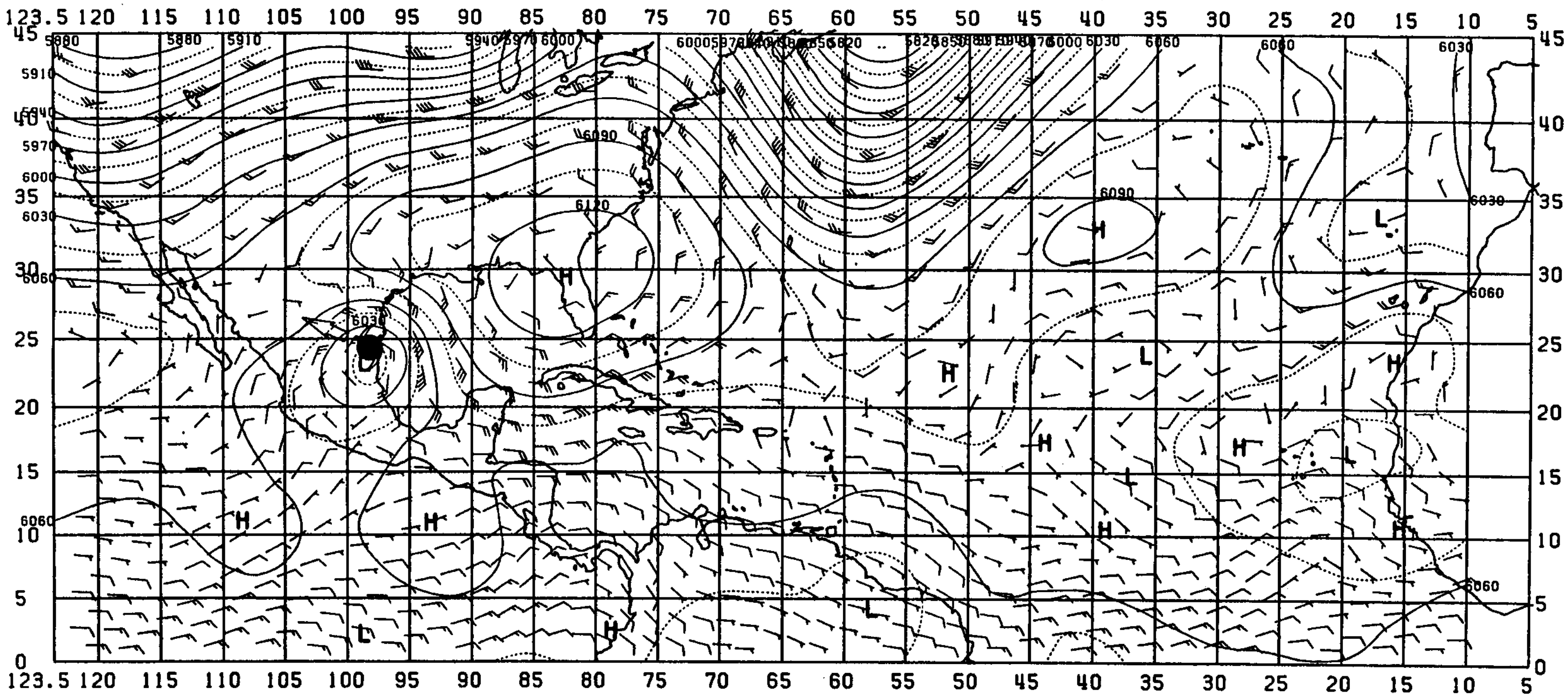
(e)


NATIONAL HURRICANE CENTER, MIAMI, FL
DEEP-LAYER-MEAN
88091500
SEP 15 1988 0000GMT
21.3N 89.5W
285/14
100KTS
GILBERT

(f)


NATIONAL HURRICANE CENTER, MIAMI, FL
DEEP-LAYER-MEAN 88091600
SEP 16 1988 0000GMT 22.5N 93.8W
294/10 100KTS GILBERT

(g)



NATIONAL HURRICANE CENTER, MIAMI, FL   DEEP-LAYER-MEAN   88091700
SEP 17 1988 0000GMT   24.4N 98.2W   294/11   80KTS   GILBERT

(h)

southeast United States through the Great Lakes states (e.g., Fig. 16c). Simultaneously, strong long-wave troughs developed over the Pacific Northwest and Canadian Maritime Provinces. Gilbert was in the region to the south of the large-scale ridge. (This area can be favorable for cyclogenesis, the development or intensification of a low pressure system [e.g., Palmen, 1949; Rex, 1950]. Perhaps, by being situated there, Gilbert's intensification was hastened and amplified.) On September 13-14, as Gilbert reached its peak intensity, a distinct high/low couplet consisting of the large-scale high, and Gilbert to the south of the high, was present along 80-85°W (Figs. 16d and 16e).

