The National Hurricane Center—Past, Present, and Future

ROBERT C. SHEETS

National Hurricane Center, Coral Gables, Florida

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ABSTRACT

The National Hurricane Center (NHC) is one of three national centers operated by the National Weather Service (NWS). It has national and international responsibilities for the North Atlantic and eastern North Pacific tropical and subtropical belts (including the Gulf of Mexico and the Caribbean Sea) for tropical analyses, marine and aviation forecasts, and the tropical cyclone forecast and warning programs for the region. Its roots date back to the 1870s, and it is now in the forefront of the NWS modernization program. Numerous changes and improvements have taken place in observational and forecast guidance tools and in the warning and response process over the years. In spite of all these improvements, the loss of property and the potential for loss of life due to tropical cyclones continues to increase rapidly. Forecasts are improving, but not nearly as fast as populations are increasing in hurricane prone areas such as the United States East and Gulf Coast barrier islands. The result is that longer and longer lead times are required for communities to prepare for hurricanes.

The sea land over lake surge from hurricanes (SLOSH) model is used to illustrate areas of innudation for the Galveston/Houston, Texas; New Orleans, Louisiana; southwest Florida; and the Atlantic City, New Jersey areas under selected hurricane scenarios. These results indicate the requirement for lengthy evacuation times. The forecast and warning process is then illustrated, starting with tropical analyses, numerical guidance, the meteorological/hydrological coordination of the forecast, and finally the warning coordination and response process. Examples are used to illustrate the sensitivity of the warning and response process to preplanning based upon SLOSH model results, the coordination between NWS and local and state officials, and the critical role played by the media for motivating people to take the desired action in an orderly fashion. These examples illustrate how this process worked to near perfection during Hurricane Hugo, but was disrupted in the Galveston/Houston area by conflicting information reaching local officials and the public during Hurricane Gilbert.

Finally, a brief look into the future is attempted, with emphasis upon new observing systems, next generation numerical models and expected improvements in tropical cyclone track and intensity forecasts and the warning process at landfall and inland. The next generation weather radar (NEXRAD) systems in the modernized and restructured NWS are expected to play a major role in improving short-term warnings of flash floods, high winds, and possible tornadoes as hurricanes move inland and start to decay.

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Corresponding author address: Dr. Robert C. Sheets, Director, National Hurricane Center, NOAA/ERL, IRE Building, Rm 631, 1320 S. Dixie Highway, Coral Gables, FL 33146.

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References

1. Introduction

a. General

The National Hurricane Center (NHC) located in Miami, Florida is one of three national centers operated by the National Weather Service (NWS). The other two are the National Severe Storm Forecast Center (NSSFC) located in Kansas City, Missouri and the parent National Meteorological Center (NMC) located near Washington, D.C. The responsibilities of NHC are much broader than providing forecasts and warnings for tropical cyclones (hurricanes). Responsibilities also include tropical analyses, interpretive messages, public, and marine and aviation forecasts yearlong for national and international interests. The area of responsibility includes the tropical and subtropical regions of the North Atlantic and eastern North Pacific oceans, the Caribbean Sea, the Gulf of Mexico and adjacent land areas.

Although the NHC has numerous other responsibilities, it is best known for its hurricane forecast and warning programs. These programs have been highly visible because of large losses of property and lives due to hurricanes in the past. A continuing concern is that potential loss due to hurricanes is increasing daily due to population growth in vulnerable areas in the United States and elsewhere in this hemisphere. To understand

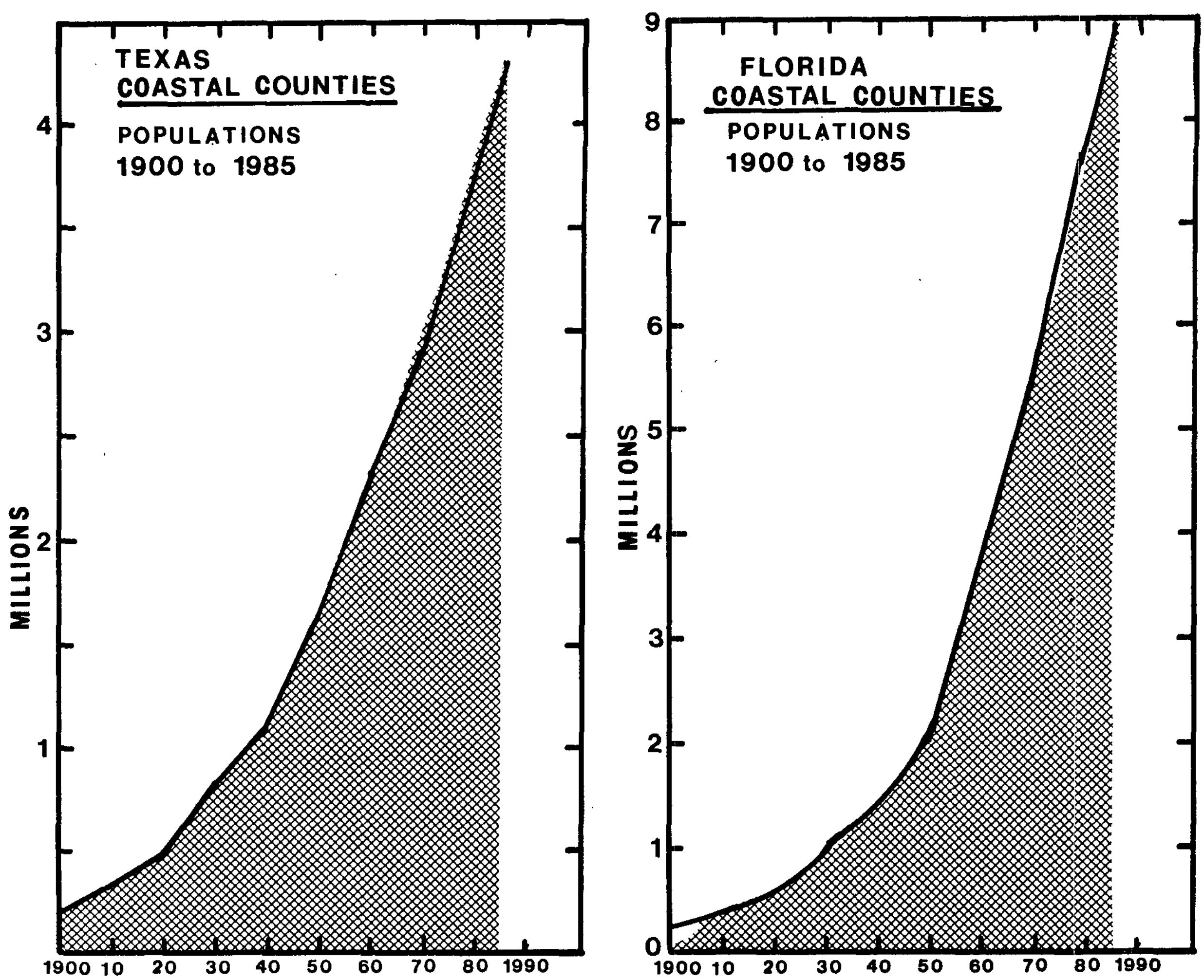


FIG. 1. Coastal county permanent population trends from 1900 to 1985 for (a) Texas, (b) Florida, and (c) Virginia, Maryland, Delaware, and New Jersey.

the present and future structure and operations of the NHC, one needs the perspective of its history and the changing nature of the hurricane threat to the citizens of the western hemisphere and specifically to Gulf and East Coast residents of the United States.

b. The United States Hurricane problem

The permanent populations of the hurricane-prone coastal counties of the United States continue to grow at a rapid rate (Fig. 1). When weekend, seasonal, and holiday populations are considered, the number of people on barrier islands such as at Ocean City, Maryland, Gulf Shores, Alabama, and Padre Island, Texas increase by 10- to 100-fold or more. Also, these areas are subject to inundation from the rapidly rising waters known as the storm surge associated with hurricanes that generally result in catastrophic damage and potentially large losses of life. Over the past several years, the warning system has provided adequate time for the great majority of the people on barrier islands and along the immediate coast to move inland when hurricanes have threatened. However, it is becoming more difficult each year to evacuate people from these areas due to roadway systems that have not kept pace with the rapid population growth. This condition results in the requirement for longer and longer lead times for safe evacuation. Unfortunately, these extended forecasts suffer from increasing uncertainty. Furthermore, rates of improvements in forecast skills have been far outpaced by rates of population growth in areas vulnerable to hurricanes.

The combination of the growing populations on barrier islands and other vulnerable locations (see Fig. 2), and the uncertainties in the forecasts poses major dilemmas for forecasters and local and state emergency management officials alike, i.e., how do you prevent complacency caused by "false alarms" and yet provide adequate warning times?

Preparations for hurricanes are expensive. When a hurricane is forecast to move inland on a path nearly normal to the coast the area placed under warning is about 300 miles in length. The average cost of preparation, whether the hurricane strikes or not, is more than \$50 million for the Gulf Coast. This estimate covers the cost of boarding up homes, closing down businesses and manufacturing plants, evacuating oil rigs, etc. It does not include economic losses due to disruption of commerce activities such as sales, tourists canceling reservations, etc. In some locations, the loss for the Labor Day weekend alone can be a substantial portion of the yearly income of coastal businesses. An example of such losses were experienced along the Florida panhandle during Hurricane Elena in 1985. If the width of the warned area has to be increased by 20% because of greater uncertainties in the forecast, the additional cost for each event would be \$10 million. If uncertainties in the hurricane strength require warning for the next higher category of hurricane (Saffir/Simpson scale, Hebert and Taylor 1988), then major increases in the number of people evacuated and preparation costs would be required. Of course, if these uncertainties meant that major metropolitan areas such as Galveston/Houston, New Orleans, Tampa, Miami, or a number of other major coastal cities would or would not be included in the warning area, the differences in preparation costs would be substantially more than the \$10 million, and the number of people evacuated would be substantially more than the tens of thousands of people. For instance, in the case of the Galveston/Houston area, an increase in storm strength of only 20 miles h^{-1} (from a category-2 hurricane to a category-3 hurricane on the Saffir/Simpson scale) would require the evacuation of an additional 200 000 people. Likewise, if major industrial areas such as Beaumont/Port Arthur, Texas, or tourist areas such as Atlantic City, New Jersey were affected by these uncertainties, the financial impact would be quite large.

Economic factors receive serious consideration from

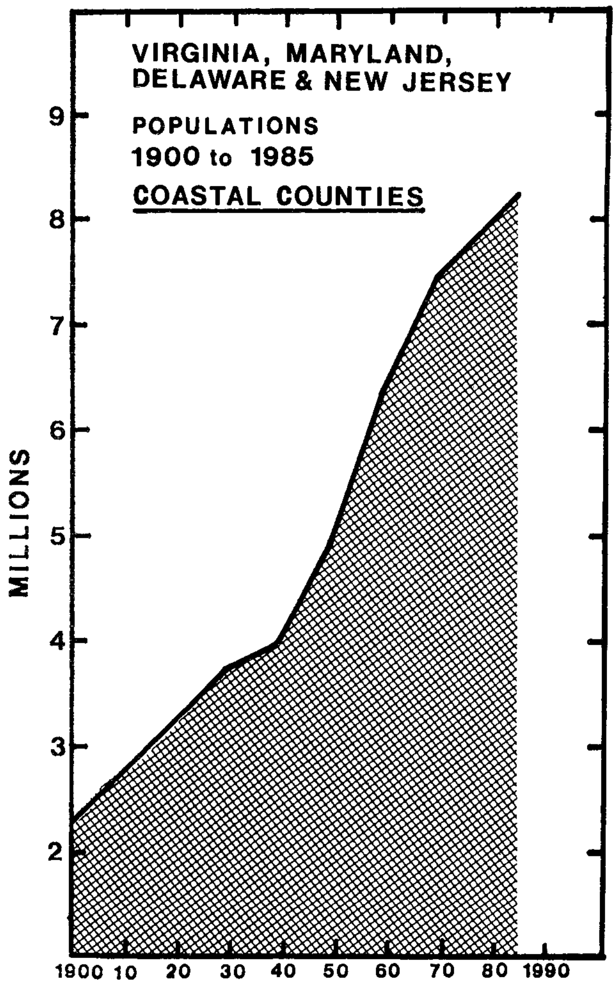


FIG. 1. (*Continued*)

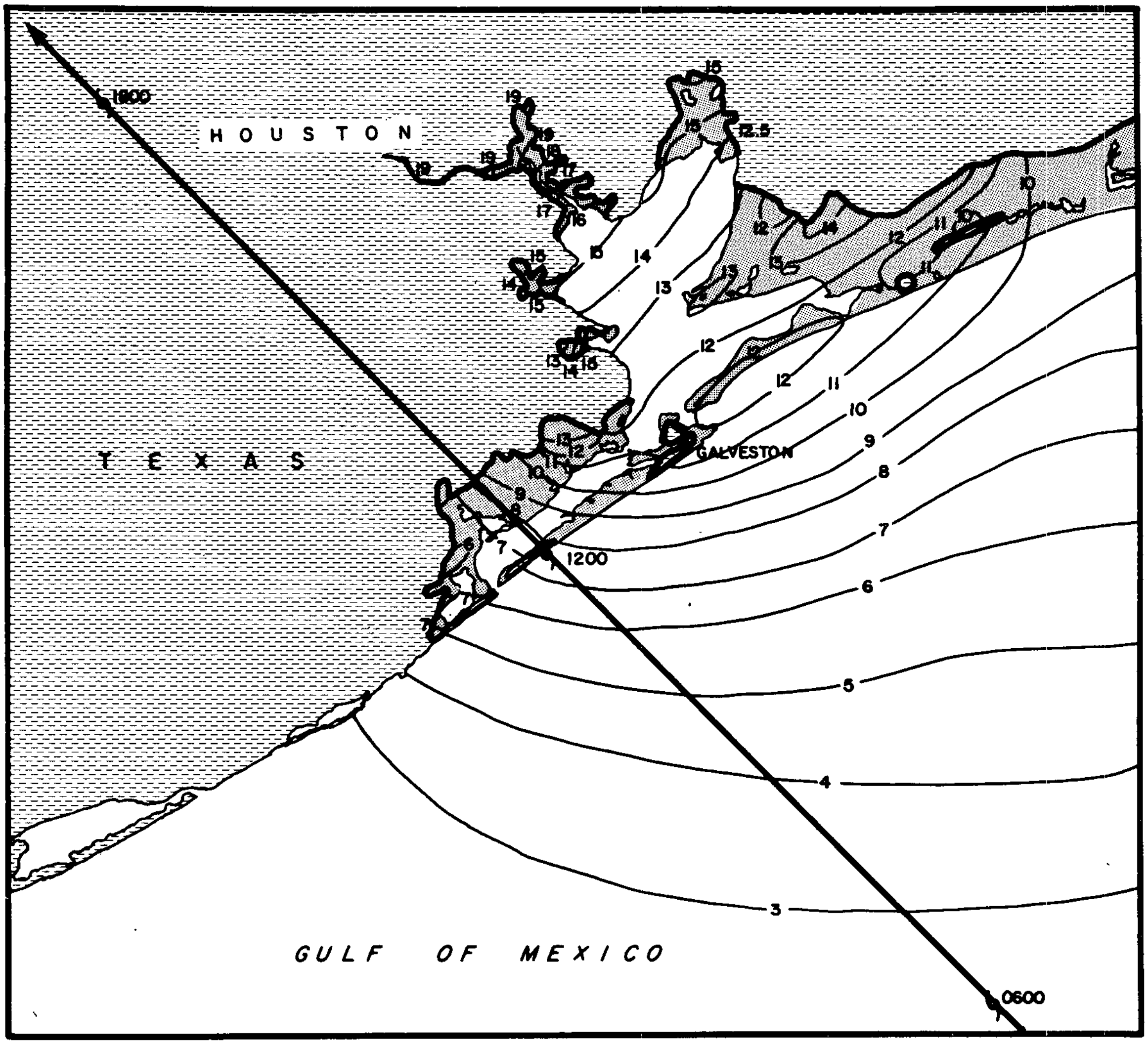


FIG. 2. Predicted inundation caused by the storm surge generated by a hurricane moving ashore on the track indicated by the bold straight line for the (a) Galveston/Houston, Texas area category-3 hurricane (b) New Orleans, Louisiana area category-4 hurricane; (c) southwest Florida area category-3 hurricane; and (d) Atlantic City, New Jersey area category-3 hurricane.

NHC, and local and state officials not only for direct but also for indirect effects on people response. People will not continually take expensive actions which, afterwards, prove to have been unnecessary. If we consistently over-warn by wide margins, people will not respond and such actions could result in large loss of life. To maintain credibility with the general public, NHC and local and state officials cannot treat all hurricanes as if they were Camilles, Gilberts or Hugos![1] Such an exaggerated approach may indeed provide maximum protection of life for a given event, but it endangers many more lives the next time when the threat may be even greater.

Finally, the hurricane problem is compounded by the fact that 80%–90% of the people who now live in the hurricane-prone areas have never experienced the core of a major hurricane (Saffir/Simpson scale-category 3 or stronger; Hebert et al. 1984). Many of these people have been through weaker hurricanes or been brushed by the fringe of a major hurricane. The result is a false impression of the damage potential of these storms. This frequently breeds complacency and delayed actions which could result in the loss of many lives. An example of the potential danger are those people living on barrier islands who might be reluctant to evacuate under "blue sky" conditions[2] until they

[1] Hurricane Camille (1969), Gilbert (1988) and Hugo (1989) were some of the most intense hurricanes to make landfall in the western hemisphere during the past three decades.

[2] Such an evacuation is presently required because of large populations with limited egness facilities.

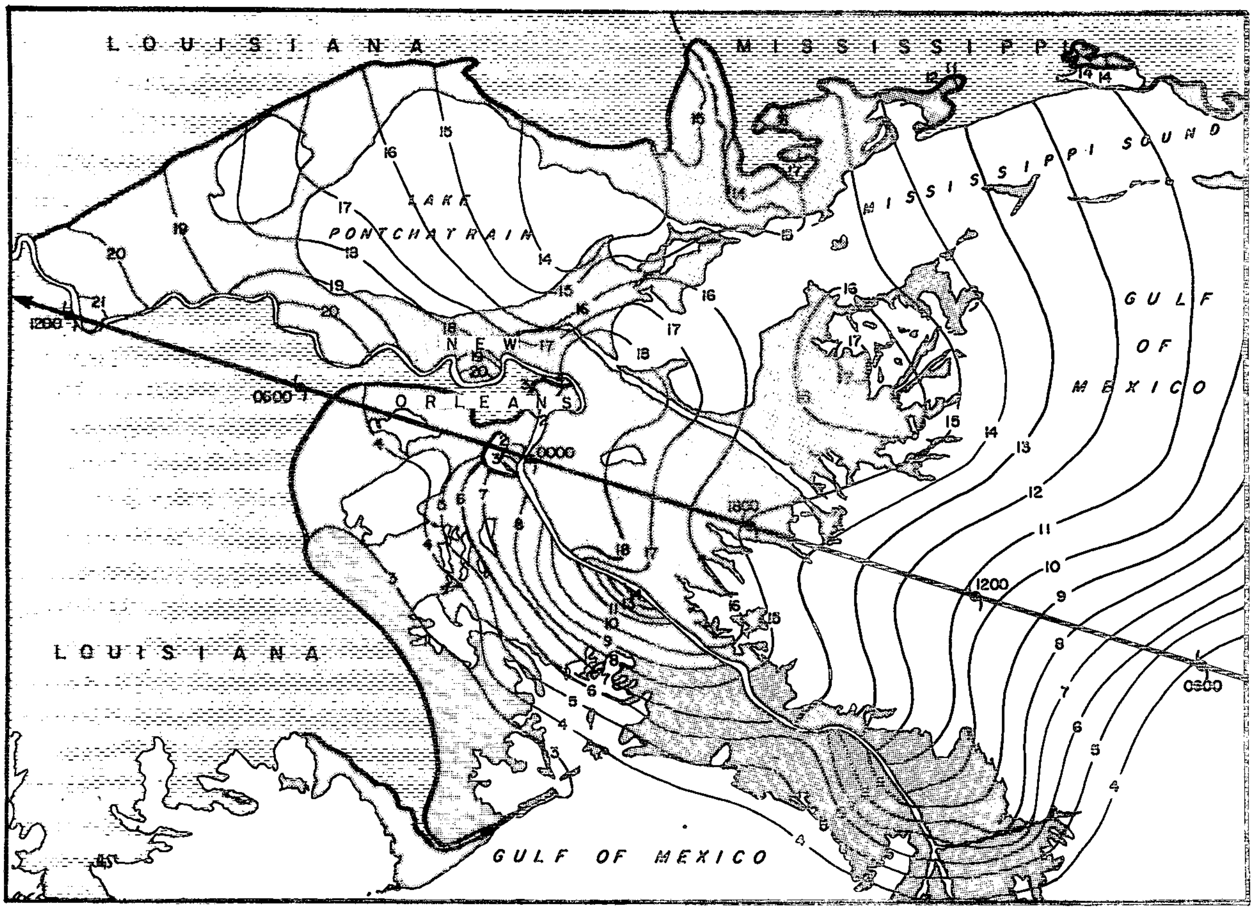


FIG. 2. (*Continued*)

see the actual threat (waters rising and winds increasing) (Simpson and Ruhl 1981). The result could be people trapped in those areas as waters cut off escape routes. This situation nearly happened for about 200 people on western Galveston Island during Hurricane Alicia of 1983.

This type of response primarily results from three major factors. First, major hurricanes are infrequent events for any given location. Second, for more than the past two decades, major hurricanes striking the United States coast have been less frequent than for the three previous decades (Fig. 3). Finally, it has been during this period of low hurricane activity that the great majority of the present coastal residents moved to the coast. The combination of these factors is illustrated in Fig. 4 which shows that property damage spiraled upward in tandem with the coastal populations until the last two decades when it leveled off. In fact, if it had not been for the more than $7 billion loss caused by Hurricane Hugo in 1989, a significant decrease in losses would have been noted. Figure 5 shows the loss of life during this period. This figure clearly demonstrates the improvement in the effectiveness of hurricane forecast, warning, and response programs since the turn of the century. Those developments are described in the following sections of this paper. However, with the tremendous increase of populations in high-risk areas along our coastlines, the concern is that we may now not fare as well in the future when hurricane activity inevitably returns to the frequencies experienced during the 1940s–60s.

2. History

a. General

The NHC has evolved from the continual efforts of the U.S. government, from the late 1800s to the present, to develop and improve warning services for storms that have been referred to as "meteorological monsters of the sea."

Records of encounters with hurricanes go back to the days of Columbus (Ludlum 1963). Dunn and Miller (1960) state that the name "hurricane" was derived from several references in various Indian dialects to monstrous storms associated with their names for storm gods, etc. There are numerous references to hurricanes in historical records of America, including studies by Benjamin Franklin who discovered that

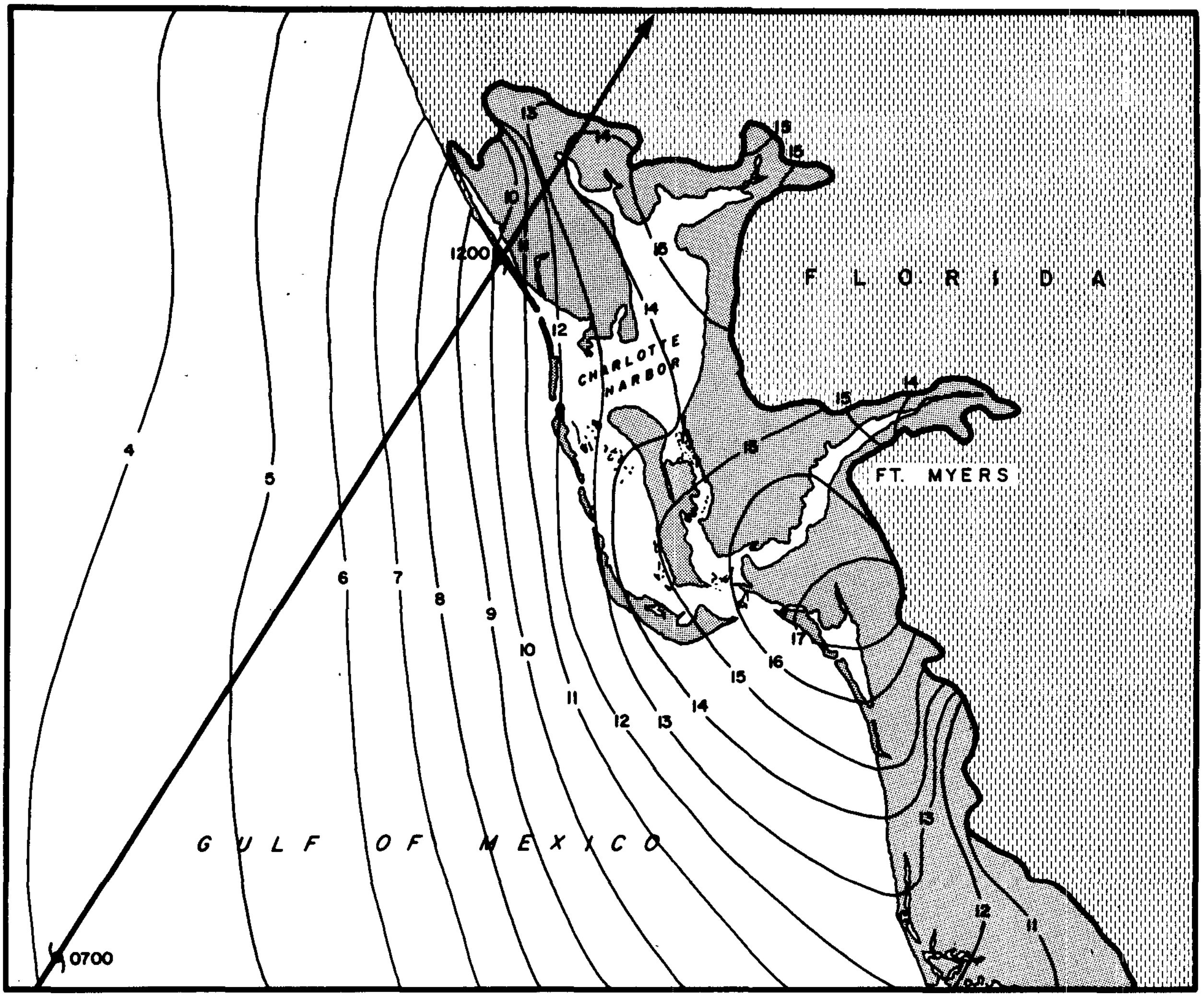
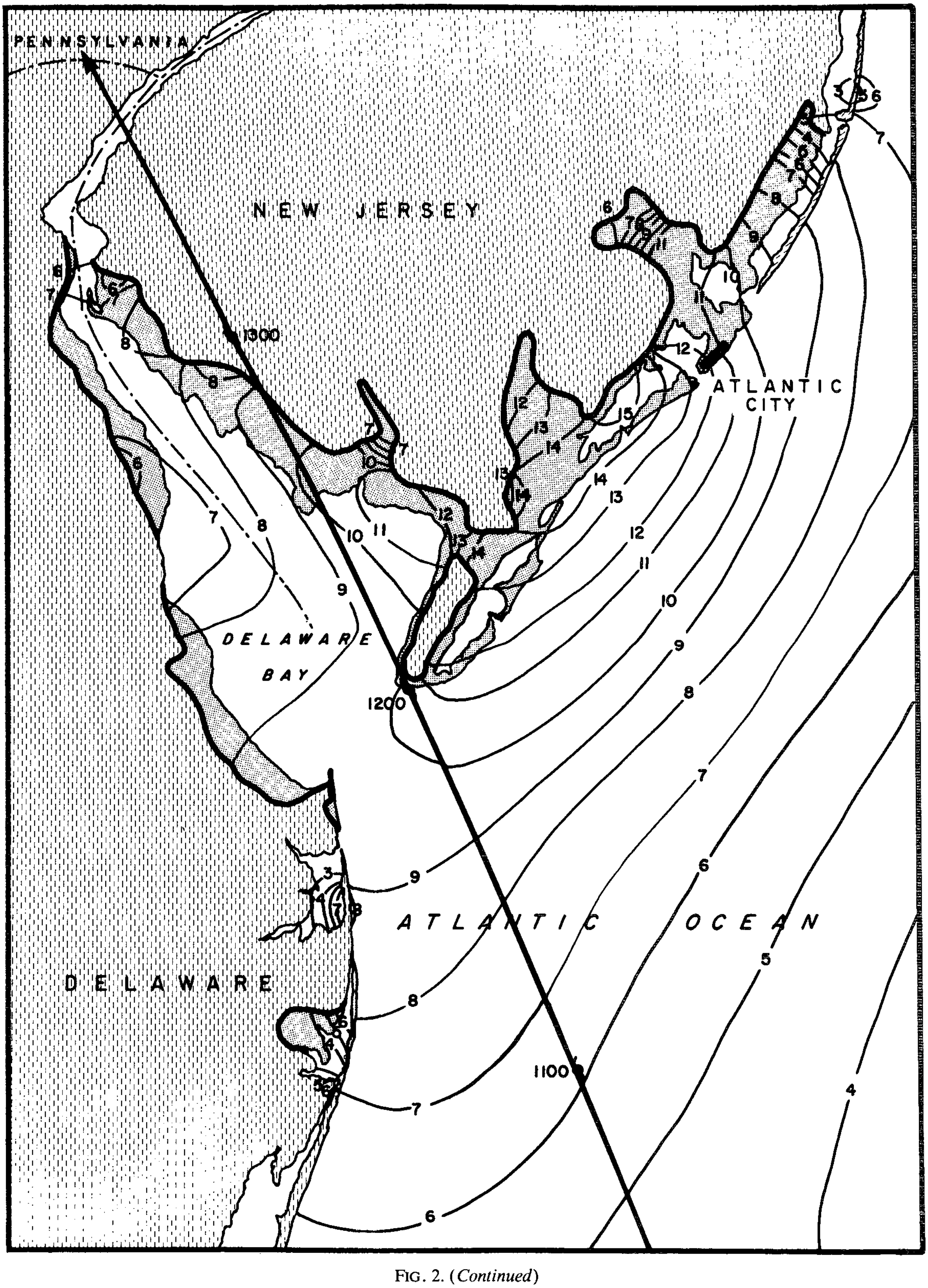


FIG. 2. (*Continued*)

hurricanes moved from one place to another, and were not "steered" by surface winds (Dunn and Miller 1960). However, it was not until 1847 that a hurricane-warning display system was first established in America. This system was established by Lt. Col. William Reid of the Royal Engineers of England while on duty in Barbados. His warning system was primarily based upon barometric readings.

Calvert (1935) states that Father Benito Vines, director of Belen College at Havana, Cuba is credited with development of the first systematic scheme for hurricane forecasts and warnings using observations of movement of upper- and lower clouds. Apparently, he routinely issued hurricane warnings starting in the early 1870s. In 1870, the U.S. Congress made appropriations for organizing a national meteorological service under the auspices of the Signal Corps of the Army. Calvert reports that this newly organized meteorological service recognized the need to provide hurricane warnings for the eastern and southern coasts of the United States. The service attempted to establish a system for receiving daily observations from islands in and around the Caribbean. It is uncertain when the first hurricane warning was issued by this new service. Calvert however, states that a warning issued on 23 August 1873, for New England and the Middle Atlantic states was probably the first for a storm of tropical origin (although it was not a hurricane).

On 16 September 1875, a strong hurricane destroyed Indianola, Texas, killing 176 people. There was little warning for this hurricane and the public's continued general dissatisfaction with the Signal Corps' weather forecasting led to the creation of the Weather Bureau in 1890 and its transfer to the Department of Agriculture (Dunn 1971). Calvert reports that several attempts were made over the next several years to establish and receive meteorological observations from various sites throughout the Caribbean. However, it was not until



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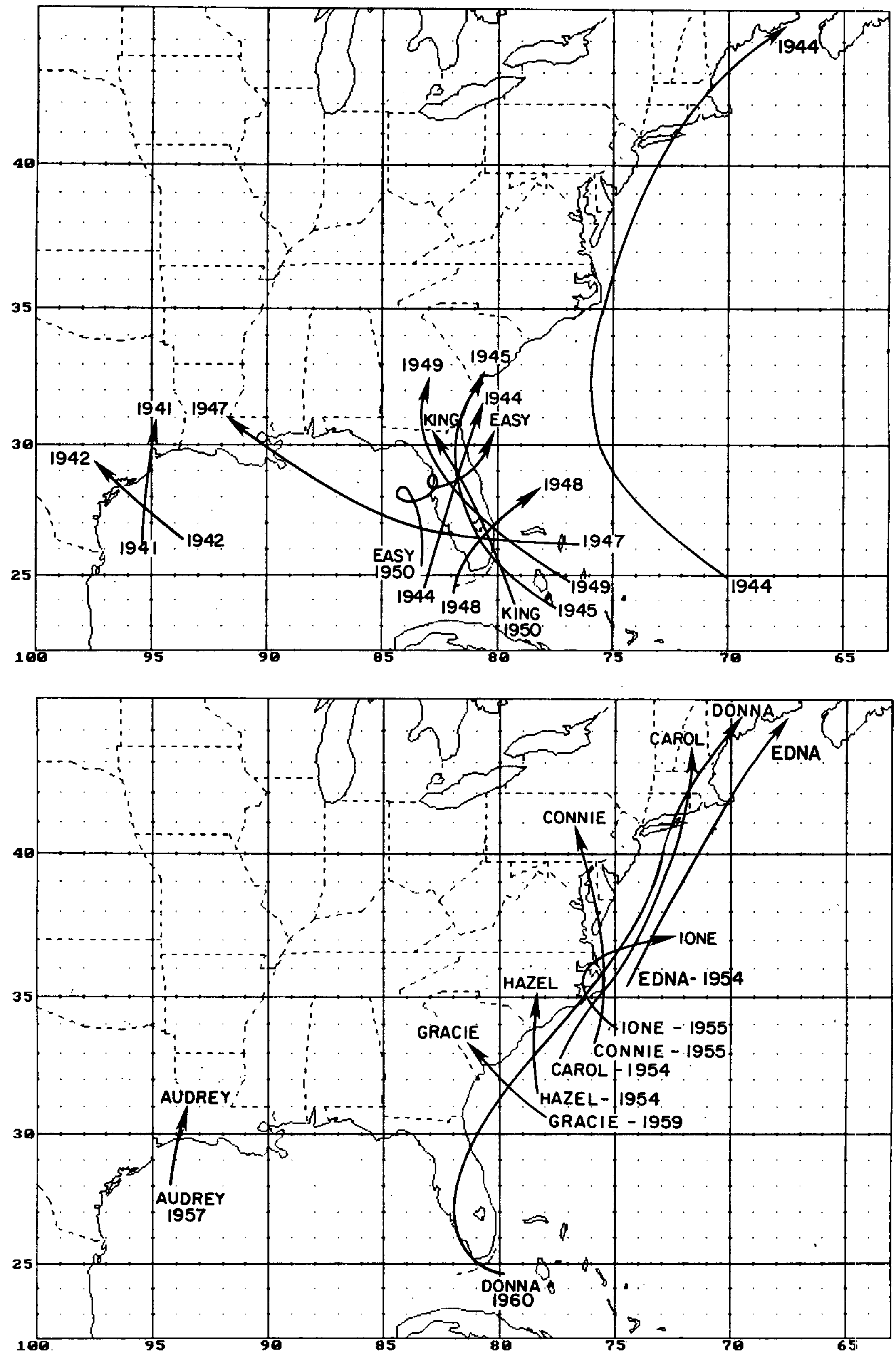
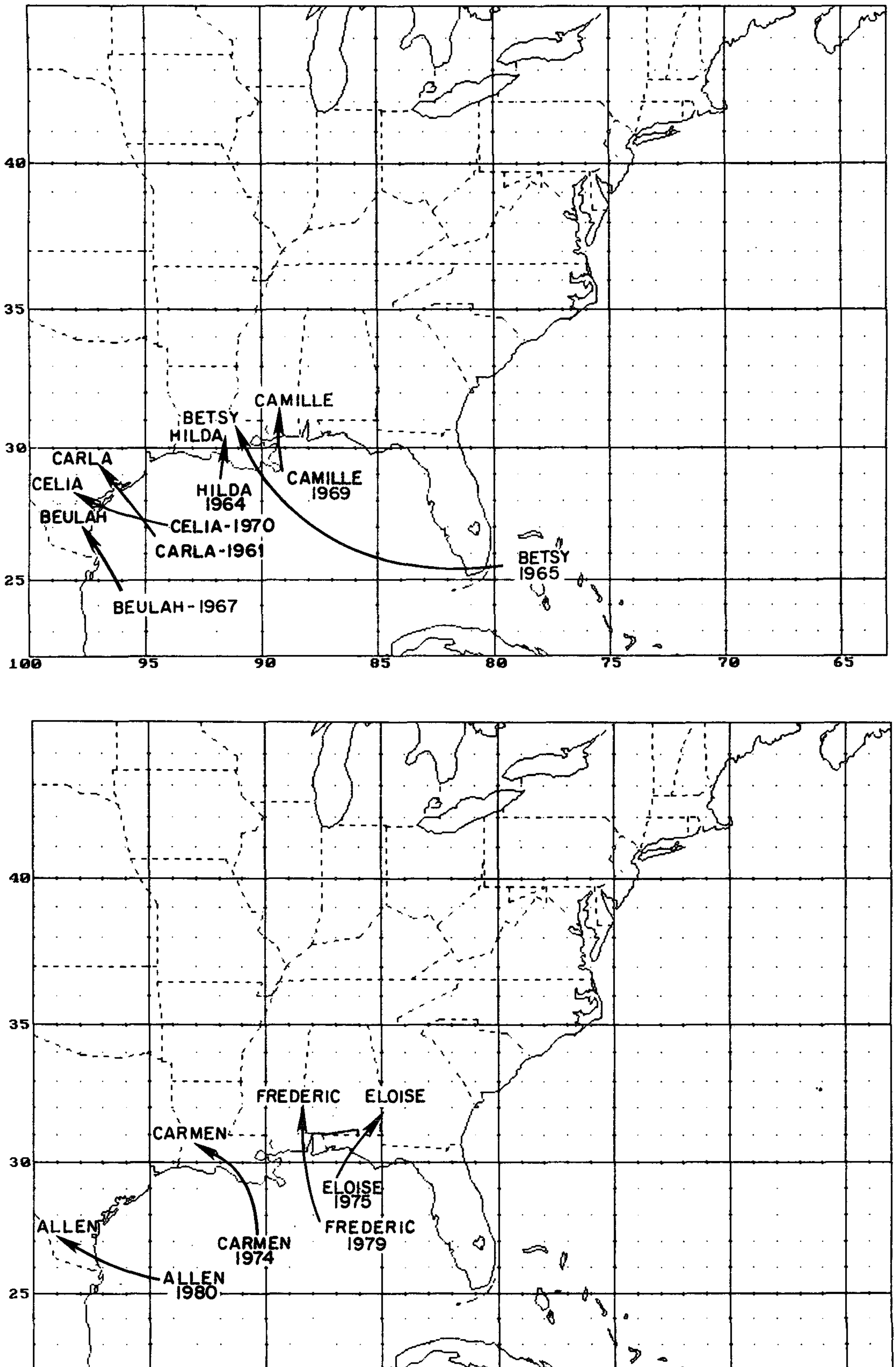


FIG. 3. Major (Saffir/Simpson-scale category-3, -4, or -5) hurricanes striking the continental United States from (a) 1941–50, (b) 1951–60, (c) 1961–70; (d) 1971–80; and (e) 1981–89 (after Hebert and Taylor 1988).



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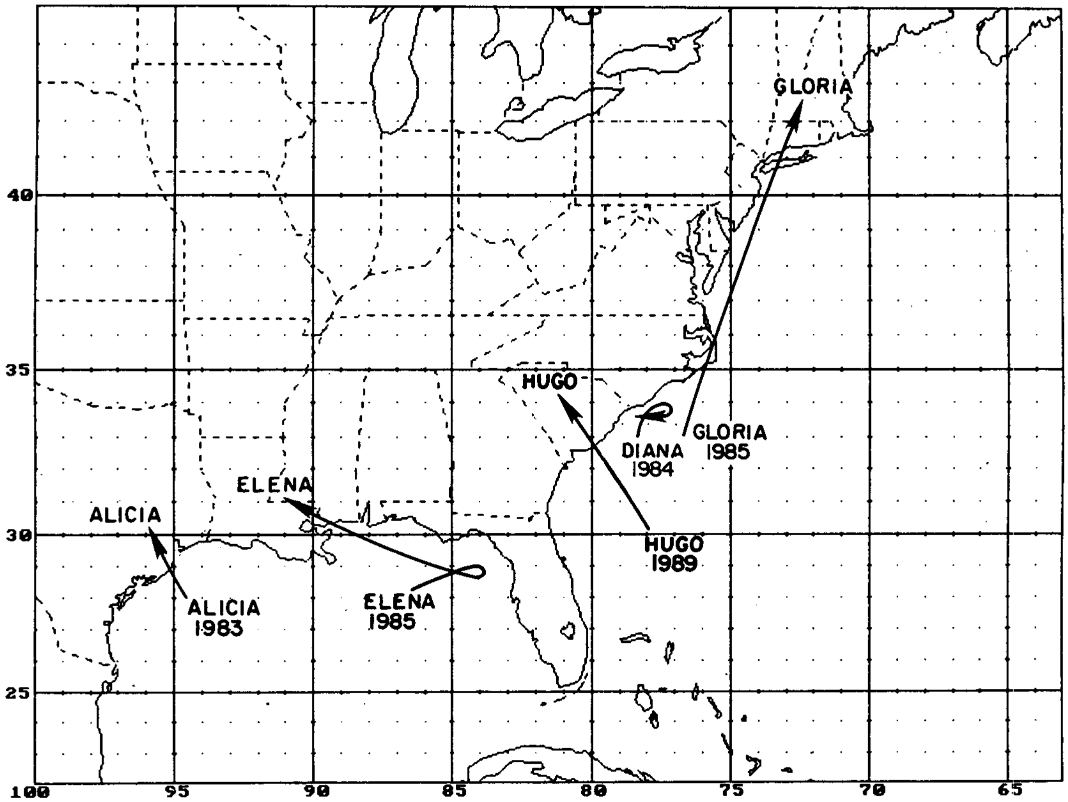


FIG. 3. (*Continued*)

the Spanish–American war in 1898, that there was a concerted effort to establish a comprehensive hurricane warning service for America. President McKinley, recalling the 1896 hurricane which killed 114 persons in the region from Florida to Pennsylvania, declared that he feared a hurricane more than the Spanish Navy (Dunn 1971). Before this time, hurricane warnings were only issued for United States coastal areas. Congress then authorized funds for establishing observing stations throughout the central and eastern Caribbean. Sites were established at Kingston, Jamaica; Port of Spain, Trinidad; Willemstad, Curacao; Santo Domingo, Santo Domingo; and Santiago de Cuba. The Weather Bureau forecasting center for the West Indies was then located at Kingston, Jamaica and provided warnings for Weather Bureau locations throughout the islands, military centers, and shipping interests.

After the war was over, other observing stations were established at San Juan, Puerto Rico, and Roseau, Dominica. On 1 February 1899, the headquarters of the forecasting service was transferred to Havana, Cuba. A system was also developed to give the entire West Indies and ships of all nationalities the benefit of the hurricane-warning service of the Weather Bureau. This recognition of international responsibility continues today under the auspices of the World Meteorological Organization (WMO).

At the turn of the century, hurricane forecast and warning services for the continental United States continued to be provided from Washington, D.C.—However, a major hurricane struck Galveston, Texas on 8–9 September 1900, killing more than 6000 people with no record of any formal hurricane warning reaching Galveston. This remains the largest natural disaster in the history of the United States. In 1902, the hurricane forecasting work of the Weather Bureau for the West Indies was transferred from Havana to Washington. In 1919, a forecast center for issuing hurricane warnings for Puerto Rico and contiguous areas was established in San Juan.

There were several instances during the late 1800s and early 1900s where communities along the hurricane-prone coasts were less than satisfied with the hurricane warning service being provided through the Weather Bureau office in Washington (Dunn 1971). There was a feeling that Washington lacked a sensitivity to hurricane problems since they were less prone to the effects of hurricanes. For instance, warnings for the hurricane that brought such devastation to Miami in 1926 were only issued as an after-thought at 2300, after most Miamians were asleep, unaware of the rapidly approaching hurricane. By the time the warnings were issued and the local meteorologist in charge was able to make his way to Miami Beach, winds were blowing

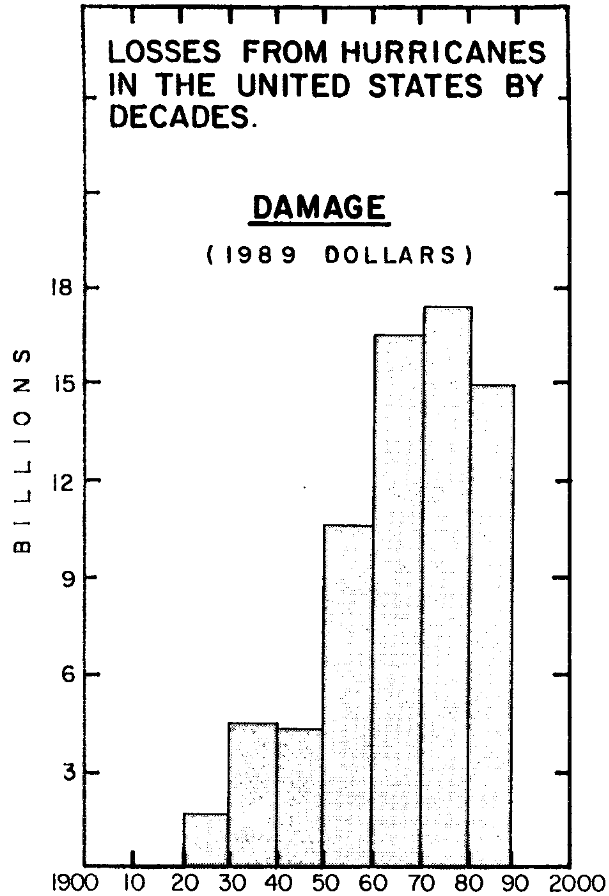


FIG. 4. Loss of property in the continental United States due to hurricanes from 1915 through 1989 (modification and update of Gentry 1974).