The large-scale high remained anchored over the southeast United States as Gilbert weakened over the Yucatan peninsula and then moved through the Gulf of Mexico (Figs. 16f and Figs. 16g). Gilbert was about equidistant from the large-scale trough over the western United States and the high over the southeast United States when the storm moved inland over northeast Mexico on September 17 (Fig. 16h). Gilbert's turn to the north and eventually to the northeast began on September 18 as the storm became increasingly influenced by the DLM flow ahead of the large-scale trough.

3.5 Sea-Surface Temperatures

Direct solar radiation heats the upper part of the tropical oceans in a shallow layer (< 100 m). The warm waters serve as a reservoir of energy required to initiate and maintain hurricanes. The sea-surface temperature (SST) must exceed about 26°C for tropical cyclone development (Palmen, 1948). As the SST rises, so does the theoretical maximum intensity of a tropical cyclone (e.g., Emanuel, 1988). Gilbert encountered very warm SSTs where it crossed the Caribbean Sea and Gulf of Mexico, ranging from about 29 to 31°C (Fig. 17).

Gilbert also modified the SST distribution over much of the southern Gulf of Mexico. The storm's broad, strong and curved wind field disrupted the normal relatively steady and moderate east or southeasterly airflow over the Gulf. Before Gilbert approached the Yucatan peninsula, the SSTs on the Yucatan's north coast were relatively low (25-28°C), reflecting a climatologically favored southeasterly flow that produces upwelling (Fig. 17a). (Ocean temperatures generally cool with increasing depth. During periods of offshore winds and when the seas become rough, the warm waters at the sea surface mix with, and are cooled by, the upwelling colder waters that they overlie.) Northerly winds on the west side of Gilbert's circulation then temporarily ended the upwelling and brought warm, near-surface water southward (Fig. 17b). This flow led to a SST rise of as much as 3°C along the coast.

As Gilbert moved across the Gulf of Mexico, the extensive area of hurricane and tropical storm force winds (see Fig. 5) led to widespread upward mixing of the colder waters. SSTs decreased by as much as 6°C, to near 25°C (cf. Figs. 17b and 17c) along the track of Gilbert. In contrast, little change in SST occurred over the eastern and central Caribbean during Gilbert's passage there.