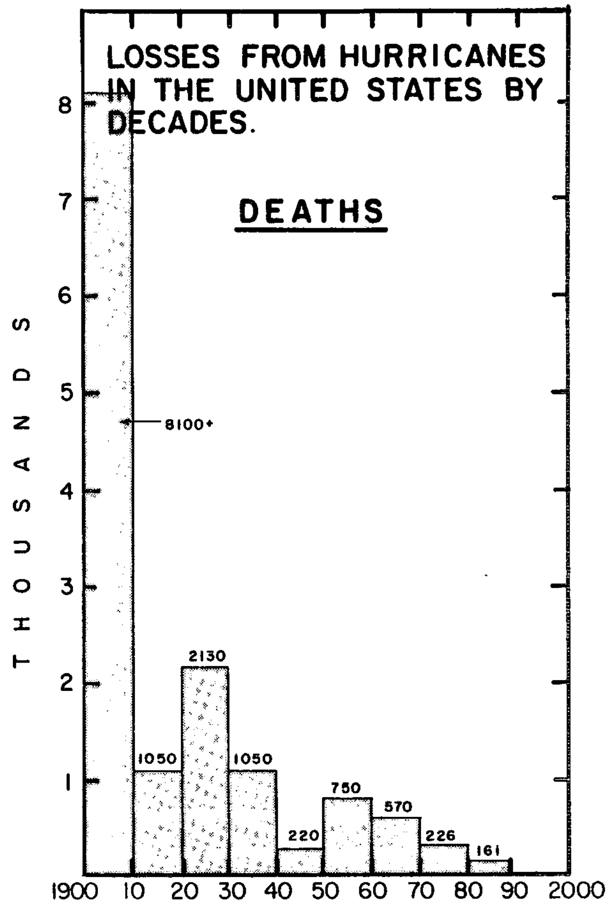


FIG. 5. Loss of life in the continental United States due to hurricanes from 1900 through 1989 (modification and update of Gentry 1974).

so hard that he required assistance to raise the hurricane warning flags. At 1 a.m., 2 hours after the warnings were issued, winds reached hurricane force along the coast.

The single incident which apparently most exemplified this lack of sensitivity occurred in 1934. Dunn states that

> A tropical storm formed in late August 1934 in the central Gulf of Mexico and on a Sunday forenoon the Washington (based) forecaster issued a hurricane warning for the Upper Texas coast. Since there would be no additional observations until 7 p.m. the forecaster, as usual, went home, planning to return in the evening to issue the regular and hurricane forecasts. In Galveston, which had continued to be a very sensitive area (to hurricane threats) since the 1900 disaster, the populace scanned the sky for indications of the forecast hurricane. It was moving more slowly than the morning advisory indicated and weather conditions remained serene. Finally, by mid afternoon, the anxious Chamber of Commerce wired the Washington Weather Bureau for the latest information. The map plotter on duty honestly but indiscreetly wired back: "Forecaster on golf course—unable to contact."
>
> In Galveston, the weather remained quiet, but temperatures in the Chamber of Commerce rose rapidly.

These incidents led Congress to appropriate \$80 000 in the 1935 budget to revamp the hurricane warning service (Calvert 1935; Dunn 1971). Improvements were to include the establishment of new hurricane forecast centers at Jacksonville, Florida; New Orleans, Louisiana; San Juan, Puerto Rico; and Boston, Massachusetts[3] and the issuance of hurricane advisories at least four times a day. San Juan would have the responsibility for the Caribbean Sea and islands east of 75°W and south of 20°N; New Orleans would be responsible for that portion of the Gulf of Mexico and its coasts west of 85°W; Jacksonville would cover the remaining portions of the Atlantic, Caribbean Sea and Gulf of Mexico areas, and associated islands and coasts

[3] The forecast center at Boston was not established until 1940.

south of 35°N; and Washington and Boston would cover the area north of 35°N. Dunn (1971) states that "Jacksonville (the only complete center of the new offices) was given two forecasters to cover all analysis and forecasting (responsibilities) 24 hours a day and 7 days a week. By the end of the first hurricane season, both forecasters were ready for hospitalization." Gordon Dunn spoke from firsthand knowledge as he was the junior assistant to Grady Norton, the chief hurricane forecaster at this office.

In 1943, the primary hurricane forecast office at Jacksonville was moved to Miami where the Weather Bureau, Air Corps, and Navy established a joint hurricane warning service under the direction of Norton. After the end of World War II, the Air Corps withdrew from the hurricane forecast operations and the Navy established an independent forecast office. The Navy unit however, remained co-located with the Weather Bureau's Miami hurricane forecast office until 1964 when the Navy unit was moved to Jacksonville, Florida. Norton continued as the meteorologist in charge of the Miami forecast office and the hurricane forecast center until his death in 1954 during Hurricane Hazel. He had established a strong reputation as an extraordinary forecaster with the ability to communicate with residents along the coast, and he is still remembered with great admiration and affection by the long-time residents of south Florida as well as by his colleagues (Burpee 1988).

Dunn, who at the time was the meteorologist-in-charge (MIC) at Chicago, was selected as the new meteorologist-in-charge at the Miami forecast office. In 1955, the Miami forecast office was officially designated as the NHC with Dunn as its first director. However, most people, including Dunn, recognize Norton as the first director of the NHC even though it had not been officially designated as such during his tenure.

In 1965, a plan was developed under the direction of George P. Cressman, director of the Weather Bureau ". . . for use as a Weather Bureau guide in the orderly implementation of an improved nation-wide Hurricane Warning Service" (Weather Bureau 1966a). This plan called for a program to

1) prevent the increasing magnitude of economic disasters which can result from possible underwarning of an erratic storm or flash flood;
2) minimize the excessive preparation costs resulting from overwarning;
3) provide completely reliable service during storm emergencies;
4) offset the potential danger of public apathy.

The decision was made to concentrate the national hurricane warning service in one office at the NHC.[4] Dunn was named as director of the National Hurricane Warning Service for the Atlantic basin (Weather Bureau 1966b). In addition, a 21-person Tropical Analysis Center was established at NHC in the fall of 1965 under the leadership of David Shideler. This unit conducted analyses and prepared prognoses from 40°N to 40°S from Central Africa westward through the eastern Pacific and was later redesignated the Regional Center for Tropical Meteorology under the WMO. In addition, the plan called for the establishment of six full-time hurricane specialist positions at NHC and two similar positions at the Weather Bureau offices in San Francisco and Honolulu.

The Weather Bureau had the primary responsibility for all tropical cyclone forecasts and warnings for all United States interests, including the Department of Defense (DoD), from Africa westward through the central Pacific. The Joint Typhoon Warning Center of DoD in Guam provided warnings for United States civilian interests in the western Pacific. Those responsibilities continue today. There were similar international responsibilities under the WMO for these same regions where the NHC provided tropical cyclone forecast and warning guidance and, in fact, directly issued warnings for several countries throughout the Caribbean region and Central America. As meteorological services improved in the region, the number of countries requiring the direct issuance of warnings from NHC decreased.

The net effect of the consolidation of the Weather Bureau hurricane warning service was that all hurricane-track and intensity forecasts for the Atlantic basin, which includes the Caribbean Sea and the Gulf of Mexico, became the responsibility of NHC. Tropical cyclones in the eastern Pacific east of 140°W and the central Pacific from 140°W to the dateline were the responsibility of the Weather Bureau hurricane warning offices in San Francisco[5] and Honolulu,[6] respectively. The former hurricane forecast offices at San Juan, New Orleans, Washington, and Boston now became hurricane warning offices. They continued to write public advisories and issue warnings for their respective areas after coordination with NHC and do other hurricane related work such as hurricane preparedness and coordination activities, but no longer prepared the "official" track and intensity forecasts.

During 1967, Dunn announced his retirement for the end of the 1967 hurricane season. His tenure was marked by an increased emphasis upon public awareness of hurricane threat, and improved international cooperation, including training and upgrading of meteorological services throughout the Caribbean. The staff of the Miami office had grown to 83 people by this time, with greatly increased responsibilities com-

[4] Report of the 1966 Interdepartmental Hurricane Warning Conference, Atlantic

[5] Later renamed eastern Pacific Hurricane Center.
[6] Later renamed central Pacific Hurricane Center.

pared to those at the inception of the NHC in 1955. Robert H. Simpson, associate director of the WB was selected to succeed Dunn. Dunn and Simpson worked side by side during the hurricane season of 1967.

Simpson served as director of NHC from 1968 through 1973. During this period, he placed a renewed emphasis upon research and development activities at NHC including establishment of small Research and Development and Satellite Applications Units (SAU) under the leadership of Banner I. Miller and Donald C. Gaby, respectively. Considerable progress was made in development of statistical and statistical/dynamical models as forecast aids during this period. Also, applications of satellite technology received special emphasis. The SAU became a Satellite Field Service Station (SFSS) under the National Environmental Satellite Services (NESS) in 1973. Ten operational meteorologists and other support personnel were assigned to this unit, bringing the total staff level at the NHC complex to more than 100 people. During this same period, NOAA was created on 3 October 1970 and the Weather Bureau became the NWS.

Simpson retired after the 1973 hurricane season and was succeeded by Neil L. Frank. Frank placed a renewed emphasis upon hurricane preparedness, making numerous talks along the hurricane-prone coasts each year. He realized that with the rapid growth of the Gulf of Mexico and Atlantic coastal populations, and the continued influx of new residents with little appreciation of the hurricane threat, many people could be trapped on barrier islands in the event of a major hurricane. Furthermore, few people (including responsible local officials) in these high-risk areas had actually experienced a major hurricane (Hebert et al. 1984). Also, no one really knew just how much time was required to evacuate these vulnerable areas in the event of a hurricane. Local community preparedness plans were marginal at best. Considering these factors and having personally surveyed numerous developments along the Gulf and Atlantic coasts (Frank 1974a), Frank visualized the possibility of a repeat of the Great Galveston Hurricane tragedy of 1900. To correct the situation, he decided to attempt to substitute education for experience. Also, storm surge models were employed in an attempt to define the degree of the problem. The primary legacy of Frank to the hurricane warning service is a heightened awareness of the hurricane problem, much improved local action plans, and the use of the electronic media to motivate people in threatened areas to respond positively during a hurricane threat.

During the 1970s, meteorological satellites became the primary observing tool for tropical analyses at NHC. By 1982, the Satellite Field Service Station was combined with the Regional Center for Tropical Meteorology under Mark Zimmer to form the Tropical Satellite Analysis Center at NHC. During this period, many of the manual tasks, such as routine plotting and analyzing of various charts, were automated. Some manual analyses continue today due to sparsity of quantitative data over the tropics and the need to integrate qualititive satellite observations into the quantitative analyses. The result of these changes was a reduction in the number of the staff and greater computerization of product generation and issuance.

Beginning in 1980, all hurricane advisories for the Atlantic basin, including public advisories, which had formerly been issued by Hurricane Warning Offices at San Juan, New Orleans, Washington, and Boston, were issued by the NHC. Administrative changes in 1984 resulted in NHC being separated from the NWS Southern Region and placed under the NMC. This process also involved the division of NHC into a smaller office with a separate, co-located, Weather Service Forecast Office (WSFO) with Paul J. Hebert as its MIC and area manager. Atlantic, Caribbean Sea, and Gulf of Mexico high-seas forecast responsibilities were retained by the WSFO with satellite and analysis support provided by the NHC. These changes reduced the staff of the NHC from almost 100 people to 37. The WSFO staff consisted of 29 people. The WSFO Public Service and Radar and Electronic Technician Units were to continue providing support for the NHC.

Frank retired as director of NHC in early June 1987, and was succeeded by the author in an acting capacity. In March 1988, the author was selected as director of NHC. During this same period, other changes were taking place at NHC as part of the modernization and restructuring of the NWS. Responsibility for Satellite Interpretation Messages (SIMS) and sea surface analyses for the Gulf of Mexico were transferred from the New Orleans WSFO to the NHC in the spring of 1987. In the spring of 1988, the responsibility for tropical cyclone forecasts and warnings, and tropical weather discussions for the eastern Pacific basin was transferred from the WSFO in San Francisco to the NHC. In 1989, the high-seas forecast responsibility for the tropical belt (equator to 30°N) from Africa to 140°W (Atlantic and eastern Pacific basins) was transferred from the WSFO's in San Francisco and Miami to the NHC. In addition, aviation forecast responsibilities for the Atlantic, Caribbean, Gulf of Mexico, and portions of the eastern Pacific formerly performed by the WSFO's in Miami and San Francisco were transferred to NHC resulting in a current staff level of 40 people.

b. Observational, data processing, and communications systems

A summary of the implementation of observational systems in the Atlantic basin is shown in Fig. 6. The following sections describe those and related systems and their evolution for operational use.

1) DATA PROCESSING AND COMMUNICATIONS

As indicated in subsection 2a, hurricane forecast and warning programs were seriously hampered for many

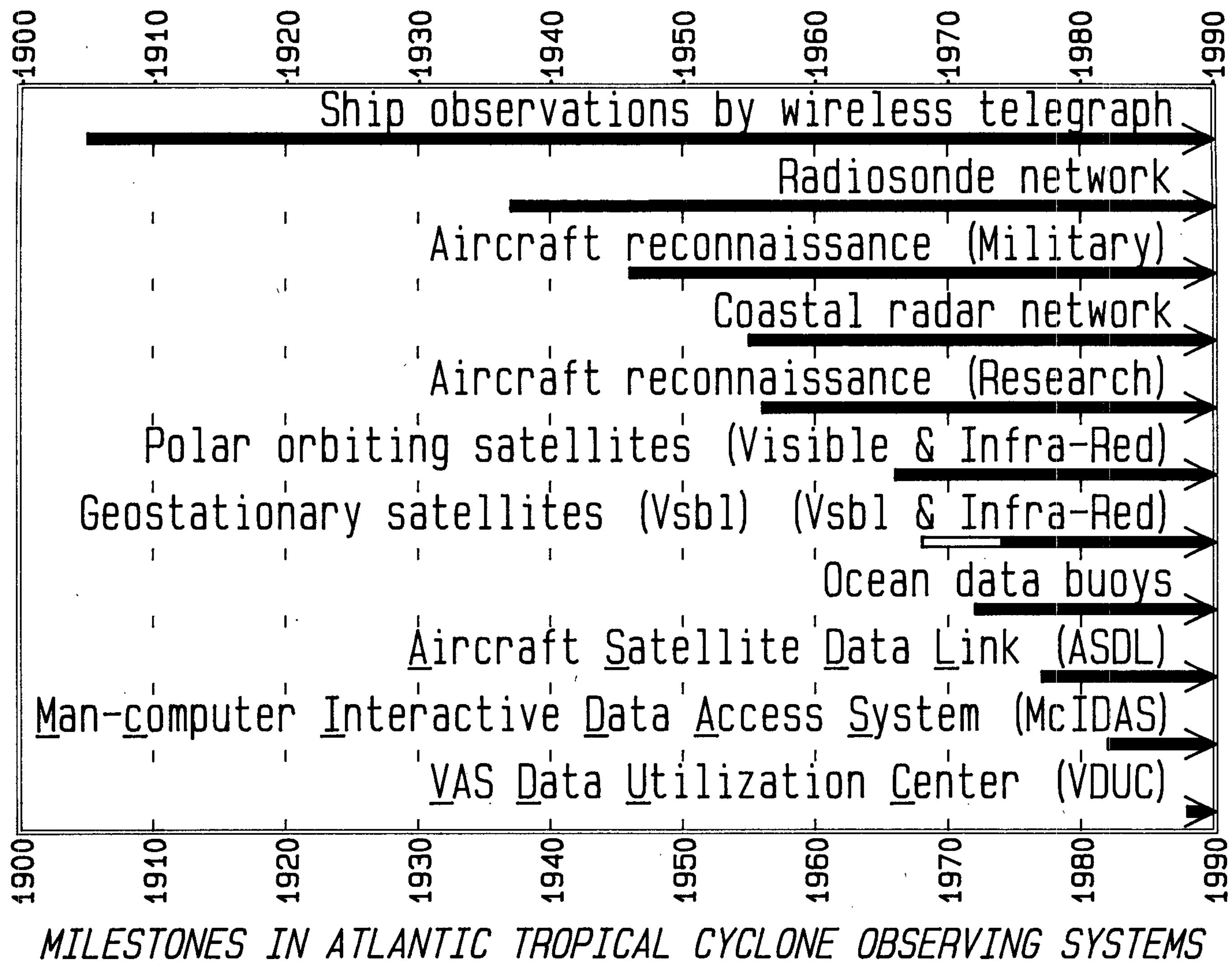


FIG. 6. Milestones in Atlantic basin tropical cyclone observing systems (courtesy of C. Neuman, NHC).

years by lack of observations and the ability to communicate observations and warnings between the forecast offices and field locations. Telegraph systems were used in the late 1800s to receive daily observations from a few locations in the Caribbean and along the Atlantic and Gulf coasts (Calvert 1935). In the early 1900s, the development of the radio permitted a great step forward in the ability to collect observations from and communicate information to ships at sea.[7]

The special appropriation by Congress in 1935 resulted in the establishment of

> a unique . . . teletypewriter set-up during the five active hurricane months . . . designed for speedy collection of observations from lifesaving storm warning stations, the distribution of land and ship reports from one forecast center to the other, including intervening first-order stations, and immediate dissemination of warnings and advices to the entire coastal area. This teletype circuit will connect the WB forecast centers at Jacksonville and New Orleans and its offices at Tampa, Miami, Key West, Pensacola, Mobile, Port Arthur, Houston, Galveston, Corpus Christi, and Brownsville. The teletype circuit will operate 24 hours a day, every day in the week, including Sundays and holidays, and will be used exclusively by the Weather Bureau (Calvert 1935).

Unfortunately, there was a shortfall in the appropriation. The circuit was completed as indicated above, but was terminated at Jacksonville with no link northward along the Atlantic coast to the home office in Washington (Dunn 1971). From time to time, more money was appropriated. The next major step was the establishment in 1937 of a radiosonde network and

[7] Reports from ships remain a very important part of tropical analyses and hurricane warning programs around the world today.

"hurricane forecasters for the first time were able to analyze, to some extent, the tropospheric currents which steer the hurricane" (Dunn 1971).

Teletypewriter systems remained the primary means of communications for the NWS to receive and transmit data and forecast information through the late 1970s. At that time, the NWS introduced the Automation of Field Operations and Services (AFOS) system (Friday 1983) as its primary means of data handling, display, and message composition and transmission. This system permits computer displays of most conventional meteorological data in numerical and graphical form, graphical output of NMC analysis and forecast guidance products potentially displayed in animated form, message composition, etc. The AFOS system remains the primary NWS analysis and communications system today, supplemented more recently by personal computers linked to the basic AFOS system.

At the NHC, several other means of receiving, processing, analyzing and displaying of information have been utilized since the mid-1960s. Primary among these have been the means of receiving and displaying satellite imagery and digital data. In the mid-1960s, an Automatic Picture Transmission (APT) receiving system was installed at NHC. Later, Muirhead recorders provided photographic imagery from the geosynchronous satellites and these images were animated using 16-mm film loops. In the late 1970s, the Muirhead recorders were phased out and UNIFAX paper copy receivers were installed. Animation was then provided through an Electronic Animation System (EAS) utilizing a TV camera to transfer hand-registered hard copy prints to a hard disk device. Nearly simultaneously, NHC received an Interactive Processing System (IPS) electronic looping device where analog signals received via a single land line were automatically received, displayed, and animated.

In 1983, a work station connected to the University of Wisconsin Man Computer Interactive Data Access System (McIDAS) was put into operation at NHC. This system had capabilities for the processing, displaying, enhancing, and animating of satellite data; overlaying data and analyses, etc.—far exceeding the capabilities of previous systems available at NHC. It quickly became the most utilized piece of equipment at NHC. In 1986, the standard Satellite Weather Information System (SWIS) was installed at NHC permitting reception of digital data and various enhancements and displays. In 1987, the McIDAS terminal previously connected to the University of Wisconsin system was connected to the VAS Data Utilization Center (VDUC) newly installed at NMC/NESDIS in Washington. In early 1989, an IBM 4381-P23 was installed at NHC and linked to direct satellite-receiving antennas. The two McIDAS work stations were switched to this in-house system in March 1989. Additional work stations were installed over the next few months, resulting in a complete VDUC system at NHC.

Computer operations progressed slowly at NHC until the middle 1970s. All locally generated analyses were hand plotted and analyzed up until the mid- to late 1960s. In 1965, the NHC, co-located with National Hurricane Research Laboratory (NHRL) at the Computer Center on the University of Miami campus, started to use the University computer to develop analysis techniques. In the early 1970s, NHC obtained a terminal connected to the ESSA (later NOAA) central computer CDC 6600 located in Washington, D.C. Also, in the early 1970s, NHC obtained a minicomputer for local processing and later plotting and analyzing of maps. That process continues today. In 1989, NHC entered a new era with the installation of the main frame IBM 4381-P23. The use of this system will be discussed in subsection 3.

2) AIRCRAFT RECONNAISSANCE

(i) *Air Force.* The first recorded premeditated flight into the eye of a hurricane was conducted by Col. Joseph P. Duckworth on 27 July 1943 (Markus, et al. 1987). Duckworth made two flights into the hurricane located off Galveston, Texas on that day. The aircraft used was a propeller-driven, single engine North American AT-6 "Texan" trainer. On the first flight, Duckworth was accompanied by Lieutenant O'Hair, a navigator and, on the second flight, by an unnamed weather officer. "Thus began one of the U.S. Air Force's largest, continuing, humanitarian efforts—the tropical cyclone reconnaissance mission of Air Force weather reconnaissance units" (AWS historical files). The major impetus for the establishment of regular reconnaissance flights into tropical cyclones resulted from massive losses suffered by the U.S. Navy as a result of encounters with two typhoons during World War II (Adamson and Kosco 1967). The formal establishment of this service was instituted on 14 February 1944, and regular flights including eye penetrations began that season by AAF Weather Service and Navy aircraft. These units later became known as the famous "Hurricane Hunters." The Army Air Force (AAF) initially flew B-24's in this mission and in 1946 switched to four-engine propeller-driven WB-29's. These aircraft were replaced by WB-50's in the mid-1950s, and in the early and mid-1960s the WC-130's became the primary aircraft used by Air Force units in tropical cyclone reconnaissance.

Two of these early Air Force units evolved into the 53rd Weather Reconnaissance Squadron (WRS) operating from various bases in the Atlantic basin over the years (Ramey AFB, Puerto Rico; Patrick AFB, Florida; Shaw AFB, South Carolina; and finally Keesler AFB, Mississippi) and the 54th WRS operating from Anderson AFB, Guam. They were joined by the 815th WRS "Storm Trackers" Air Force reserve unit in 1973, flying from Keesler AFB. That unit and the 53rd remain as the only DoD units flying tropical cyclone reconnaissance today. They utilize WC-130 "E"- and "H"-model four-engine turboprop aircraft in these operations with normal flight levels of 10 000 ft in hurricanes and 1500 ft for less intense systems.

Instrumentation on board these aircraft evolved from drift meters to Doppler radar systems for navigation and wind computations to Omega assisted Inertial Navigation Systems (INS). The later system was first installed on a prototype Advanced Weather Reconnaissance System (AWRS) built in 1970 in response to direction from the president and Congress after the disaster of Hurricane Camille (1969). Reconnaissance aircraft at that time were equipped with Doppler navigation systems for determining the displacement of the aircraft relative to the earth for wind computations. In that situation, the Doppler beams occasionally locked on to the moving precipitation and spray, rather than the fixed earth, resulting in erroneous Doppler shift information. Therefore, they were not able to provide accurate wind measurements in the intense part of the hurricane. In addition, the aging Navy aircraft (Super Constellations) were not considered safe enough to fly through the core of this strong hurricane, resulting in critical periods when reconnaissance data were not available to the hurricane forecasters at NHC. The AWRS cost a little over $16 million to develop to military specifications. It later proved so cumbersome to maintain and operate that it was taken out of operational use. Efforts continued to upgrade instrumentation on the Air Force fleet using modern computer technology. The Office of the Federal Coordinator under the direction of William S. Barney, and later, Robert Carnahan provided direction and financial support for these efforts. The assistance of Col. Charles B. Coleman, commander of the 920th Weather Reconnaissance Group, was especially critical in the early 1980s in permitting "proof of concept" installations on a reserve aircraft. These efforts have culminated in an Air Force program which now has several aircraft equipped with portions of an Improved Weather Reconnaissance System (IWRS). The entire fleet is scheduled for installation of complete systems by the end of 1990. Capabilities include nearly instantaneous satellite data links providing high density and high accuracy data transmitted from the computers aboard the aircraft in the storm to the computers at the NHC.

(ii) *Navy.* The first Navy aircraft reconnaissance units were formed as a direct result of Admiral Halsey's encounters with typhoons in 1944 and 1945. These units were formed in 1946 and were called VPW-1, -2, and -3. Units were stationed in Miami, the Philippines, and Guam, utilizing four-engine propeller driven PB4Y2 aircraft (Navy version of the B-24). In 1953 the Navy started using twin-engine P2V's in addition to the PB4Y2's. In the late 1950s, these aircraft were replaced by the famed four-engine Super Constellation aircraft and finally, in 1972 by WP3A's. The increased use of weather satellites and the availability of data buoys in the early 1970s minimized the need for routine "synoptic track" flights over the Atlantic, Gulf of Mexico, Caribbean and eastern North Pacific and permitted more selective use of reconnaissance aircraft into storms. The result was that there was no longer a need for two large operational units to conduct necessary tropical cyclone reconnaissance. Therefore, in 1974, the Navy disbanded its weather reconnaissance fleet, leaving the primary operational responsibility in the hands of the Air Force.

(iii) *Commerce.* In 1955, Simpson established the National Hurricane Research Project (NHRP) in response to disasters caused by Hurricanes Carol, Edna, and Hazel (1954) and Connie and Diane (1955), to investigate the structure of hurricanes and develop improved forecasting techniques (Staff, NHRP 1956). Aircraft and people were assembled at West Palm Beach, Florida in 1956 to begin field operations (Simpson 1980). The aircraft fleet consisted of two TB-50A, four-engine, propeller-driven aircraft (comparable to the WB-50's used operationally by the AWS and one B-47B turbojet powered aircraft. These specially instrumented planes were operated and maintained by the AWS (Hilleary and Christensen 1957). At the end of the 1958 hurricane season, the Air Force withdrew support of the flight operations. In April 1959, the operations of the project were moved to Miami to be co-located with NHC. In 1960, the Department of Commerce purchased two used, four-engine, propeller-driven DC-6 aircraft and obtained a WB-57 on loan from the Air Force. At this time, the aircraft operations were separated from the NHRP to form the Research Flight Facility (RFF) and moved to Miami International Airport.[8]

The use of the WB-57 aircraft was discontinued in 1971 as it proved too costly to operate and maintain for the limited amount of reliable data that was being obtained from its use. In 1973, a WC-130B was also obtained on loan from the Air Force (Gentry 1980). Also, in 1973, Congress appropriated $30 million to be spread over the next 3 years to upgrade the research aircraft fleet and their instrumentation. This appropriation was primarily in support of a research program entitled Project Stormfury (Gentry 1974; Sheets 1981) which was investigating possible means for reducing the strength of mature hurricanes. Two WP-3's with state-of-the-art instrumentation were obtained as a result of this funding and put into operation in 1976 and

[8] This organization, and its successors over the years has provided field support for numerous atmospheric research projects other than hurricanes. Thus, a broad spectrum of the meteorological community has directly benefited from assets generated in response to the hurricane problem.

1977. Also, as part of this process, the RFF was restructured and renamed the Research Facilities Center (RFC) in 1975. These new flying laboratories marked the beginning of a new era in hurricane research and hurricane reconnaissance (Sheets 1978). The DC-6's were phased out of operation in 1975 and the C-130 was returned to the Air Force in 1982. In 1983, the RFC was restructured again with various functions added and renamed the Office of Aircraft Operations (OAO) of NOAA. In 1989, it was renamed the Aircraft Operations Center (AOC).

The co-location of the NHRP (under the directorship of R. Cecil Gentry) with the NHC provided major benefits for both organizations. Close working relationships developed between the researchers and the operational meteorologists over the years with special emphasis upon meeting operational forecast needs. In 1965, the NHRP became the National Hurricane Research Laboratory (NHRL). Several other changes in organizational structure and unit name have occurred over the years and it is now known as the Hurricane Research Division (HRD) of the Atlantic Oceanographic and Meteorological Laboratory (AOML). Directors of this organization have been Robert H. Simpson (1956–58), R. Cecil Gentry (1959–74), Noel E. LaSeur (1975–77) and Stanley L. Rosenthal (1977–present). It remained co-located with NHC from 1959 until 1983.

The combination of the NHRL [now Hurricane Research Department (HRD)] and the AOC (formerly RFF, RFC, and OAO) have made considerable contributions to the operational hurricane forecast and warning programs, utilizing these aircraft reconnaissance systems. Major contributions have been in the area of improved understanding of the structure and characteristics of the hurricane (LaSeur and Hawkins 1963; Shea and Gray 1973; Hawkins and Imbembo 1976; Colon 1980; Anthes 1982; Sheets 1982; Powell 1987; Willoughby et al. 1982; Marks and Houze 1987). In addition, these units have developed and/or applied new instrumentation for improved measurements and transmission of data from the reconnaissance aircraft in the hurricane to the operational center. One of the major accomplishments in this area was the development and implementation of an Aircraft Satellite Data Link (ASDL) on NOAA's research aircraft to NHC (Pifer, et al. 1978; Parrish et al. 1984). Until the implementation of this system, data were transmitted by radio/voice links.[9] Such links highly limited the information that could be transmitted. Figure 7 is an example of the wind field plotted out at NHC from data received through this satellite link superimposed on digitized radar data obtained aboard NOAA's research aircraft during hurricane Gilbert (1988). Figure 8 shows a vertical radar display for the same flight. These types of radar data will soon become available to the forecaster in real time.

3) METEOROLOGICAL SATELLITES

The greatest single advancement in observing tools for tropical meteorology was unquestionably the advent of the geosynchronous meteorological satellite. If there was a choice of only one observing tool for use in meeting the responsibilities of the NHC, the author would clearly choose the geosynchronous satellite with its present day associated accessing, processing, and displaying systems available at NHC. The very nature of the tropics and subtropics with vast oceanic areas limit the availability of conventional observations, particularly upper-air data. For instance, there is only one upper-air station for more than 4 million miles^2 for the tropical and subtropical Atlantic between the southeast United States and Africa. By comparison, there is one upper-air station for approximately every 40 000 miles^2 over the continental United States. Thus, the needs for meteorological data over the tropical and subtropical regions must primarily be met by meteorological satellites.

The first United States meteorological satellite (*TIROS 1*) was launched on 1 April 1960 (Johnson et al. 1976). This research satellite primarily provided cloud cover photography. *NIMBUS-1,* launched 28 August 1964 provided the first High-Resolution Infrared Radiometer for night pictures. On 10 September 1965, the first *Air Force Defense Meteorological Satellite Program* (*DMSP*) was launched (Markus et al. 1987). *ESSA-1,* launched February 3, 1966 became the first operational satellite and carried two wide-angle TV cameras. *ESSA-2* launched 25 days later carried Automatic Picture Transmission (APT) cameras and the era of heavy reliance upon satellite data for operational tropical (and other) meteorological analysis and forecasting began. The next major advancement was the launch of the experimental *Applications Technology Satellite* (*ATS*) in a geosynchronous orbit on 6 December 1966. This satellite contained a "spin-scan" camera invented by Verner E. Suomi at the University of Wisconsin. This technology evolved into the first *Geostationary Operational Environmental Satellite* (GOES) on 16 October 1975 which routinely produces images that span the entire hemisphere at 30-min intervals. The GOES system remains the backbone of tropical meteorological observations and analysis today.

Polar-orbiting satellites operating at lower altitudes provide superior spatial resolution and sounding capabilities as compared to geostationary satellites, but suffer greatly from a lack of temporal resolution. Barrett and Martin (1981) provide an excellent summary of

[9] In the early 1970's, the Navy had experimented with a Data Acquisition and Logging System (DALS) which involved manual entering of data on a paper tape, and then transmission through a radio system with mixed results (NHOP 1971).

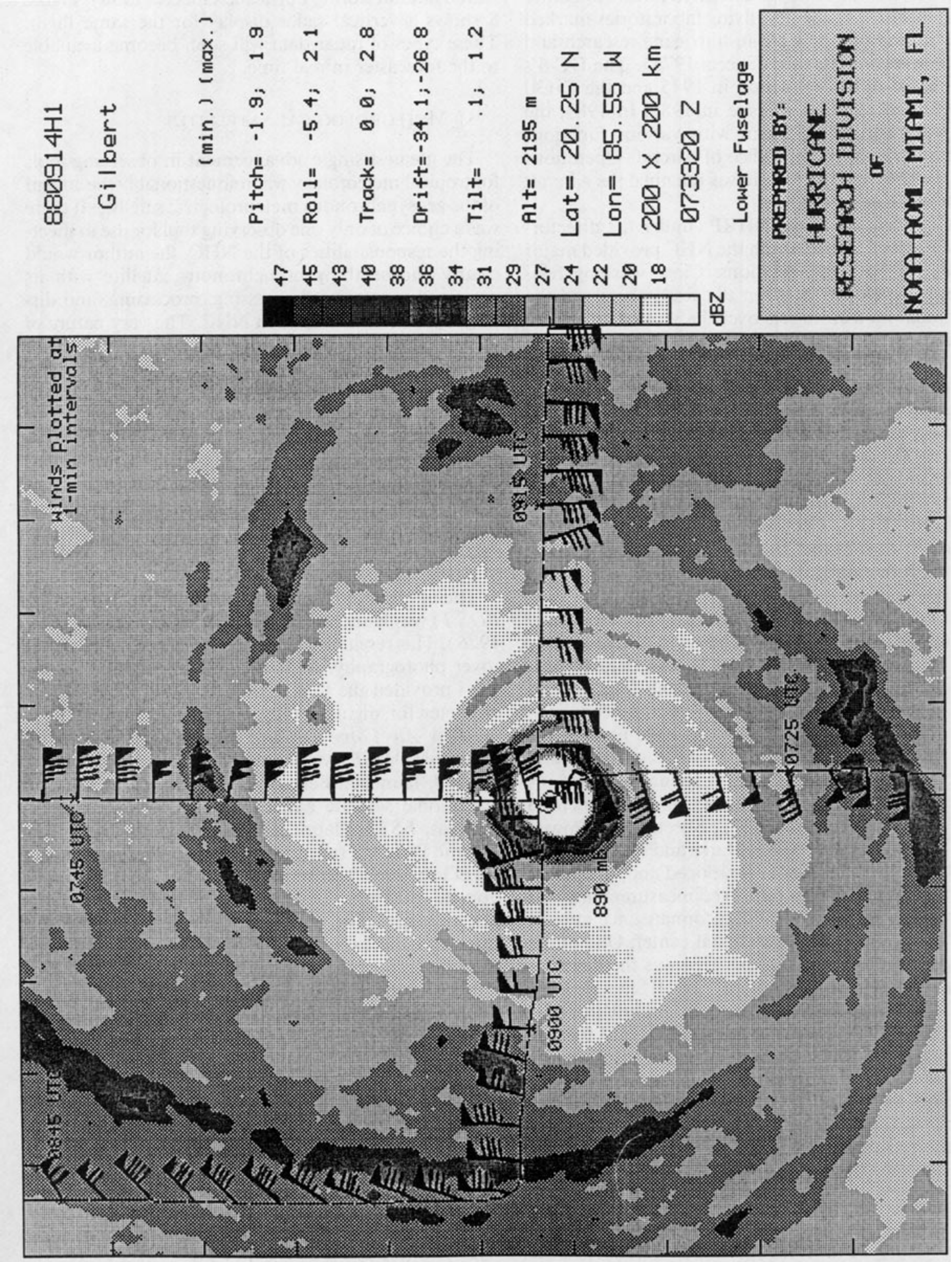


FIG. 7. Digitized plan position indicator (PPI) radar data recorded by a NOAA research aircraft flight into Hurricane Gilbert on 14 September 1988. Superimposed are wind observations transmitted to and plotted at the National Hurricane Center in real time through a satellite data link (courtesy of F. Marks, Jr., HRD).

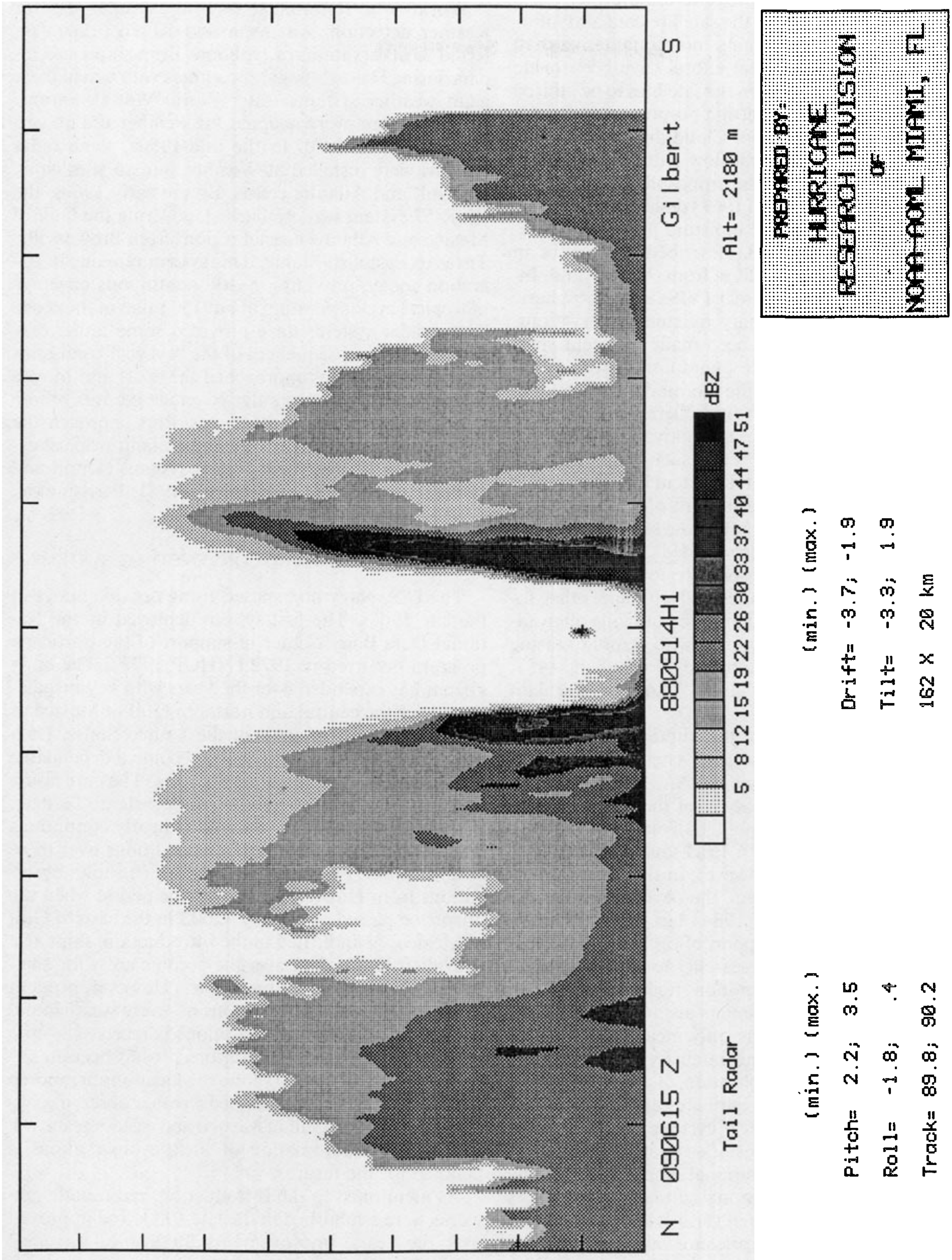


FIG. 8. Digitized range height indicator (RHI) radar data recorded by a NOAA research aircraft during the period illustrated in Fig. 7 (courtesy of F. Marks, Jr., HRD).

the observing characteristics of the two types of satellites and their utility for environmental monitoring.

Over the years, much of the satellite data and information has been and remains more qualitative than quantitative. However, great efforts have been made to quantify information from the satellites to be utilized in initial analyses for diagnostic purposes and for numerical model initialization. Cloud drift "winds" became a vital part of tropical flow pattern analyses at low and upper levels in the troposphere. Wark and Fleming (1966) and Smith (1967) describe early efforts to obtain temperature and moisture profiles from radiation data. Smith (1983) described early work in deriving atmospheric profiles from Visible and Infrared Spin-Scan Radiomenter (VISSR) Atmospheric Sounder (VAS) geostationary radiance observations. Great advancements have been made in recent years in obtaining more accurate quantitative estimates of the vertical distribution of the thermodynamic and kinematic properties of the troposphere using satellite-based technology. In spite of these advances, it appears that it will be several years before such technology can replace the current radiosonde system for atmospheric soundings. However, in the author's opinion, there are no reasonable alternatives to remote sensing from satellites for obtaining the much needed "sounding" data over the tropical and subtropical regions of the world. Considerable effort continues at NHC and other locations to improve tropical analyses utilizing all available conventional data coupled with remote sensing data from satellites (Veldon and Goldenberg 1987; Veldon et al. 1984; Lewis et al. 1987; Lord and Franklin 1987; Burpee et al. 1984).

It is not practical to list the hundreds of research papers published in the area of satellite-based technology supported by NASA, NOAA, NSF, DoD, etc. The list is growing daily. Some of the pioneering researchers and their work included Fett (1964); Sadler (1964); Fritz et al. (1966); Erickson (1967); Oliver and Anderson (1969). However, in the estimation of the author and many others, the development of the Dvorak technique (1972, 1984) has been the single greatest achievement in support of operational tropical cyclone forecasting by a researcher to date. This technique is used with only minor modifications at all tropical cyclone forecast centers around the world today. In most cases, it is the only means available for estimating tropical cyclone intensity over the open oceanic areas. Proper application of the system generally provides consistent estimates and a relative estimate of changes in tropical cyclone strength. However, it is an indirect means of estimating tropical cyclone strength, and operational application of the system has resulted in occasional substantial differences in strength estimates between various analysts and also differences with wind and pressure values recorded by reconnaissance aircraft (Sheets and McAdie 1989; Mayfield et al. 1989).

4) RADAR

World War II initiated the era of radar use for weather detection. Adamson and Kosco (1967) referred to observations of typhoons from shipboard radars during Halsey's tragic encounters with two of these giant weather systems. After World War II, various military radars were adapted for weather use aboard aircraft and on land. In the mid-1950s, some radar systems were installed at Weather Bureau sites along the Gulf and Atlantic coasts. By the early 1960s, the WSR-57 system was established, covering the Gulf of Mexico and Atlantic coastal regions from Brownsville, Texas to Eastport, Maine. This system remains in operation today, providing nearly continuous coverage of tropical cyclones within about 150 miles of the coast. These radar systems have provided some rather dramatic time-lapse sequences of the "eyewall" and rainbands as hurricanes approached the coast and moved inland. Therefore, this radar coverage permits refinement of hurricane warnings as storms approach the coast. Also, much has been learned about tropical cyclones over the years using these systems (Dunn and Miller 1960; Jordan and Schatzle 1961; Parrish et al. 1982).

5) BUOYS, SHIPS, AND CONVENTIONAL SYSTEMS

The U.S. Navy first started using oceanic buoys in the late 1960s. The first system deployed by the National Data Buoy Center in support of the hurricane program occurred in 1972 (NHOP 1972). The buoy system has expanded over the years with key installations over the central and northern Gulf of Mexico as well as off the East coast of the United States. Data provided by these systems have become a dependable and routine part of the daily analyses. They are also a vital part of the hurricane-warning system. To date, they are the only means of making nearly continuous direct measurements of surface conditions over these oceanic areas. Figure 9 (Metzger 1986) shows observations from Hurricane Kate for the period when the hurricane passed over buoy 42003 in the eastern Gulf of Mexico. As indicated in the Introduction, ships also provide valuable data over the oceanic areas for analyses of conditions over the tropics. However, prudent ship captains avoid core regions of severe weather and if a report of hurricane conditions is received from a ship, it usually means that a forecast has been in significant error. Figure 10 shows the locations of moored buoys and C-MAN (automated weather observing systems) sites for the Gulf of Mexico and eastern seaboard. Much greater automation of surface observations is planned for the future.