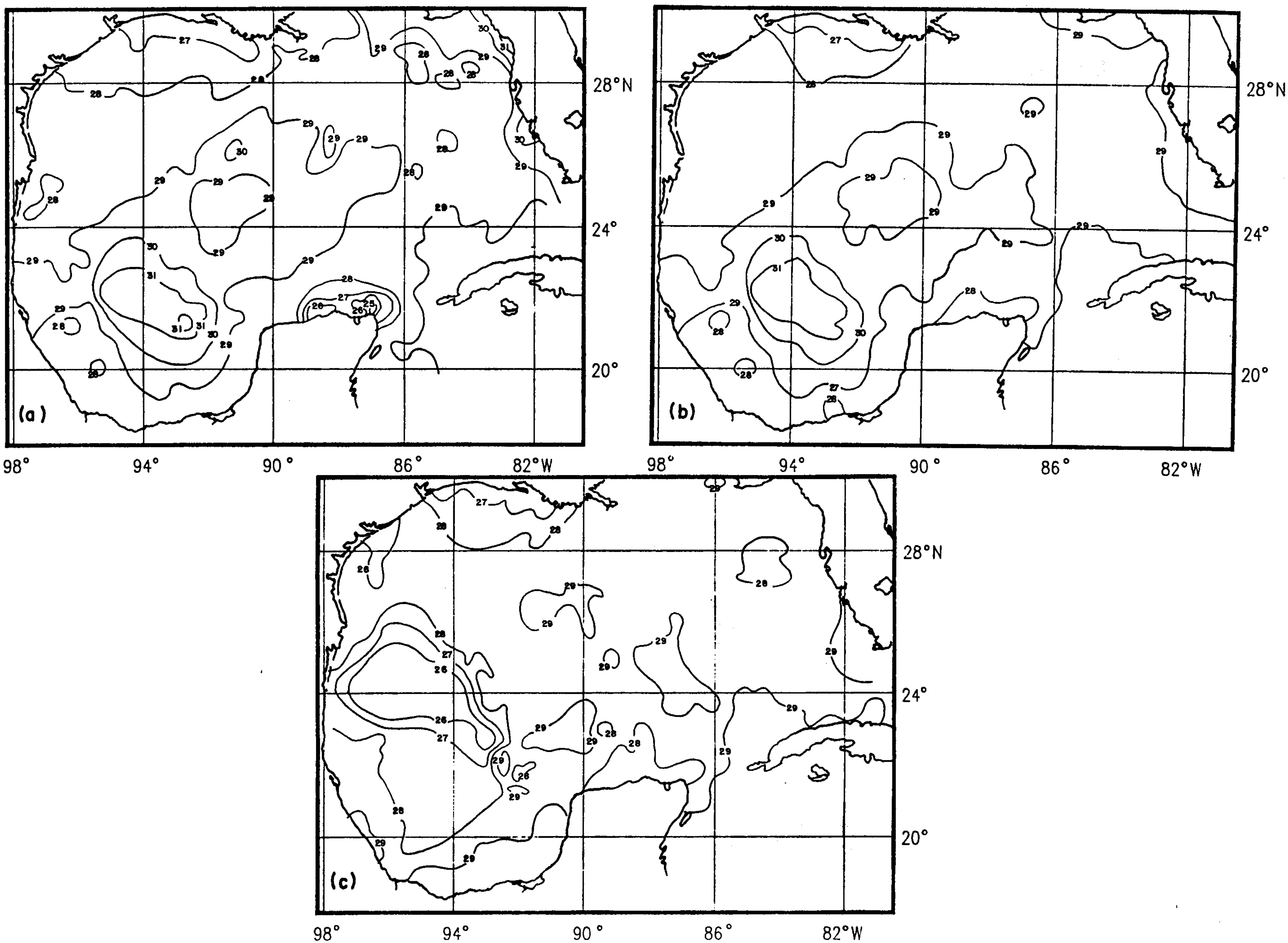


Fig. 17. Sea-surface temperature pattern near Hurricane Gilbert on (a) September 10 through (b) September 13 to (c) September 17, 1988. Contours labeled in °C.

4. NHC FORECASTS AND WARNINGS OF GILBERT

As required by domestic statute and international agreement, the NHC is responsible for providing tropical cyclone forecasts and warnings for the Atlantic (and eastern Pacific) tropical cyclone basin(s). The NHC provides a variety of forecast and warning services to the users of its products. Forecasts of tropical cyclone track and issuances of tropical cyclone watches and warnings constitute two of the NHC's critical requirements. In this section, the NHC forecasts and associated guidance products for Hurricane Gilbert are reviewed.

4.1 Numerical Model Track Forecasts

Numerical models have been used for over 30 years in the prediction of tropical cyclone tracks. Operational tropical cyclone models have either a statistical or dynamical framework. Statistical models draw from one or more of four sources of predictive information, including: climatology, persistence, environmental data and numerically forecast environmental conditions. Dynamical models derive skill from mathematical formulations of the physical processes in the atmosphere. The accuracy of dynamical models depends upon the physical assumptions used in the model and upon the quality and density of data used to start the simulation. Some "statistical-dynamical" models combine these characteristics by using data from a dynamical model for input, but process the information in a statistical prediction framework.

Six track models for the Atlantic basin, CLIPER (Climatology and Persistence), HURRAN (Hurricane Analog), SANBAR (Sander's Barotropic), NHC83, BAM (Beta and Advection Model) and QLM (Quasi-Lagrangian Model) were available to forecasters at NHC during Hurricane Gilbert. Figure 18 shows the forecasts from CLIPER, QLM and NHC83 (representing statistical, dynamical and statistical-dynamical models, respectively) for Gilbert along with the track of the storm. Table 7 shows a summary of the performance of the models from 12 through 72 hours.

From an historical perspective, CLIPER performed very well during Gilbert, although the model tended to have a "right bias" during the period preceding the storm's landfall on the Yucatan peninsula. The high quality of CLIPER forecasts is an indication that the storm did not make any sudden or sharp turns or follow a track which varied much from the average track for that location, initial motion and time of year.

The CLIPER model also serves as a convenient benchmark for comparing the skill of more sophisticated models. By comparison, the QLM model did not forecast well the track of Gilbert (Fig. 18b, Table 7). The QLM model was just introduced operationally in 1988 and for Gilbert had a strong right bias, particularly during the period when the storm was over the Caribbean. (It should be kept in mind that we are using hindsight to judge the performance of the model, an option not available to the forecasters in real-time.)

Table 7. Gilbert track error (n mi).

Model	Period (h)			
	12	24	48	72
BAM	30	70	198	327
CLIPER	26	39	88	214
NHC72	25	66	179	410
SANBAR	27	48	93	178
QLM	82	111	171	199
NHC83	25	33	82	147
NHC official	26	48	109	191
NHC official (1978-1987)	59	118	242	363