As mentioned in the Introduction, radiosonde networks were established in the late 1930s and improved over the years. Improvements for tropical coverage reached its zenith with the "downrange" stations associated with the space program in the 1970s. With

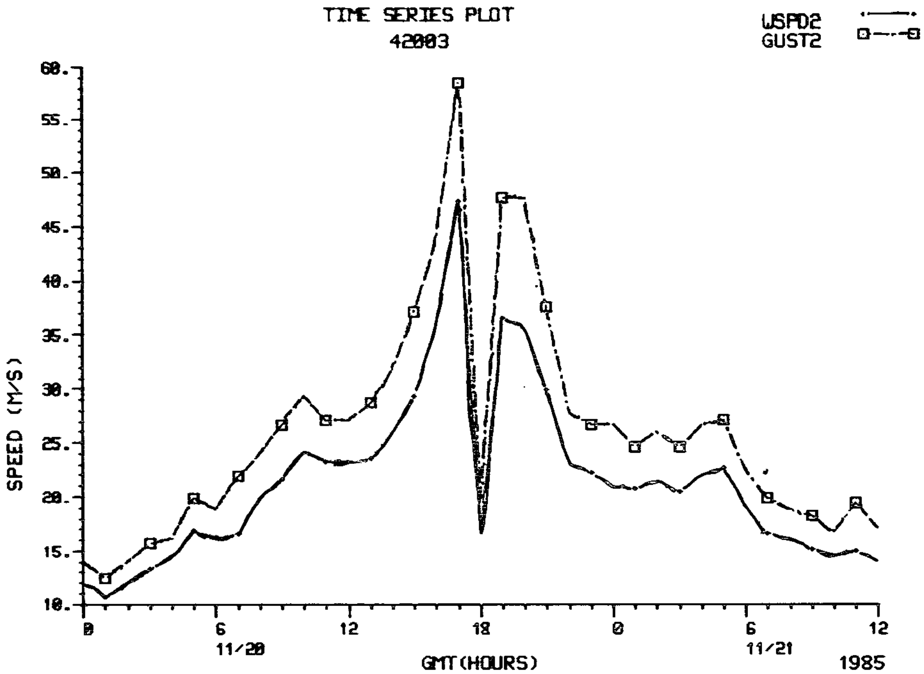


FIG. 9. Time series plot of wind speed and gusts recorded on buoy 42003 in the eastern Gulf of Mexico during the passage of Hurricane Kate on 20–21 November 1985 (courtesy of G. Hamilton, NDBC).

the advent of the satellite era, weather ships which had provided upper-air information were phased out along with the downrange stations in the mid- to late 1970s.

3. Current structure and responsibilities

a. Structure

The NHC is composed of four primary units. These are the Hurricane Specialist/Forecast, Tropical Satellite Analysis and Forecast, Techniques Development and Applications, and the Communications/Charting and Computer Operations Units. The Communications/Charting and Computer Operations Unit primarily provides support for the two analysis and forecast units and acts as an interface for providing specialized products to the user community. The small Techniques Development and Applications Unit develops and/or applics techniques for improved analyses and forecasts and efficiency of operations. Special emphasis has been placed upon statistical and statistical/dynamical analysis and prediction techniques with large numerical modeling left to others. In addition, risk-analyses programs have been developed along with detailed applications of storm surge models to determine areas and degrees of risk associated with tropical cyclones.

b. Responsibilities

The mission of the NHC is to provide tropical and subtropical meteorological and oceanographic products to governmental, private, and international users. These products consist of two types. The first group consists of interactively derived meteorological and oceanographic analyses and associated aviation and marine forecasts routinely issued for NHC's area of responsibility. The second type of product is tropical cyclone forecasts and warnings issued on a case-by-case basis. These products are the primary basis used in the decision-making process for action to protect potentially hundreds of thousands of lives for each major hurricane threat. In addition, multimillion-dollar decisions are made based upon this information to protect billions of dollars worth of property from the hurricane threat.

The NHC area of responsibility (Fig. 12) includes the tropical and subtropical portions of the Atlantic and Pacific oceans from 32°N to the equator east of 140°W. This area includes the Caribbean Sea, the Gulf of Mexico and adjacent land areas. In addition, tropical and subtropical cyclones moving to higher latitudes remain the forecast and warning responsibility of the NHC. In addition to its national responsibilities, the NHC is a designated Regional Specialized Meteorological Center (RSMC) under the auspices of the United Nations WMO. Analyses, forecasts and guidance products are provided year long on a routine basis to all United States interests as well as the international community of the Caribbean and northern South America, Central America, and North America. In addition, when tropical cyclones occur, the NHC has the direct responsibility for issuance of forecasts and warnings for these systems for all United States interests

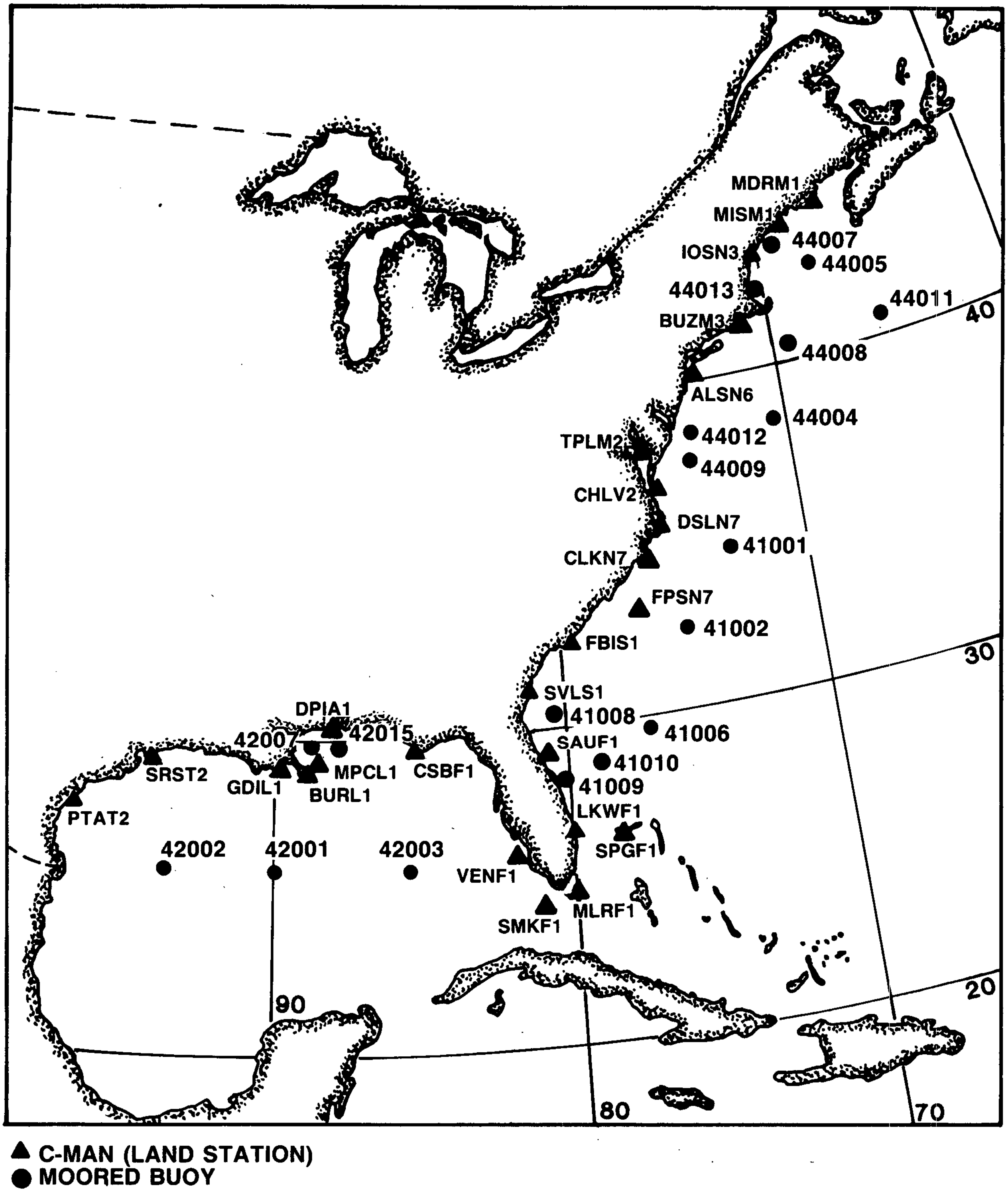


FIG. 10. Network of National Data Buoy Center (NDBC) moored buoys and automated weather observing systems (C-MAN) for the Gulf of Mexico and eastern seaboard of the United States (courtesy of G. Hamilton, NDBC).

(includes DoD and DoS) in this region. Also, under agreements of the Hurricane Operations Plan for Region IV of the WMO, the NHC provides the primary forecast guidance products for member countries, direct warnings for some countries and acts as a backup for other countries in the region.

1) TROPICAL ANALYSES, FORECASTS, AND ASSOCIATED PRODUCTS

Several analyses are performed routinely for the NHC area of responsibility, which includes the North Atlantic and eastern North Pacific Oceans and adjacent land masses primarily south of 40°N to the Equator, the Caribbean Sea and the Gulf of Mexico. Analysis and interpretive products are distributed over national and international circuits. These products include tropical weather discussions for the entire area and SIMS issued every 6 hours. The SIMS contain general information for the entire area and specific mesoscale discussions for Puerto Rico and the United States Virgin Islands, the Florida peninsula, and the northern Gulf of Mexico. In addition, synoptic surface analyses are completed and transmitted every 6 hours and an entire set of near-surface, 200-mb, shear, deep-layer mean, lower- and upper-layer mean charts, heavily influenced by satellite-derived data, are completed and transmitted every 12 hours. Also, a detailed Gulf Stream and sea-surface temperature analysis for the Gulf of Mexico as well as general sea-surface temperature analyses are prepared thrice weekly and made available to marine interests through a dial-up system.

Marine forecast products include high seas forecasts issued at 6 hourly intervals for the North Atlantic south of 32°N, the Caribbean Sea and the Gulf of Mexico as well as the eastern North Pacific east of 140°W, and south of 30°N. Aviation products include international area forecasts for essentially the same areas and International SIGMETS[10] for the San Juan, Miami, Houston and Oakland (south of 30°N) flight information regions (FIR's) (Fig. 12).

2) THE TROPICAL CYCLONE FORECAST AND WARNING PROCESS

(i) *Before the storm.* The tropical cyclone forecast and warning process begins well before the event appears on the horizon. The first step in the process is to determine the vulnerability of coastal locations. This is accomplished through applications of the SLOSH model developed by Jelesnianski (Jarvinen and Lawrence 1985). There are several steps involved in the application of this model. The first is the basin development which is the application of the model to a particular basin. This step is accomplished by the Techniques Development Laboratory (TDL) of the NWS using bathymetry data and topographical maps to obtain water depths and land heights for input to the model grid. The next step involves tests of the model versus historical hurricane information. Each past hurricane affecting the area is carefully researched and reconstructed to determine its path, its wind and pressure field distributions and its water levels. The model is then run for each hurricane situation, and predictions of water rises or falls are compared with the historical values.

The next phase is an actual detailed reconnaissance of the basin to check actual land heights and barriers, such as interstate highways, to refine information derived from topographical maps. This activity involves TDL, NHC and local NWS personnel and local emergency management officials. The model is adjusted to accommodate any geographical features not previously represented in the model. The model then receives final testing and at that stage is turned over to NHC for operational applications.

NHC then simulates various storm scenarios for the given basin. The number of storm simulations for a basin can range from about 250 to more than 500. The result is maps of maximum envelopes of water depicting areas covered by the potential storm surge for various storm scenarios. These maps are composited for a family of storms of a given strength and movement with a range of points of landfall to account for uncertainties in the forecast track. By contrast, Fig. 2 contains maps of inundation for a single specific storm event. The next step is to complete evacuation studies based upon these predicted areas of inundation. These evacuation studies include transportation analyses, shelter analyses, and population behavior studies. This portion of the program is completed by the U.S. Army Corps of Engineers and local and state governments. Prior to this application, local National Weather Service and local and state government, as well as FEMA and Corps of Engineers officials, attend a workshop conducted by NHC on the use of the SLOSH products. The result is a definition of the problem along with required evacuation or lead times for various hurricane scenarios. This interagency program is funded by NOAA, FEMA, the Corps of Engineers, and sometimes state and local governments. It averages two calendar years and five to six man years to complete for each basin.

(ii) *The forecast: tools and techniques.* The tools used for tropical cyclone forecasting start with standard hemispheric synoptic and subsynoptic scale meteorological analyses at the surface and standard pressure levels and predictions of synoptic and subsynoptic scale features derived from global, hemispheric and regional models from NMC (Bonner 1989; Petersen and Stackpole 1989; Hoke et al. 1989; Junker et al. 1989; Caplan and White 1989) and the European Centre for Medium-Range Weather Forecasts (ECMWF) (Bengtsson 1985). More specialized analyses performed at NHC include the previously mentioned 200 mb level and analysis of the tropical oceanic lower layer (ATOLL) streamline and isotach analyses over the tropical and subtropical belts of the North Atlantic and eastern North Pacific ocean regions. These analyses take ad-

[10] SIGMETS are any meteorological phenomena such as clusters of thunderstorms, clear air turbulence, etc. that could be hazardous to aircraft in flight.

vantage of low-level and upper-level cloud drift "winds" derived from geosynchronous satellites in combination with aircraft reports and standard upper-air soundings. Other analyses include low-level, upper-level and deep-layer mean flow as well as vertical shear analyses of the horizontal wind, and time cross sections from selected upper-air stations from west Africa westward through the Caribbean and Central America. These analyses provide time histories of the strengths and levels of possible circulations associated with tropical waves (Frank 1974b). Nearly 60% of all tropical storms in the Atlantic basin during the past 20 years formed from tropical waves traced back to the African coast (Avila and Clark 1989).

The historical section noted some of the early methods used for tropical cyclone track forecasting such as pressure changes and upper-level winds. Several empirical techniques are described by Hebert (WMO 1979) including such methods as surface geostrophic steering, changes in the midlevel heights and/or winds at standard pressure levels well removed from the tropical cyclone (Miller and Chase 1966), etc. Statistical methods were used in the late 1950s and early 1960s to predict the motion based upon climatology and persistence (Veigas et al. 1962; Hope and Neumann 1970). By the late 1970s, seven primary tropical cyclone track forecast models were being used at NHC. These were HURRAN (Hope and Neumann 1970), an analog model based on tracks of all Atlantic tropical cyclones since 1886; CLIPER (Neumann 1972), a regression equation model utilizing predictors derived from climatology and persistence; NHC67 (Miller et al. 1968), a regression equation model utilizing predictors derived from climatology, persistence and ob-

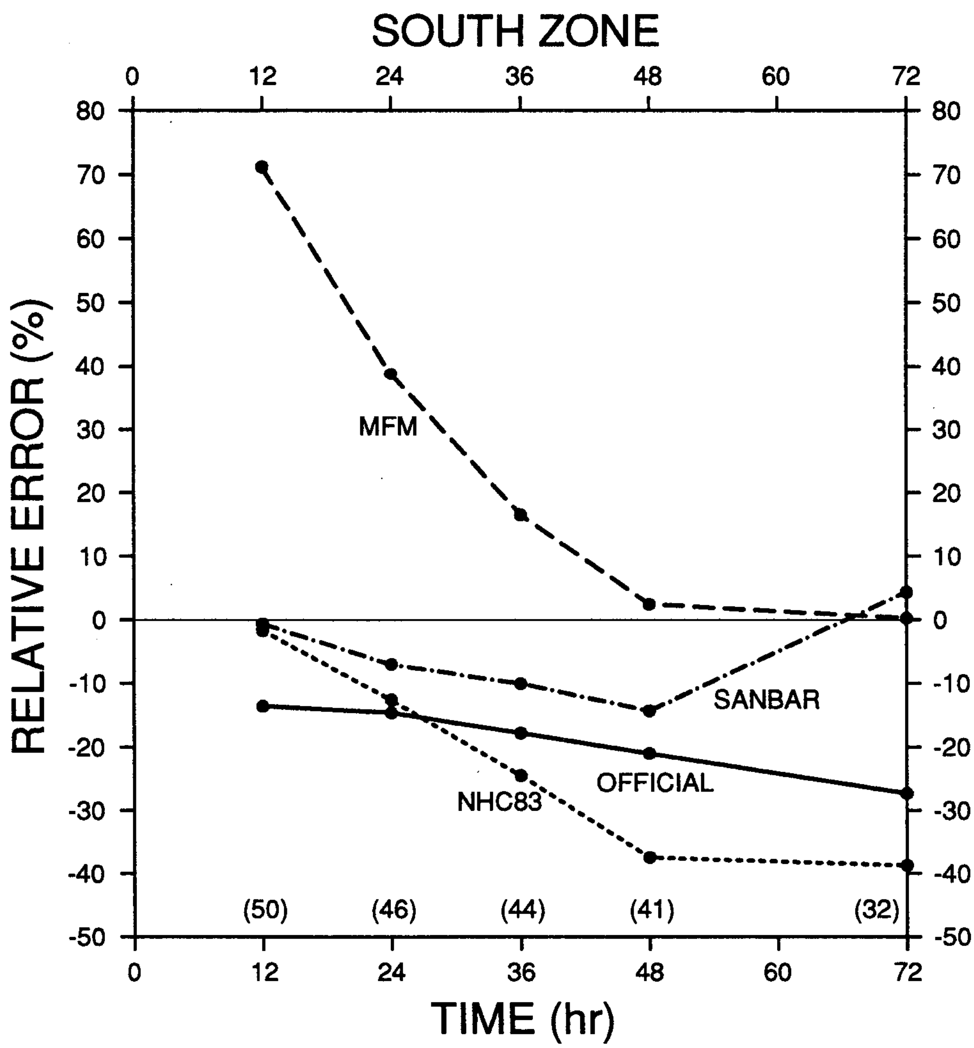
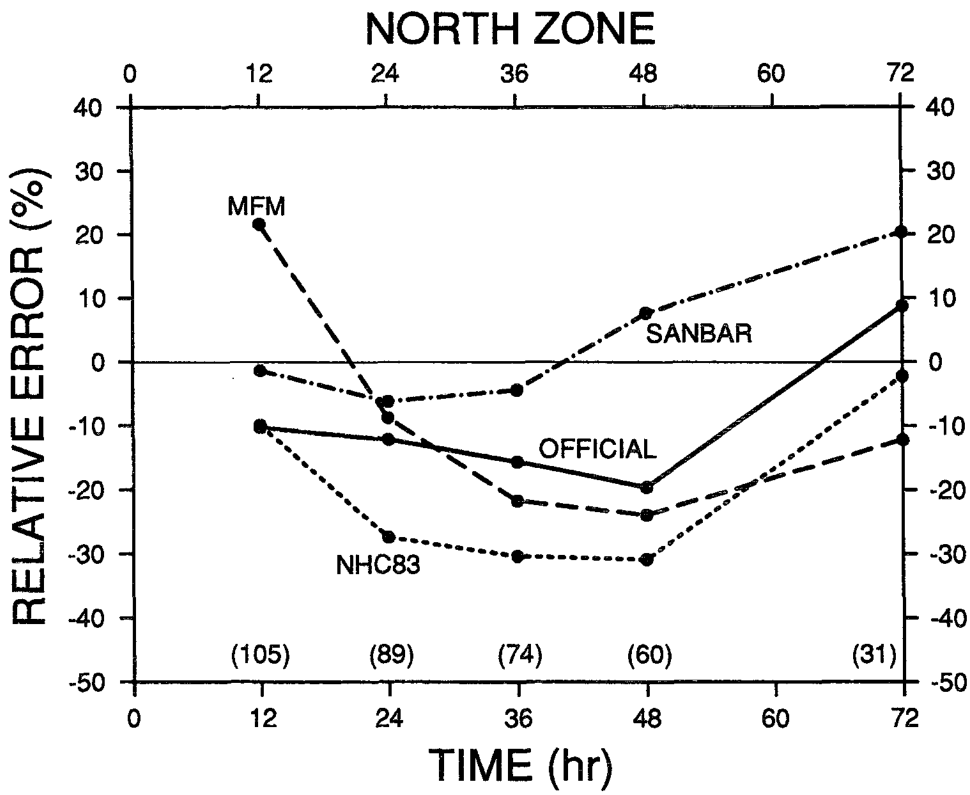


FIG. 11. Performance statistics of selected tropical cyclone track forecast models normalized relative to CLIPER for the Atlantic basin. Stratifications are based on the initial position being; (a) south; or (b) north of 24.5°N latitude; and (c) for a homogeneous sample from 1983 through 1988 (DeMaria et al. 1990).



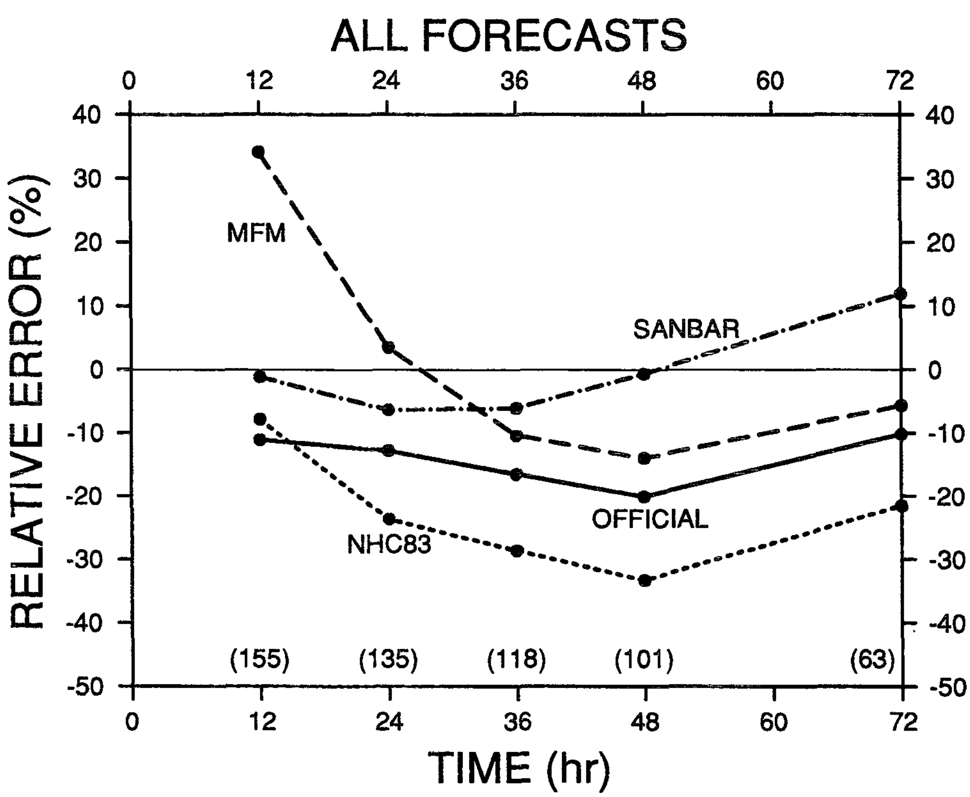


FIG. 11. (*Continued*)

served geopotential height data; NHC72 (Neumann et al. 1972), a regression equation model utilizing predictors derived from output of the CLIPER model and *observed* geopotential height data; NHC73 (Neuman and Lawrence 1975), similar to NHC72 with addition of predictors from numerically *forecast* geopotential height data; SANBAR (Sanders et al. 1975), a barotropic model based on a pressure-weighted wind field averaged through the troposphere; and the MFM (moveable fine mesh, Hovermale and Livezey 1977), a baroclinic model having ten levels in the vertical and 60-km grid spacing in the horizontal. The SANBAR and MFM models are applicable to the Atlantic and eastern Pacific basins while the statistical and statistical dynamical models required separate developments for eastern Pacific applications (Neumann and Leftwich 1977; Leftwich and Neumann 1977). A paper by Neumann and Pelissier (1981) provides an operational evaluation of the performance of these models in the Atlantic basin.