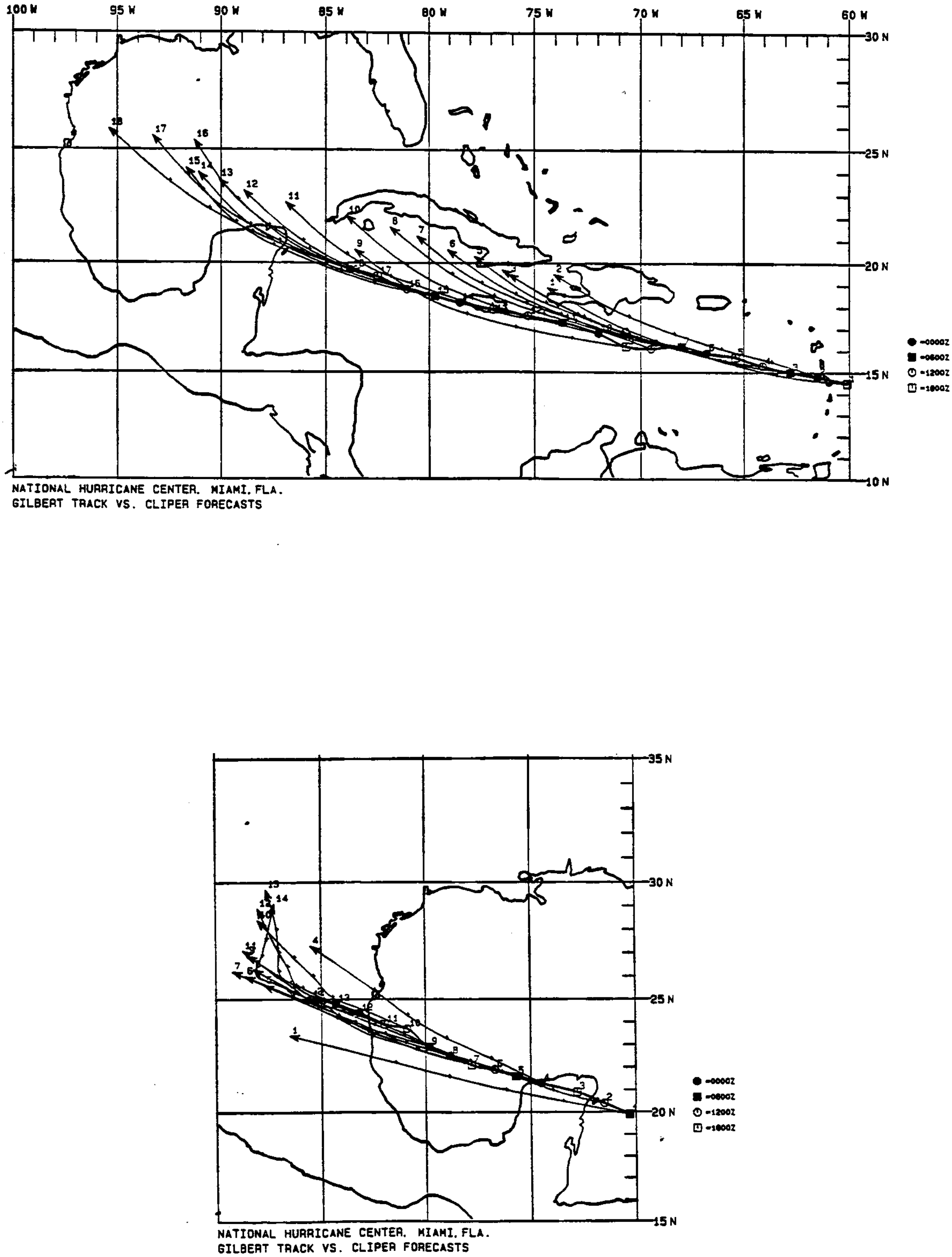
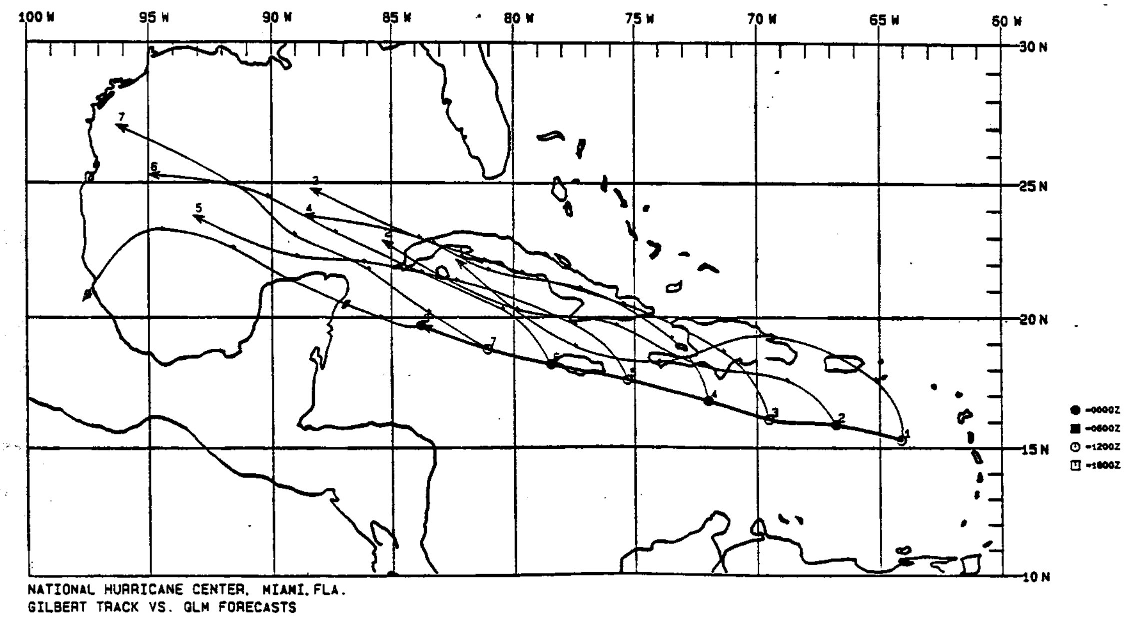


Fig. 18. (a) CLIPER forecasts (thin lines) and NHC final best track (bold line) for Gilbert.



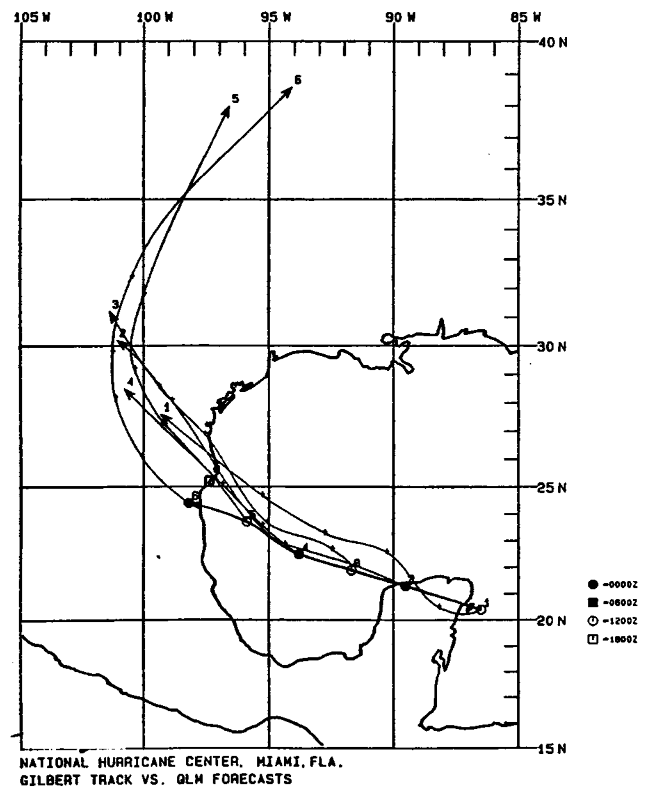
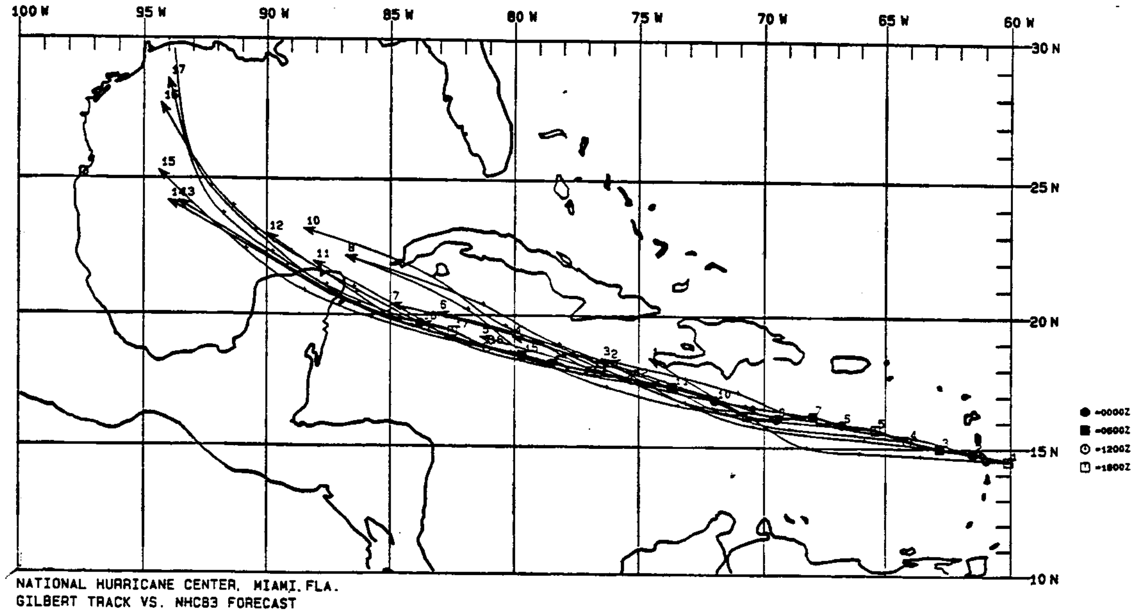


Fig. 18 (cont.). (b) QLM forecasts (thin lines) and NHC final best track (bold line) for Gilbert.