Two new models (NHC83, Neumann 1988; BAM, Holland 1983) and a revised SANBAR (Goldenberg 1987) were introduced in the late 1980s. In addition, a new model, the QLM (quasi-lagrangian model, Mathur 1988) was developed at NMC as a replacement for the MFM. The NHC83 model borrowed features from the NHC73 but its primary predictors are based upon deep-layer-mean geopotential heights as derived from NMC's medium-range forecast (MRF) model. During a 5-yr test period, this model out performed all other models by a significant margin. Therefore, in 1988, NHC67, NHC72, and NHC73 were dropped from operational use. Figure 11 shows the performance of several of these models for a homogeneous sample from 1983–87. The percent error has been computed relative to CLIPER which is considered a no-skill forecast. Improvement over CLIPER is reflected by negative numbers. Here, NHC83 shows superior performance. The beta advection model (BAM) developed by Holland has also proven to provide good results in many cases. The new QLM provided poor results in 1988 but with some adjustments for the 1989 season seemed to perform well in some difficult forecast situations.

Two statistical models were developed for use in predicting tropical cyclone intensity changes. These are SHIFOR (Jarvinen and Neumann 1979) and SPIKE which is a modification of SHIFOR using thickness values (Pike 1985). These models remain in use today for the Atlantic and Eastern Pacific basins.

(iii) *The forecast: the process.* The actual tropical cyclone track and intensity forecasts involve several steps and NWS units. The primary current environmental guidance results from specialized analyses conducted at NHC as previously described. In addition, current animated satellite imagery is analyzed for qualitative assessments of flow pattern changes. Special emphasis is placed upon animated water vapor imagery for regions of moist and dry flow. The primary guidance for predicted environmental conditions is obtained from the NMC package of global, hemispheric and regional models with secondary guidance from ECMWF and the United Kingdom Meteorological Office (UKMO) models.

The next step involves detailed analyses of the tropical cyclone itself. These analyses involve all available satellite, reconnaissance aircraft, buoy, radar, etc., data, and ship observations to determine present and past motion, wind and pressure-field distributions, etc. This information is used as inputs to the numerical models described earlier. All models, except the QLM are run on the NHC computers or through linkage with the NMC computers. A package of five to seven tropical cyclone track forecast models are routinely run for each forecast cycle for both the Atlantic and eastern Pacific basins. In addition, the two (SHIFOR and SPIKE) intensity forecast models are run for each case. All this information is used by the NHC hurricane specialist to arrive at his tropical-cyclone track and intensity forecasts for a period of 72 hours including wind-field distribution forecasts. NMC forecasters arrive at an independent track forecast primarily based upon NMC model guidance. Also, forecasters at NWSF offices in areas that may be affected by the tropical cyclone sometimes arrive at their independent forecast primarily based on large-scale guidance and local conditions. In addition, if the tropical cyclone is threatening a coastal region of the United States, the NHC runs the SLOSH model for the appropriate basins for the expected tropical cyclone track and intensity. This may actually be a family of storm situations to account for uncertainties in the forecast.

(iv) *The forecast: meteorological/hydrological coordination.* The NWS Hurricane Hotline is used for a conference call involving an NMC forecaster (expert on large models), forecasters at local NWSF offices that might be affected (experts on local meteorological/hydrological/sociological conditions) and the NHC hurricane specialist (expertise in all aspects of the hurricane). In addition, forecasters from the NMC Heavy Precipitation Branch and the National Severe Storms Forecast Center (tornado expertise) are included in the conference call when appropriate. Others generally listening in on the discussions include NWS headquarters and Southern or Eastern Region headquarters personnel as well as U.S. Navy personnel at Norfolk and Jacksonville. All independent track forecasts are logged at NHC and a discussion is held concerning the reasoning behind the particular forecasts. The official forecast track is determined, with NHC having the final decision on the forecast. Discussions then center around potential impacts and the timing and areas for possible warnings. This portion of the decision making process is heavily dependent upon the several man years of work surrounding the SLOSH model applications and associated vulnerability and evacuation

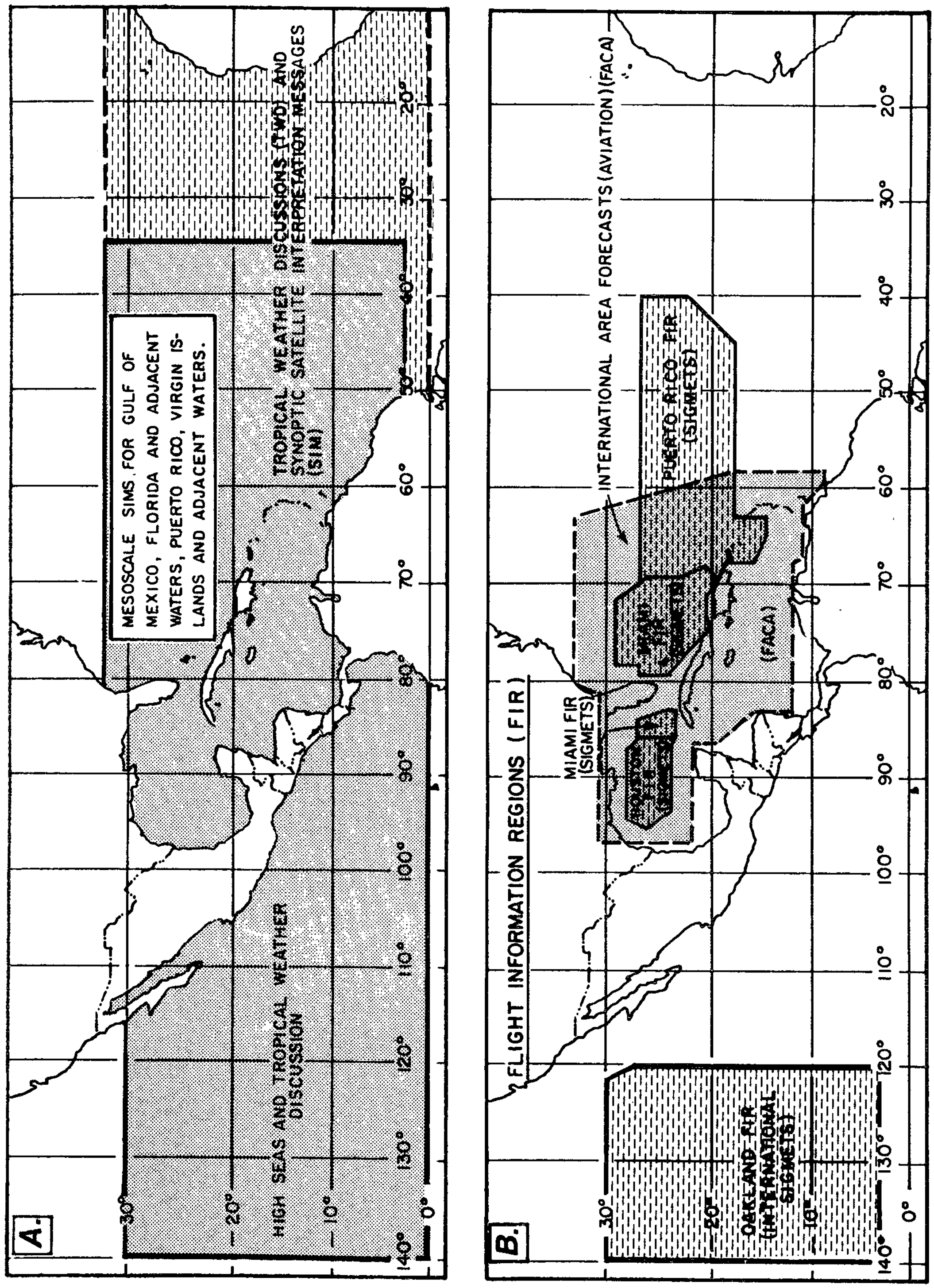


FIG. 12. NHC areas of responsibility for (a) tropical analyses, interpretation products, and high seas; and (b) aviation forecasts and SIGMETS.

studies discussed earlier. If "watches" or "warnings" are deemed necessary, preliminary timings and areas for those factors are determined.

(v) *The warning.* The actual warning process involves a highly coordinated team effort between three major groups: 1) the NWS meteorologists, who have the statutory responsibility for the determination of the meteorological and hydrological conditions expected and associated warnings required for protection of life and property; 2) the local and state officials who determine what response is needed; and 3) the media who provide the means to make the warnings effective through communication with the general public. Again, this process does not start at the time of the event, but involves procedures and plans worked out by the three groups prior to each hurricane season.

Three primary factors come into play in the watch and warning decision process.[11] First, sufficient lead time must be provided for the protection of life and, to a lesser degree, property. Second, overwarning must be kept to a minimum to avoid large expenditures for preparation costs and the complacency associated with the "cry wolf" syndrome. That is, the "watch" and "warning" decision is always a delicate balance between sufficient warning and overwarning. The third factor is to optimize response. Obviously, this factor is intertwined with the first two factors. The ideal "advisory" process becomes one of a steady step-wise elevation of the perceived threat for areas at risk to the specific hurricane, avoiding "on-again, off-again", and shifting of warning areas as *much as possible.* A critical element in this process is the timing of issuances designed to trigger specific actions and responses. For instance, except in extreme situations, it does little good to issue a watch or a warning after people at risk have retired for the night.

The first step in the actual warning process is the meteorological coordination described above. The next step involves local and state officials. The NHC forecaster uses the National Warning System (NAWAS) hotline for a conference call to affected state and local officials. Some states have direct drops on the system at nearly all county Emergency Management offices while others go through a state system for internal distributions. Officials are given a general briefing of planned warning areas and times of warnings and expected conditions to be encountered. These officials also feed information back to the NHC which might cause some adjustments to the warning areas and timings of warnings as well as special emphases to be included in the warning. Local and regional NWS offices also participate in this conference call. These NWS offices then work closely with their respective local and state officials to refine the NHC warnings for detailed local applications.

The final step in the warning process is to communicate the warning to the user community in a manner designed to generate the desired response in a timely fashion. The media plays a vital role in these efforts. The events surrounding the hurricane threat is treated as a warning process and not a news event. Therefore, every effort is made to remove the competitive aspect of the media business from the process. The printed "advisory", which is the message containing information on the tropical cyclone including associated warnings, is transmitted over a distribution system that permits every user to receive it nearly simultaneously. These advisories are then followed by statements issued by local NWS offices which give specific information for their respective communities. Frequently, an electronic media "pool" (including print media) is established by prior agreement at NHC and sometimes at affected local NWS offices. Competing network, regional and local station personnel work side by side, sharing equipment and often helping each other to assure that the best possible product is being transmitted to the public in an effective and timely fashion. By being part of the system, the reporter or correspondent soon realizes the sensitive role and the responsibilities they have for generating the desired response in communities at risk.

The "pool" system with associated satellite communications links permits the NWS to provide a direct, rapid, and orderly distribution of information to the potentially affected areas. This system minimizes the confusion that was frequently encountered prior to these communications capabilities being available. In that era, the printed "advisory" information was subject to many levels of interpretation and embellishment. Many rumors started and local residents looked to various sources to get the correct *information.* Of course that information was often in conflict with other information from a different source in the same community. A prime example of this occurred during tropical storm Babe in 1977 which will be discussed later. The present system permits the general public to receive the information directly from the source of the warnings. Although, this has not totally eliminated the problem cited above, as was illustrated by some conflicting information in the Galveston/Houston, Texas area during hurricane Gilbert of 1988, it clearly has greatly improved the warning and response process. The effectiveness of this warning system is clearly illustrated by the trend of major reductions in the loss of life associated with hurricanes striking the continental United States over the past few decades (Fig. 5).

[11] A hurricane watch is an announcement for specific coastal areas that a hurricane or an incipient hurricane condition poses a possible threat, generally within 36 hours. A hurricane warning is that sustained winds ≥ 64 kt (74 miles h^{-1}) associated with a hurricane are expected in a specified coastal area in 24 hours or less. A hurricane warning can remain in effect when dangerously high water or a combination of dangerously high water and exceptionally high waves continue, even though winds may be less than hurricane force.

4. Operational examples

The preceding sections discussed observational and forecast tools available to the hurricane forecaster and the forecast and warning process. This section will use actual cases to illustrate (a) how those tools have been operationally applied during the past year with varying degrees of success, (b) how the national and international coordination process works, and (c) problems caused in the response process by conflicting information.

a. Forecasts

1) HURRICANE JERRY, OCTOBER 1989

Hurricane Jerry presented several forecast and warning problems resulting from erroneous observations and poor numerical guidance. Tropical Storm Jerry formed over the Gulf of Campeche, about 700 miles south of Beaumont, Texas, on 11 October and began to show signs of developing into a hurricane. The only known factor which seemed to disfavor development was shear caused by strong southerly winds at outflow levels. Center positions determined from the various satellite analysis units and aircraft reconnaissance were in good agreement through the early evening hours of 13 October. Jerry had been moving fairly steadily toward the north at 4–5 m/s, with the deep-layer mean-flow dominated by the upper-level southerlies. An Air Force reconnaissance aircraft provided a center position at 2312 UTC (1812 CDT) 13 October. Based upon this position and previous aircraft reconnaissance and satellite based positions, the storm was moving northward at slightly more than 5 m/s (Fig. 13). This movement was a little faster than previously indicated, but still suggested landfall about 40 hours later.

Synoptic-scale flow analyses and hurricane track-prediction computer models gave conflicting indications of where the storm might move during the next 72 hours. Potential landfall points ranged from northern Mexico, north and eastward along the Texas and Louisiana coasts to the mouth of the Mississippi. The most reliable model (NHC 83) indicated the forward movement of the storm would slow and that it would not reach the coast within the next 72 hours. None of the other dynamical and statistical/dynamical track prediction models indicated landfall less than 36 hours from the evening of 13 October and more likely it would be near 48 hours before such an event. Also, the storm was small and conditions were not favorable for major intensification. However, the time was nearing when decisions had to be made concerning possible issuances of tropical storm or hurricane watches and/or warnings.

The three primary factors involved in the watch and warning decision process described earlier were taken into account in the "Tropical Storm Jerry" situation. During the early evening hours of 13 October the NHC decided that the issuance of a tropical storm "watch" would not be necessary until the following day. There were signs that the storm could weaken and its future course was quite uncertain. It was felt that by the next morning, with new synoptic data and later computer model predictions, perhaps there would be a greater confidence in the future motion and strength of the system, permitting a narrower zone to be placed under a watch or warning.

During critical forecast periods when hurricane watches and/or warnings may be issued, reconnaissance aircraft are scheduled at approximately 3-h intervals. The next aircraft reconnaissance "fix" (i.e., position, minimum pressure, maximum wind, wind field, etc.) after the 2312 UTC fix was scheduled for 0300 UTC on the fourteenth. Unfortunately, due to mechanical problems, the scheduled aircraft and a backup aircraft were not able to complete their scheduled mission. The next actual aircraft reconnaissance fix was at 1205 UTC, a 13-h gap. Because, the storm was a considerable distance from land, only satellite-based determinations of storm position, size, and strength were possible through the night.

Satellite-based position estimates provided by the Satellite Analysis Branch (SAB) of the National Environmental Satellite Data and Information Service (NESDIS) and the Tropical Satellite Analysis and Forecast (TSAF) unit of NHC at 0000 UTC 14 October were in near exact agreement[12] and on course with previous position estimates from reconnaissance aircraft and satellites. However, these new position estimates indicated a significant increase in forward speed. These new fixes caused moderate concern about their accuracy since they located the center about 60 miles north of the aircraft fix only 48 min earlier. The indicated motion was not representative of analyzed steering flow, although forward motion could be increasing due to greater influence of the upper-level flow in the developing system. The hurricane forecaster on duty continued to closely monitor the satellite imagery to determine if the forward speed of Jerry had accelerated. Satellite analysts on duty at SAB and TSAF both indicated that they felt the storm was indeed moving faster.

By this time, the hurricane forecaster knew that no reconnaissance aircraft observations would be available to determine if the satellite estimates were correct in time for preparation of the forecast and advisory that would be used for the late evening news, the last newscast that most people in the threatened area would see or hear before the next morning.

After consultation with the director of NHC, and NWS forecasters on duty in New Orleans and San An-

[12] They generally confirm each other.

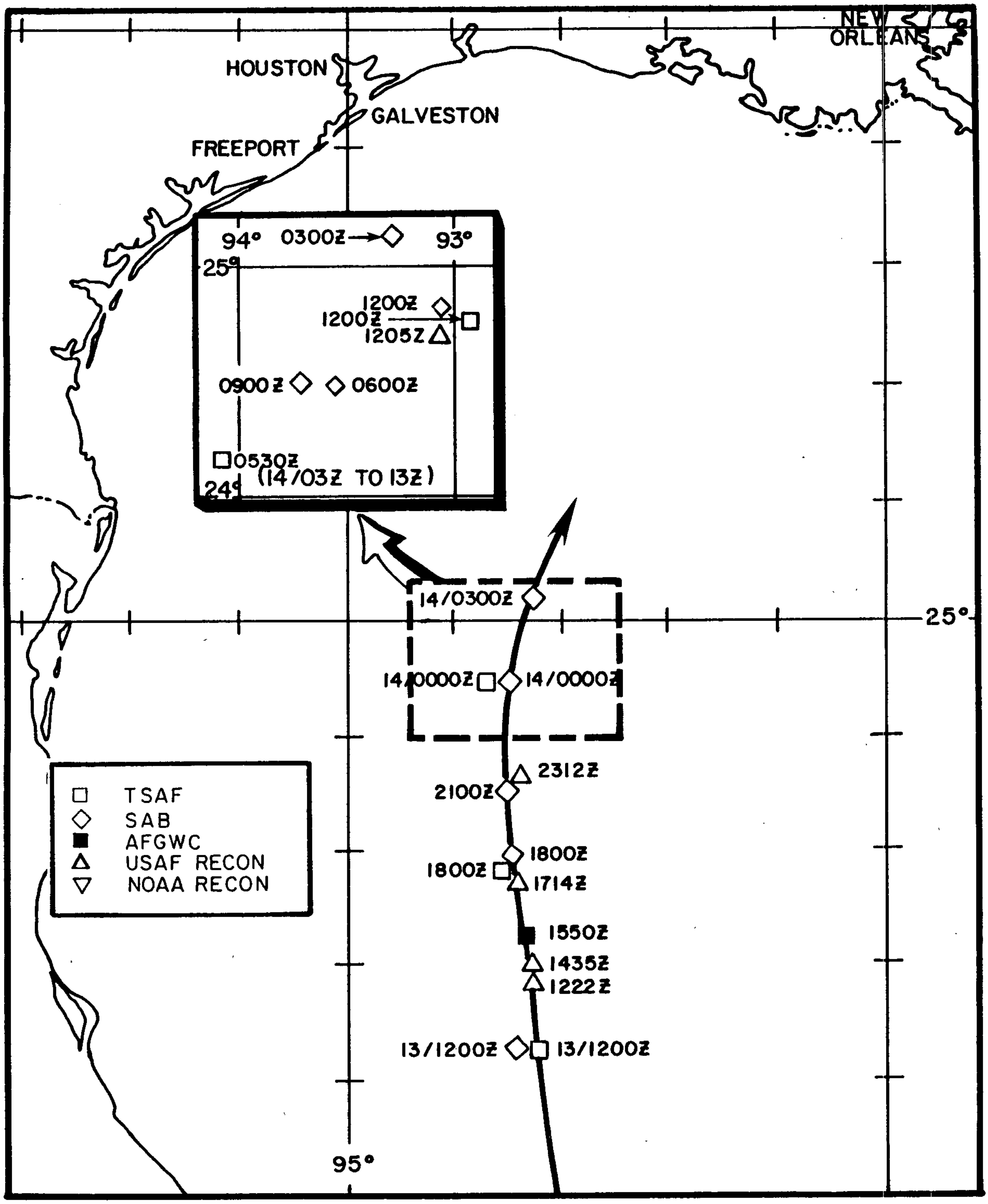


FIG. 13. Track of tropical Cyclone Jerry (1989) as determined from satellite position estimates (SAB—Satellite Analysis Branch, NESDIS; TSAF—Tropical Satellite Analysis and Forecast Unit, NHC; AFGWC—Air Force Global Weather Center) and Air Force reconnaissance aircraft "fixes".

tonio, it was decided that there was no choice, but to issue a hurricane watch for the Louisiana coast in time for the late evening news. This condition arose even though everyone thought that the storm was not moving as fast as the satellite estimates indicated, and that positions were probably being distorted by upper-level shear, the timing was such that only slight changes in forward speed would become critical factors for the warning process. For instance, if the hurricane had actually increased its forward speed by only 1–2 m/s (a strong possibility), the center could be on the coast in less than 24 hours. Again, because of the small size of the storm, the expectation that it would not become a major hurricane, and therefore, that major evacuations would not be necessary, indicated that there would be time to issue a hurricane warning at daybreak. In addition, the Air Force was preparing a backup aircraft which would obtain more complete information on the strength and location of the storm sometime after midnight. Although not desired, refinement of warnings could be made at that time. Unfortunately, that aircraft also experienced mechanical problems which meant no additional aircraft reconnaissance information was actually received until the next morning near 0700 CDT. In the mean time, the SAB analysts provided another center fix estimate at 0300 UTC that continued the faster forward speed. By their estimation, the storm was now north of 25°N and significantly closer to the coast.