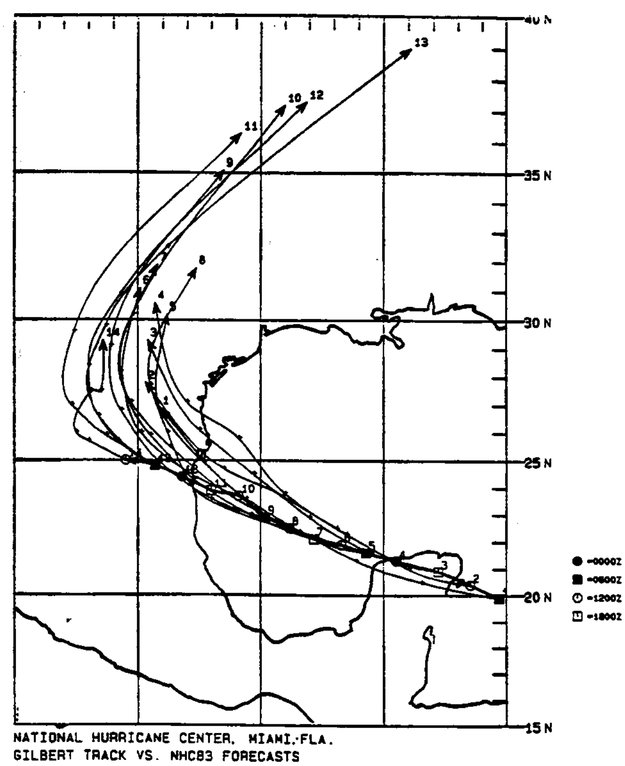
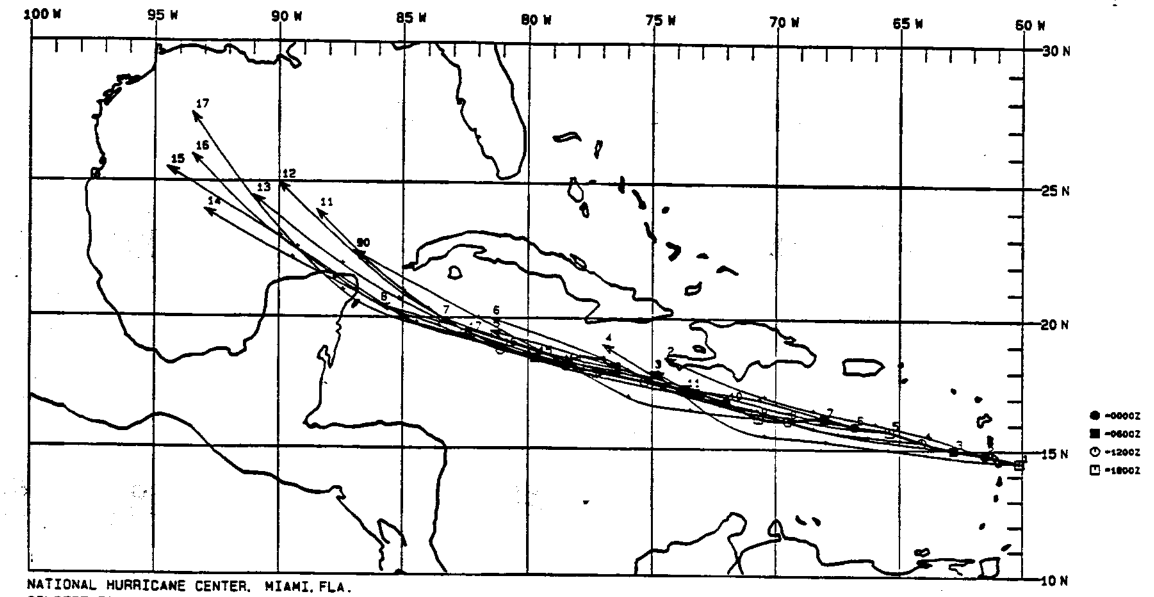


Fig. 18 (cont.). (c) NHC83 forecasts (thin lines) and NHC final best track (bold line) for Gilbert.



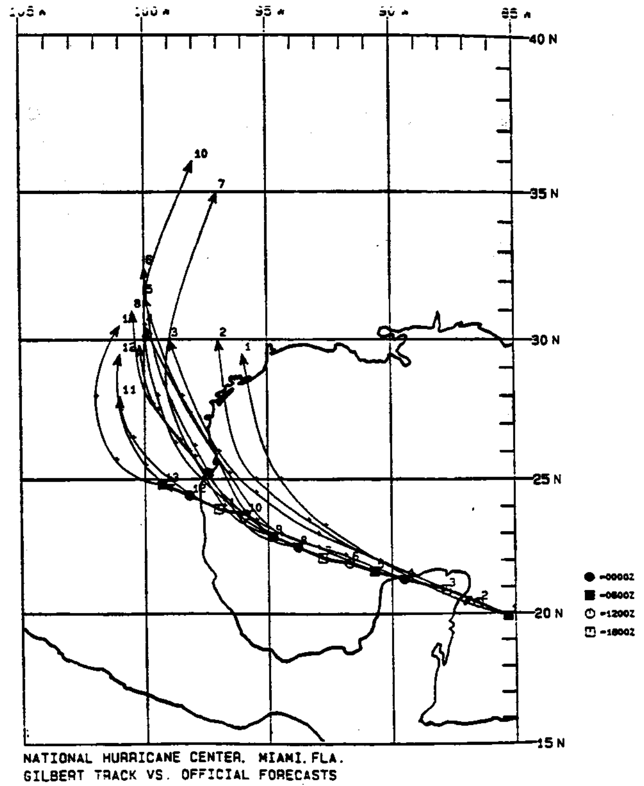


Fig. 18 (cont.). (d) Official forecasts (thin lines) and NHC final best track (bold line) for Gilbert.

The NHC83 model was the preferred operational and generally most accurate model available to NHC (Neumann, 1988). Overall, NHC83 was the most accurate model during Hurricane Gilbert. Errors at each forecast period were close to one-third of the 10-year average (of official forecasts).

4.2 NHC Forecasts

Each of the numerical models available to NHC has at least one unique performance characteristic justifying its use (e.g., Neumann and Pelissier, 1981). Unfortunately, the models are inconsistent. The accuracy of the models tends to vary between storms and for an individual storm. Forecasters must decide which model is likely to be best for a given situation and then how that model's forecast can be improved upon. The forecaster's prediction becomes the NHC "official" forecast.

Figure 18 and Table 7 show the performance of official NHC forecasts for Hurricane Gilbert. Most of the official forecasts were very good compared to the long-term average and, on average, the errors of the official forecasts were comparable to, but slightly larger than, those of NHC83. For comparison, Table 7 also shows the average errors for the NHC "official" forecasts for the 10-year period concluding with the 1987 season.

4.3 NHC Watches and Warnings

The NHC's watches and warnings (Table 8) were generally appropriate and timely (NHC, 1988a). Hurricane warnings were issued 22 hours before the eye of Gilbert made landfall on Jamaica. The analagous lead times for the Yucatan peninsula and northeast Mexico were 26 and 34 h, respectively.

As Gilbert approached the coast of northeast Mexico, a hurricane warning was issued along the coastline from Tampico, Mexico to Port O'Connor, Texas and a hurricane watch was posted from Port O'Connor to Port Arthur, Texas. The length of coastline covered by the combined warning and watch was large, exceeding 500 miles. The long length was necessitated primarily by Gilbert's unusually large area of hurricane force winds (e.g., Fig. 5).

For a period of about 50 hours preceding Gilbert's final landfall, there was no deviation in the official forecasts which [illegible] that the center of Gilbert would come ashore [illegible] over northeast Mexico or [illegible] Texas (Fig. 18).

MARY

nondescript tropical wave and ost powerful tropical cyclones m was mostly toward the west to Gilbert crossed the Lesser ade a direct hit on Jamaica as

Hurricane Gilbert grew fro environment to become one of on record. The track of the s west-northwest at about 15 Antilles as a tropical storm

Table 8. Watches and warnings issued on Gilbert (UTC).

Location	Type	Effective	Discontinued
southern coast of Dominican Republic	Tropical Storm Warning	10/2200	12/1300
Barahona peninsula of Dominican Republic	Hurricane Watch	10/2200	11/0230
Barahona peninsula of Dominican Republic	Hurricane Warning	11/0230	12/1300
southern coast of Dominican Republic	Hurricane Watch	11/0230	12/0100
southern coast of Haiti	Hurricane Warning	11/1000	12/1900
Jamaica	Hurricane Watch	11/1000	11/1900
south coast of Cuba east of Cabo Cruz	Hurricane Watch	11/1600	12/1300
Jamaica	Hurricane Warning	11/1900	13/1300
Cayman Islands	Hurricane Watch	12/1000	12/1300
south coast of Cuba east of Camaguey	Hurricane Warning	12/1300	12/2200
Cayman Islands	Hurricane Warning	~~13~~ 12/1300	14/0700
south coast of Cuba east of Camaguey to Cienfuegos	Hurricane Watch	12/1300	13/0100
northeast Yucatan from Felipe Carrillo Puerto to Progreso including Cozumel and Cancun	Hurricane Watch	12/2200	13/1300
western Cuba for the province of Pinar Del Rio and Isle of Youth	Hurricane Watch	13/0100	13/1300
northeast Yucatan from Felipe Carrillo Puerto to Progreso including Cozumel and Cancun	Hurricane Warning	13/1300	15/1000
western Cuba for the province of Pinar Del Rio and Isle of Youth	Hurricane Warning	13/1300	15/0700
Yucatan peninsula south of Felipe Carillo Puerto to Chetumal on the east coast and south of Progreso to Champoton on the west coast	Hurricane Warning	14/1000	15/1000
northern district of Belize	Hurricane Watch	14/1300	14/1600
Texas coast from Brownsville to Port Arthur	Hurricane Warning	15/0100	16/1900
northeast Mexico from Tampico northward	Hurricane Watch	15/0100	15/1200
Texas coast from Brownsville to Port O'Conner	Hurricane Warning	15/1200	17/0400
northeast Mexico from Tampico northward	Hurricane Warning	15/1200	17/1000

a category 3 hurricane. It then intensified at an extraordinarily rapid rate, 72 mb over 22 hours. The central pressure dropped to 888 mb, the lowest ever noted in an Atlantic hurricane. The hurricane then sideswiped the Cayman Islands before slamming into the Yucatan peninsula at nearly full force, with category 5 intensity. Gilbert's final landfall came as a category 3 hurricane over northeast Mexico. The storm quickly weakened and lost its tropical characteristics over northern Mexico and the central United States.