Within four hours of issuance of the hurricane watch (2130 CDT) new satellite-based estimates indicated that the previous fixes by the two units were possibly erroneous. The TSAF unit estimate at 0530 UTC was more than 30 nautical miles SOUTHWEST of the estimate they had provided less than 6 hours earlier and more than 75 nautical miles southwest of the position provided by SAB less than 3 hours earlier (see insert in figure 13). Thirty minutes later, SAB indicated that their two previous positions had been wrong and that at 0600 UTC the storm was centered about 45 nmi south of their estimate 3 hours earlier. However, they were still about 30 miles northeast of the position estimate from TSAF. They made another estimate at 0900 UTC which was slightly west of their 0600 UTC position, again indicating a great deal of uncertainty in the true position and motion of the storm in a highly sheared environment.

At 1205 UTC 14 October, an Air Force reconnaissance aircraft arrived at the storm and found the center basically on track with the slower northward movement from the previous afternoon and evening. This position was more than 70 N mi northeast of the 0530 UTC TSAF position and 40 N mi east-northeast of the 0900 UTC SAB position. Finally, shortly after the aircraft reconnaissance position estimates were obtained, TSAF and SAB provided position estimates (formal satellite position estimates are obtained 30–60 min after observation time although the hurricane specialist frequently monitors the imagery as it is received and has a preliminary estimate within about 15–20 minutes after the image time) which were very close to the position determined by the aircraft. It is not known whether these position estimates were partially "calibrated" by knowledge of the aircraft information or arrived at independently. In this case, the low-level center was being exposed by shear and, therefore, it is likely that this was an independent assessment.

Now that the past track and current motion of the tropical storm was well established, and the storm was located in the most data-rich area of the Atlantic basin (historically, tropical cyclone forecast position errors are smaller for the Gulf of Mexico region than for similar latitudes in the Atlantic basin), one might expect excellent guidance from the statistical, statistical/dynamical and dynamical models concerning the future motion of this storm. Figure 14 shows a portion of the past track, and the tropical cyclone track–prediction guidance package through 72 hours for Tropical Storm Jerry resulting from the initial data time of 1200 UTC 14 October 1989. Note the *Slight* divergence of opinions at this time. Also shown is the actual after-the-fact "best track" and the official forecast track issued at this time. One might say that the QLM and VICBAR (an experimental baratropic model being developed by Ooyama and others) did quite well. However, only 24 hours earlier, the QLM had predicted landfall south of Brownsville, Texas. Similar inconsistencies were noted for VICBAR and most of the other models. Since NHC83 had been the most reliable model for the past few years and it is based upon the NMC MRF model which would be expected to perform well in this data-rich area, and pressure change analyses indicated a general north to north-northeast motion, the official forecast track predicted landfall over southeast Louisiana.

It is particularly significant that model guidance initialized at 1200 UTC 14 October indicated that landfall was at least 36 hours and more likely 48 hours away. Also, with upper-level shearing taking place, no major change in strength was expected for at least the next 24 hours. Under those conditions, it is highly unlikely that a hurricane watch would have been issued the previous evening had the true positions of the storm been known and, in fact, may have been delayed a few more hours until the future course and strength of the storm was a little more certain.

Problems were not over with this storm. During the day, the storm weakened slightly with indications of further weakening possible. The hurricane watch was changed to a tropical storm watch as the storm continued moving northward. By late in the day, some possible north-northwest movement was indicated (Fig. 15). Most guidance continued to indicate landfall along the central or southeastern Louisiana coast.

At 0700 CDT (1200 UTC) 15 October, the tropical storm watch was extended westward to Port O'Connor, Texas and discontinued east of Morgan City, Louisiana. The storm now showed signs of some strengthening and continued on a north-northwest course. At 1100 CDT (1600 UTC), Jerry attained hurricane strength and hurricane warnings were issued for the upper Texas and western Louisiana coasts. The center

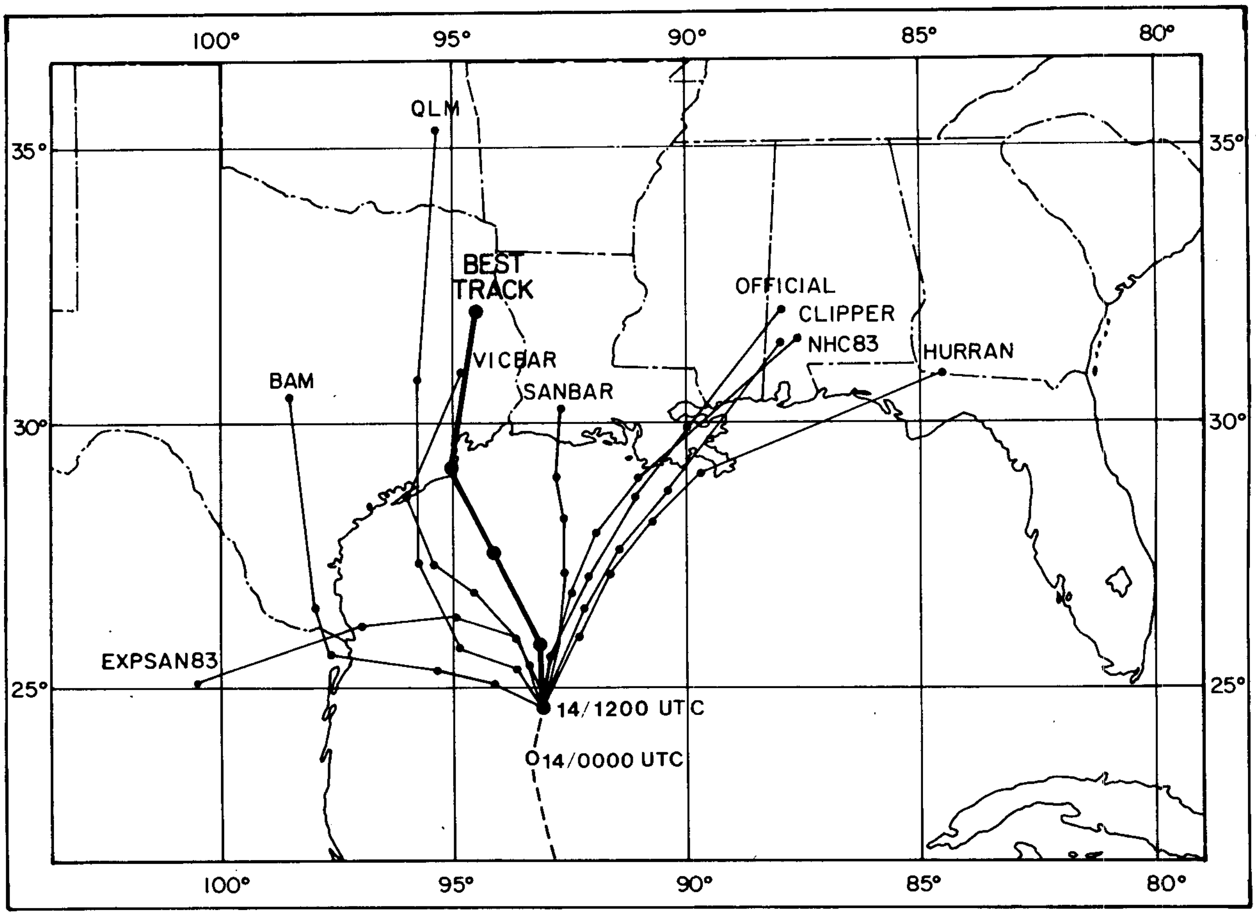


FIG. 14. Tropical Cyclone Jerry forecast track guidance from an initial data time of 1200 UTC on 14 October 1989. Also shown is the "official" forecast track issued at that time and the actual track of the tropical cyclone.

of this very small category-1 hurricane finally made landfall on Galveston Island near 2000 CDT (0100 UTC) Sunday evening, where sustained winds of 75 mi h^{-1} (34 m/s) and a peak gust of 100 mi h^{-1} (45 m/s) were recorded. This meant that actual lead time for preparations were less than 8 hours as sustained tropical storm force winds (usually all preparation activities must be complete by this time) were first reported at Galveston at 1800 CDT (2300 UTC). This was certainly less than desired, but fortunately, local officials said it turned out to be sufficient due to the small size of the category-1 storm and the fact that no major evacuations were needed. Also, the storm quickly passed over the area so only a short period of hurricane conditions were experienced.

2) HURRICANE HUGO, SEPTEMBER 1989

Hurricane Hugo was the strongest storm to strike the continental United States since Hurricane Camille of 1969. Due to its large size, it caused much more damage than did Camille. The total property loss was more than $10 billion dollars with more than $7 billion of that in the continental United States and the remainder in the northeastern Caribbean. Fortunately, by contrast to Jerry, the forecast and warning process for Hugo went smoothly and those factors combined with the excellent public response have been credited with saving many lives. The total loss of life was 28 in the Caribbean and 21 in the continental United States, remarkably low considering the widespread destruction.

Although forecast errors were substantially less for Hugo than the previous 10-yr average (Table 1), the fact that the forecast and warning process went well was not due to perfect guidance or perfect forecasts. However, there were no critical periods when appropriate data were not available and even though guidance showed considerable disagreement at times, correct decisions were made at the critical forecast and warning times.

Figure 16 shows all the "official" track forecasts issued for Hugo. These forecasts are generally issued at 6 hourly intervals with forecast positions at 12-, 24-, 36-, 48-, and 72-hours into the future from the initial time of the forecast. Also shown is the after-the-fact

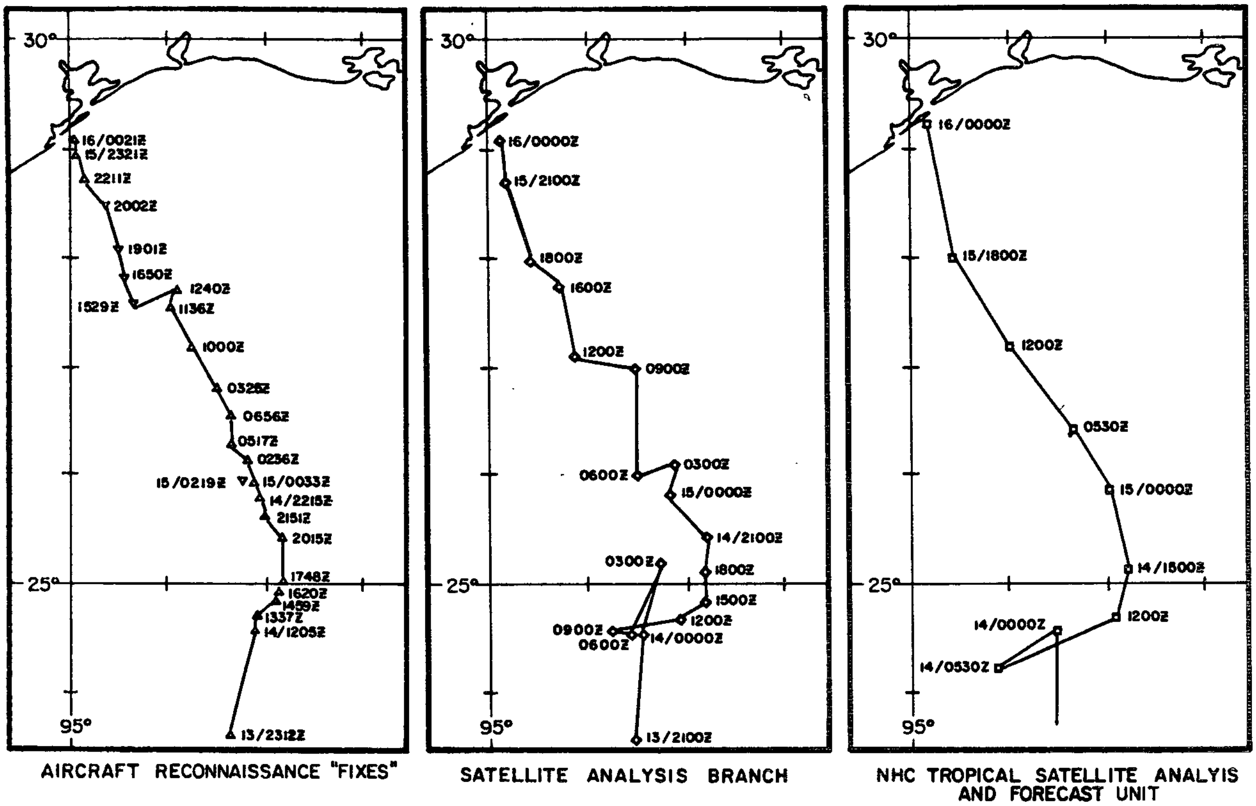


FIG. 15. Tropical Cyclone Jerry center positions determined by reconnaissance aircraft (left), SAB (middle), and TSAF (right).

"best track" at 6-h intervals. Note that the forecast track through the eastern Caribbean was extremely accurate. The forecast for the period when the hurricane was in the Atlantic north of Puerto Rico was marked by a bias to the left. The forecast tracks for the 2-day period that Hugo was approaching the South Carolina coast were also quite accurate. There was very little deviation from the actual point of landfall, but there was a temporary bias to the right for a few forecasts inland. In addition, timing was quite good with the forecast time of landfall being only 2 to 3 hours slow for the forecast issued at the time hurricane warnings were initiated.

TABLE 1. Hurricane Hugo average track forecast errors compared to previous 10-yr average. Errors are given in nautical miles and the number of cases is contained in the parentheses for this nonhomogeneous sample (courtesy of M. B. Lawrence, NHC).

	Forecast period (hours)					
Model	0	12	24	36	48	72
Official	10	33	65	98	122	154
	(43)	(43)	(41)	(39)	(37)	(33)
BAM	51	50	84	123	154	268
	(17)	(17)	(16)	(15)	(14)	(13)
CLIPER	10	37	73	119	161	216
	(43)	(43)	(41)	(39)	(37)	(33)
NHC83	12	38	61	88	106	178
	(42)	(42)	(40)	(38)	(36)	(32)
QLM	7	81	90	119	172	268
	(19)	(19)	(18)	(17)	(16)	(14)
SANBAR	8	28	55	92	141	302
	(15)	(15)	(15)	(14)	(13)	(11)
Official 1979–88	18	56	111	—	224	342

Figure 17 shows a selection of track forecast guidance packages which are representative of those available at the critical periods when hurricane watches and/or warnings were being considered for the eastern Caribbean and the eastern seaboard of the United States. Note the relatively small divergence of predicted tracks at low latitude and much larger differences at higher latitudes, where recurvature[13] presented a forecast problem. This is a typical distribution of forecast guidance which generally results in forecast errors being smallest at low latitudes.

Figure 18 shows a series of forecast tracks from the NHC83 and QLM computer models through 72 hours. Note the left bias of both models over the Bahamas.

[13] Period when the tropical cyclone change from moving basically westward to moving basically eastward.

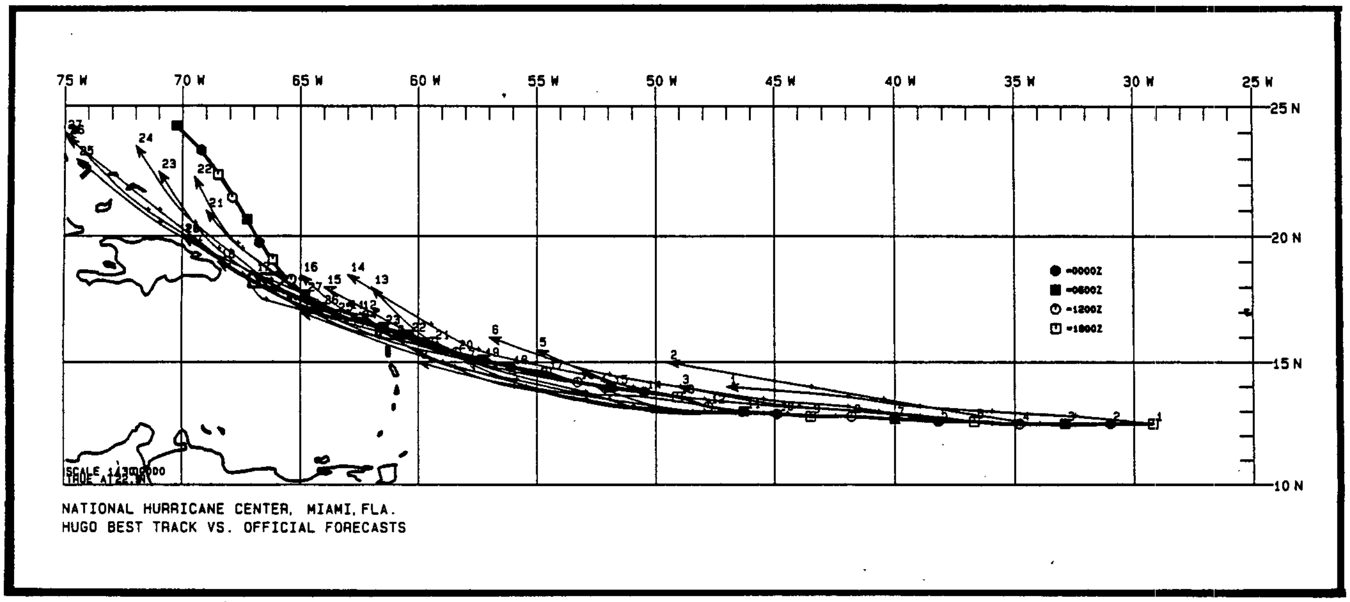


FIG. 16. Hurricane Hugo "official" forecast tracks (normally issued at 6-h intervals) through 72 hours for each of (a) the first 31 forecast issuances, and (b) the last 14 forecasts issued. Each forecast track is identified by the thin line with a number at the initial point and an arrow at the 72-h point. Also shown is the after-the-fact "best track" (bold line) with symbols at 6-h intervals.

These forecasts were consistent with NMC guidance which forecast a westward extension of the strong subtropical ridge north of the hurricane during this period. That guidance also predicted the formation of a mid- to upper-level low pressure center over Georgia about 20 September which was forecast to drift southwestward over the Gulf of Mexico. Later, the western extension of the subtropical ridge was expected to erode quickly resulting in Hurricane Hugo turning toward the northeast rather rapidly near the time of landfall. The European Centre for Medium-Range Weather Forecasts with forecast initiation time of 1200 UTC 17 September provided excellent guidance 168 hours into the future. However, these products also lacked consistency from forecast to forecast. Forecast tracks for hurricane Hugo, generated by models at NMC, the ECMWF and the United Kingdom Meteorological Office (UKMO) are shown in Fig. 19. These guidance products and factors were taken into account and somewhat reflected in the official forecasts illustrated in Fig. 16.

In addition to track forecasts, storm strengths are considered in the warning process. Hugo strengthened markedly during the last 12 hours before landfall on the continental United States. This increase in strength was not forecast in a timely fashion. At the time the warnings were issued (0600 EDT 1100 UTC 21 September), maximum sustained wind speeds were estimated to be 110 miles h^{-1} (49 m/s) and little change in strength was expected. However, this wind speed was only 1 mile h^{-1} (0.5 m/s) below a category-3 storm and therefore, local and state officials were advised to prepare for a category-3 hurricane. By noon EDT (1600 UTC) that day, the hurricane had been upgraded to a category-3 hurricane and by early evening to category 4, with maximum sustained winds estimated to be 135 miles h^{-1} (60 m/s).

The strength of the wind field associated with a hurricane is determined from several sources such as satellite-based Dvorak estimates, reconnaissance aircraft measurements, and buoy and ship observations. One popular misconception is that forecasters simply take the wind measured at flight level and state that as the sustained surface wind. In actual practice, empirically derived pressure/wind relationships are used as a first guess until clearly overruled by actual observations. The convective nature of the storm is also considered in determining what reduction in flight level winds should be applied for surface wind estimates when no direct measurements are available.

Figure 20 shows the after-the-fact "best track" minimum sea-level pressure and estimated maximum sustained surface wind speed graphs for Hurricane Hugo along with the data from which they were derived. Note that when the first reconnaissance aircraft arrived in the hurricane on 15 September it measured a minimum sea-level pressure (MSLP) of 918 mb, 30 mb less than estimated by satellite units in Washington (SAB) and at NHC (KMIA). Also, note the apparent scatter of aircraft derived maximum sustained wind speeds. These plots contain values reported in the standard "vortex" messages transmitted from the aircraft. Such reports can cause confusion for the casual or uninformed user and therefore, for responsible officials and

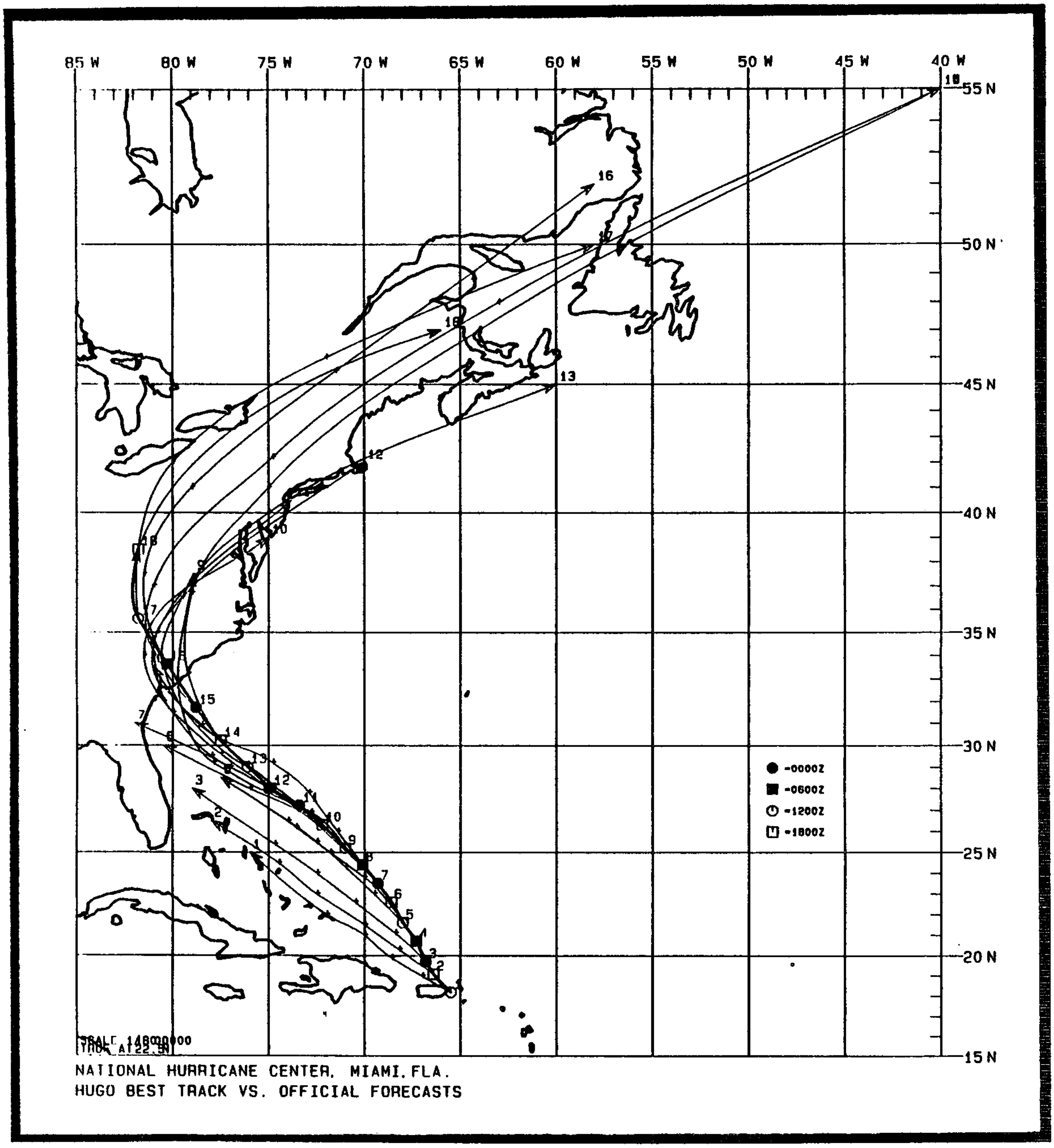


FIG. 16. (*Continued*)

the general public. An example of such a problem will be given later concerning Hurricane Babe of 1977.[14]

On 15 September Hurricane Hugo was a category-5 hurricane with a MSLP of 918 mb and an estimated

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[14] Standard "vortex" messages generally report the maximum sustained wind on the last inbound leg prior to the determination of the center location and associated minimum pressure and temperature; i.e., the wind is frequently measured in weaker parts of the hurricane. Likewise, surface wind estimates require that the surface can be seen from the aircraft flight level (generally 5000–10 000 ft for hurricanes). Of course, the maximum wind generally occurs in the eyewall where the surface cannot be seen. The forecaster takes these factors into account by looking at the total wind field as well as using a first guess from the empirically derived pressure/wind relationship (open circles), the level of the observations, and the convective nature of the storm in surface wind-field determinations. Recently, the vortex message was modified to include the maximum sustained wind encountered in the last passage through all four quadrants in attempt to more accurately portray the strength of the storm.