Gilbert's size was immense, its upper-level circulation covering millions of square miles at a time. It influenced an area far greater than the areas covered by the 1935 Labor Day Hurricane or Hurricane Camille in 1969, the only two category 5 hurricanes known to have struck the United States during this century.

Gilbert killed 319 people. Most of the fatalities occurred in a single flood event in inland Mexico. Over the course of its life, more than $10 billion damage was inflicted by the hurricane. These losses occurred in spite of accurate forecasts and warnings, issued with substantial lead times.

The conclusion drawn from a statistical analysis of the data is foreboding: A hurricane of Gilbert's intensity is expected to occur somewhere in the Atlantic hurricane basin about every seven years.

ACKNOWLEDGEMENTS

The authors thank the National Hurricane Center staff, especially Robert Sheets, Max Mayfield and Miles Lawrence for their helpful suggestions about the manuscript; Joan David and Sandra Potter for their skillful assistance in the production of this document; and Joel Cline for providing the plots of track forecasts. Frank Marks, of the Hurricane Research Division, AOML, made available the figures of aircraft reconnaissance data. Charles Neumann of Science Applications International Corporation, provided the plots of the deep-layer mean height fields and advice on the calculation of mean return periods.

REFERENCES

Dikkers, R.D., R.D. Marshall, H.C.S. Thom, 1971: Hurricane Camille, August 1969. NIST Technical Note NBS 569, National Institute of Standards and Technology, U.S. Department of Commerce, Boulder, CO, 67 pp.

Dunn, G.E., and B.I. Miller, 1960: Atlantic hurricanes. Louisiana State University Press, Baton Rouge, LA, 326 pp.

Dvorak, V.F., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Technical Report NESDIS 11, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, DC, 47 pp.

Elsberry, R.L., W.F. Frank, G.J. Holland, J.D. Jarrell, and R.L. Southern, 1985: A global view of tropical cyclones. University of Chicago Press, Chicago, IL, 185 pp.

Emanuel, K.A., 1988: The maximum intensity of hurricanes. J. Atmos. Sci., 45(7), 1143-1155.

Hebert, P.J., and R.A. Case, 1990: The deadliest, costliest, and most intense hurricanes of this century (and other frequently requested hurricane facts). NOAA Technical Memorandum NWS NHC 31, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, DC, 31 pp.

Ho, F.P., J.C. Su, K.L. Hanevich, R.J. Smith, and F.P. Richards, 1987: Hurricane climatology for the Atlantic and Gulf coasts of the United States. NOAA Technical Report NWS 38, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, DC, 195 pp.

Neumann, C.J., and J.M. Pelissier, 1981: Models for the prediction of tropical cyclone motion over the North Atlantic: An operational evaluation. Mon. Wea. Rev., 109(3), 522-538.

Neumann, C.J., 1987: The National Hurricane Center risk analysis program (HURISK). NOAA Technical Memorandum NWS NHC 38, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C., 56 pp.

Neumann, C.J., 1988: The National Hurricane Center NHC83 model. NOAA Technical Memorandum NWS NHC 41, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, DC, 44 pp.

NHC (National Hurricane Center), 1988a: Diagnostic report of the National Hurricane Center, 1(2). NOAA/National Weather Service, Coral Gables, FL, 155 pp.

NHC (National Hurricane Center), 1988b: Diagnostic report of the National Hurricane Center, 1(3). NOAA/National Weather Service, Coral Gables, FL, 76 pp.

Palmen, E., 1948: On the formation and structure of tropical cyclones. Geophysica, 3, 26-38.

Palmen, E., 1949: On the origin and structure of high-level cyclones south of the maximum westerlies, Tellus, 1, 22-31.

Rex, D.F., 1950: Blocking action in the middle troposphere and its effect upon regional climate, Tellus, 2, 196-211.

Saffir, Herbert S., 1972: Report on the nature and extent of structural damage caused by Hurricane Camille. NOAA/NWS Contract No. 22-197-72 (N), National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, DC, 73 pp.

Simpson, R.H., H. Riehl, 1981: The hurricane and its impact. Louisiana State University Press, Baton Rouge, LA, 398 pp.

Simpson, R.H., A.L. Sugg, and Staff, 1970: The Atlantic hurricane season of 1969. Mon. Wea. Rev., 98(4), 293-306.

Tebeau, C.W., 1971: A history of Florida. University of Miami Press, Coral Gables, FL, 502 pp.

Tsokos, C.P., 1972: Probability distributions: An introduction to probability theory with applications. Duxbury Press, Belmont, CA, 657 pp.

Willoughby, H.E., J.M. Masters, and C.W. Landsea, 1989: A record minimum sea level pressure observed in Hurricane Gilbert. Mon. Wea. Rev., 117(7), 2824-2828.

U.S. Army Engineer District, Mobile, 1970: Report on hurricane Camille 14-22 August 1969. U.S. Army Corp of Engineers, Mobile, AL, 80 pp.