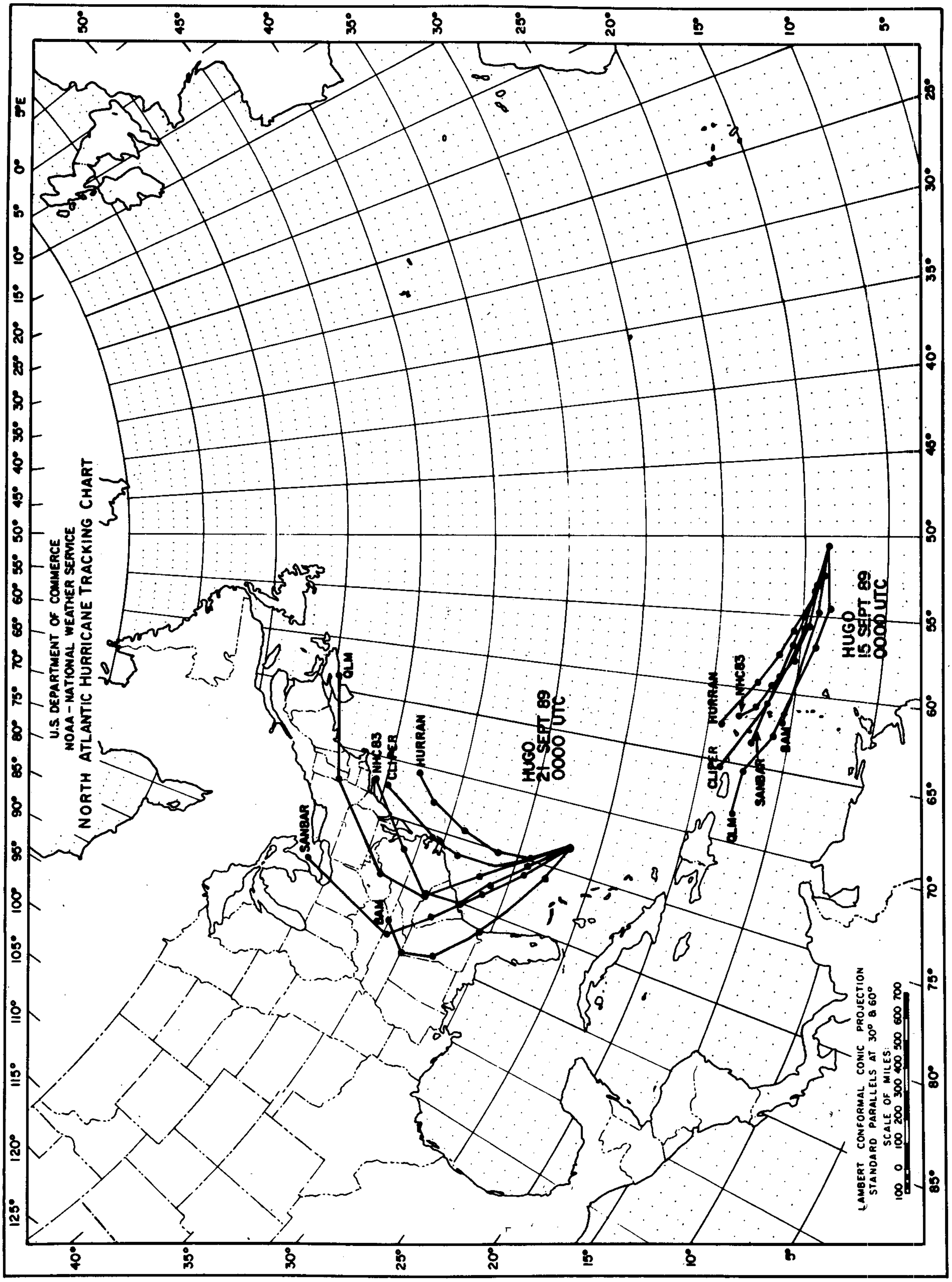


FIG. 17. Selected track forecast guidance through 72 hours for hurricane Hugo with initial data times of 0000 UTC on 15 and 21 September 1989.

maximum sustained surface wind speed of 160 miles h^{-1} (72 m/s) prior to entering the Caribbean. Fortunately, the hurricane weakened to a category-4 hurricane before entering the Caribbean and then exited north of Puerto Rico as a category-3 hurricane with a MSLP pressure of 945 mb. Some further weakening occured east of the Bahamas where the MSLP rose to 966 mb. From 0100 UTC 21 September until 1700 UTC 21 September, the minimum pressure only decreased by 3 mb. The maximum sustained wind speed was slightly below category-3 status during this period with aircraft measured winds being less than indicated by pressure/wind relationships. At 1600 UTC (noon EDT) 21 September, Hugo was upgraded to category-3 status with estimated maximum sustained wind speeds of 115 miles h^{-1} (51 m/s) and a MSLP of 947 mb. The public advisory was headlined ". . . MAJOR HURRICANE HUGO MOVING TOWARD SOUTHEAST U.S. COAST. . . ." The pressure then began to decrease rapidly as the hurricane approached the South Carolina coast. By 1900 UTC (1500 EDT), the pressure had dropped another 2 mb to 945 mb and the maximum sustained wind speeds were estimated to be 125 miles h^{-1} (56 m/s). The public advisory was then headlined ". . . MAJOR HURRICANE HUGO STRONGER AND MOVING FASTER TOWARD CAROLINAS. . . ." At 2200 UTC (1800 EDT), Hugo was upgraded to a category-4 hurricane with wind speeds of 135 miles h^{-1} (60 m/s). The MSLP had dropped an additional 4 mb in the previous 3-h period to 941 mb. The headline was now ". . . EXTREMELY DANGEROUS HURRICANE HUGO NEARING SOUTH CAROLINA COAST. . . ." The center finally moved across the barrier islands just east of Charleston, South Carolina near midnight with a MSLP of 934 mb.

b. National and international coordination

1) HURRICANE HUGO, 14–18 SEPTEMBER 1989

When Hurricane Hugo first threatened the Caribbean area, the RA IV Hurricane Operations Plan was put into effect. NHC forecasters individually contacted by telephone the meteorological services in Barbados, Curacao, Martinique, Antiqua and the NWS office in San Juan, Puerto Rico as well as maintaining the standard U.S. Navy contacts. The government meteorological services in the countries just mentioned not only have the responsibilities for their own warnings but have coordination responsibilities for other islands in their respective areas. For instance, Barbados has additional responsibilities for Grenadine, St. Vincent, St. Lucia and Dominica. Martinique is additionally responsible for Guadeloupe, the French half of St. Martin and other smaller islands in the area and Antigua is also responsible for Montserrat, St. Christopher, Nevis, Barbuda, St. Barthelemy, Anguilla, Anegada, and other small islands in the area. Curacao is responsible for St. Eustatius, the Dutch half of St. Maarten and other small islands in the northeast Caribbean as well as several islands in the southern Caribbean. The San Juan WSFO is responsible for local adaptation of NHC warnings for Puerto Rico and the U.S. Virgin Islands such as St. Croix, St. Thomas and St. John as well as some smaller islands in the area.

As the designated Regional Specialized Meteorological Center for the region, the NHC not only provides forecast and warning guidance for all nations in the region, but attempts to assure that watches and warnings are consistent throughout a threatened region. As illustrated by the list above, numerous meteorological services and different government units were involved when Hugo threatened the northeast Caribbean. There is considerable interaction between people on the various islands in the area including fishing and tourism traffic. These tourists are from around the world, many on small and medium size boats, and are frequently confused by different names or spellings for the same island such as St. Martin (French) and St. Maarten (Dutch). Imagine the confusion that would result if one island in the middle of a line of islands had warnings up while the others did not, or if the French half of St. Martin had warnings up while the Dutch half of St. Maarten did not. The RA IV Hurricane Operations Plan was developed to generate cooperative efforts and to try to prevent such problems. Each of the countries mentioned above were individually contacted by phone every time a proposed watch or warning change was suggested for their respective areas of responsibility. Later, as Hugo moved into the northeast Caribbean, the Dominican Republic and the Bahamas were added to the coordination list.

A hurricane watch was first issued for the northeastern Caribbean islands from St. Lucia through St. Martin and the British Virgin Islands the evening of 15 September. Later that day, hurricane warnings were issued and the following day extended to include Puerto Rico and the U.S. Virgin Islands. This meant that well over 24 hours of warning were provided prior to the center moving into the eastern Caribbean in the late evening and early morning hours of the 17 and 18 September. Response in the region was excellent based upon the relatively low loss of life from this category-4 hurricane which produced about $2 billion in damage in the region. This effective warning and response system was not something that just happened when Hugo appeared. It was the result of years of cooperative work by governments in the region.

2) HURRICANE HUGO, 19–22 SEPTEMBER 1989

The effective warning and response for the southeast coast of the United States during Hugo also did not happen overnight as Hugo approached. Fortunately, the SLOSH model simulations had been completed for the Charleston and Savannah areas during the past

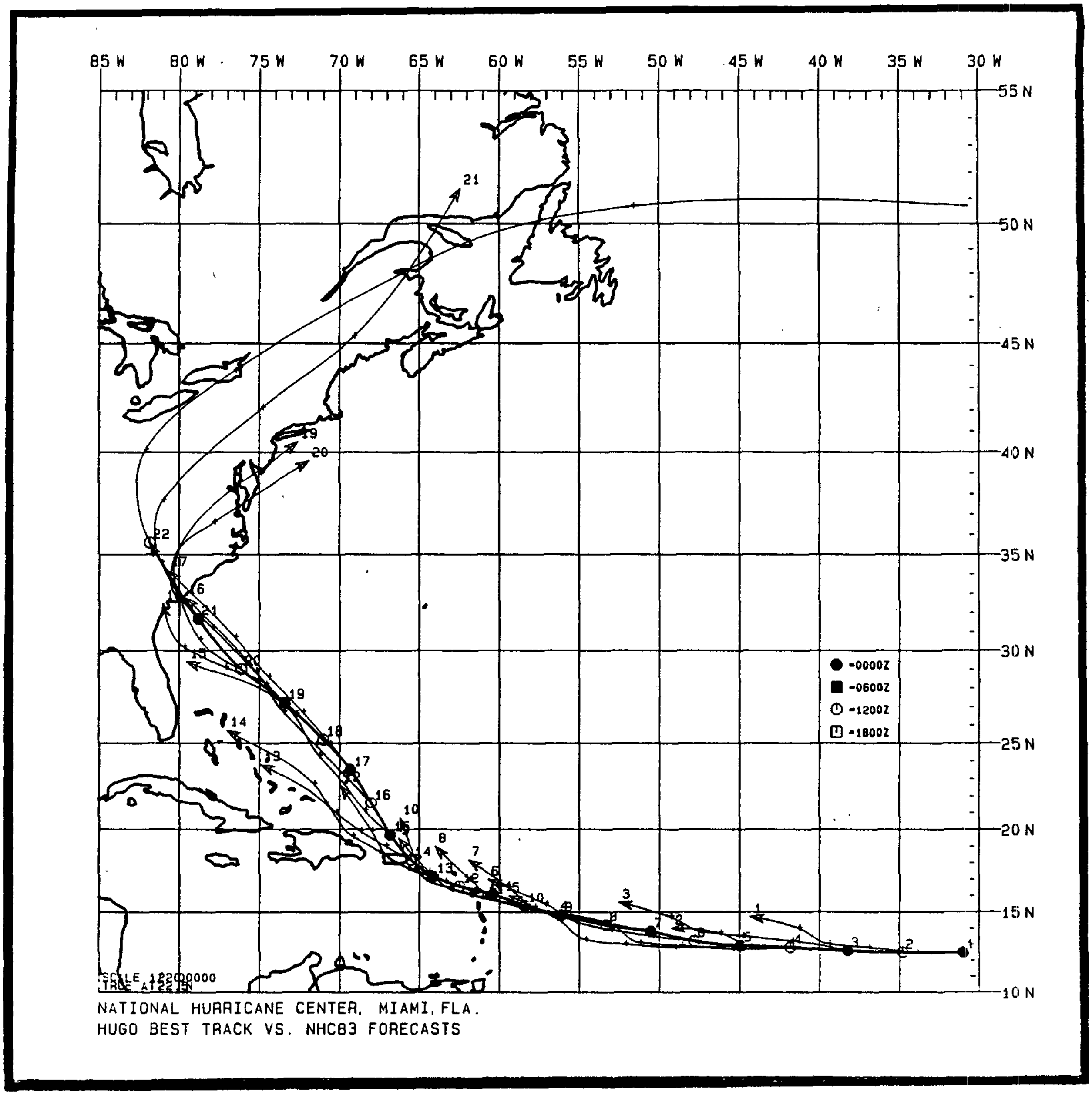


FIG. 18. Forecast tracks for Hurricane Hugo (1989) through 72 hours issued at 12-h intervals generated by the (a) NHC83 statistical/dynamical model; and (b) QLM dynamical model. Model outputs are available at 6-h intervals from NHC83, but only at 12-h intervals from the QLM.

few years. Several workshops had been conducted in the area on the use of this tool as well as other NWS forecast and warning products for response to a hurricane threat. One such workshop was held in Charleston as late as 13 July 1989. Local and state officials, NWS, Federal Emergency Management Agency (FEMA) and U.S. Army Corps. of Engineers representatives participated in these meetings as well as some media personnel; i.e., all responsible groups knew the high risk areas in the region and required evacuation times. The process now became one of the delicate balances mentioned earlier of providing sufficient warning, but minimizing expensive overwarning.

Throughout the day of 20 September, statements were frequently made during telecasts from the NHC that a hurricane watch would likely be required later that day or early the next day for portions of the southeast United States coast from central Florida to North Carolina. The effect of these statements, even prior to issuance of an actual watch, was that some people in

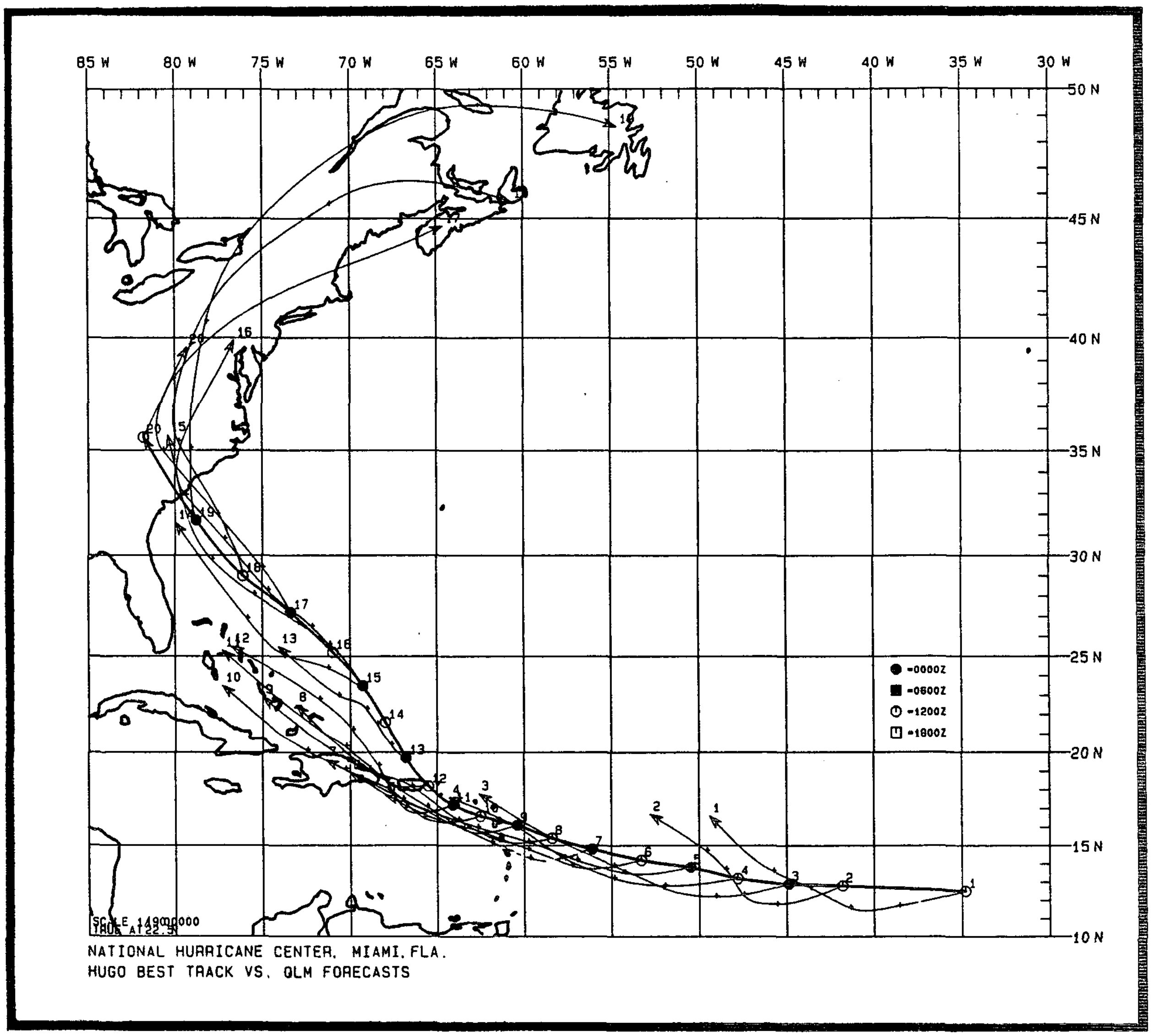
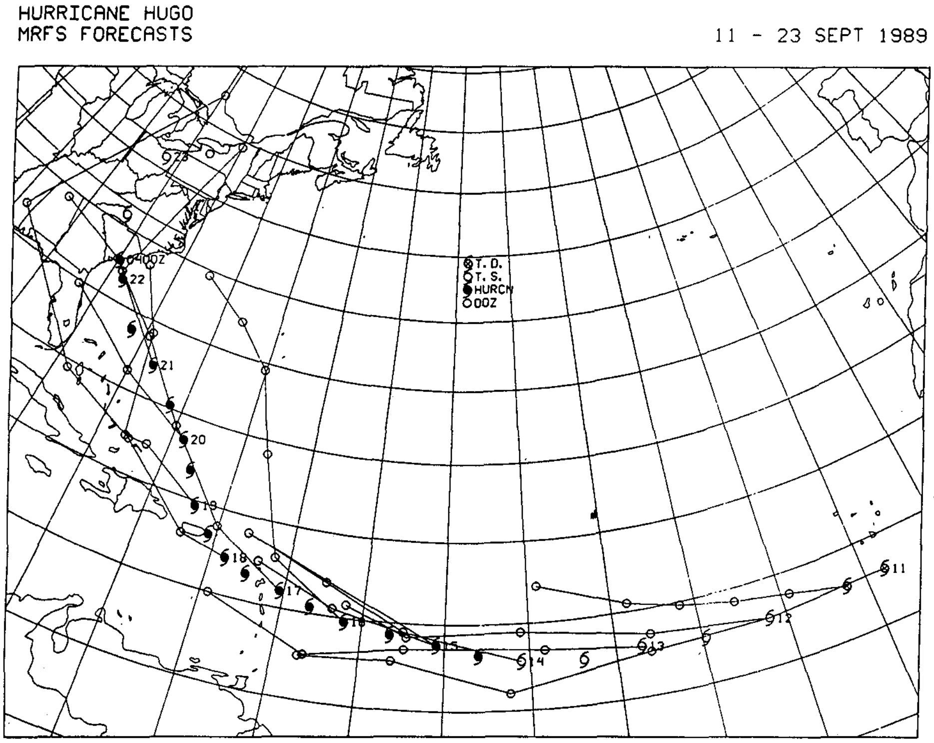


FIG. 18. (*Continued*)

the area started preparations and, in fact, some started evacuations. At 1800 EDT (2200 UTC) 20 September, a formal hurricane watch was issued for the coastal region from St. Augustine, Florida to Cape Hatteras, North Carolina. It was also stated in the advisories and numerous telecasts that evening that a hurricane warning would likely be issued for a portion of the region at 0600 EDT (1000 UTC) the next morning. These issuances and statements as well as statements being issued by local NWS offices, and local and state government officials increased preparation activities on the coast with many more people now evacuating prior to the actual issuance of a warning. The effect of this steady, stepwise increase in perceived threat was to reduce required evacuation time for vulnerable areas when the actual warning was issued. Historically, people who evacuate early are those who want an extra margin of safety and are less likely to complain after the fact. Such complaints may be reflected in increased complacency for the next time. Approximately 15% to 20% of people in vulnerable areas along the Georgia and South Carolina coasts (local emergency management officials, personal communication) evacuated prior to the issuance of the warning. This process permitted a delay in the warning which allowed some narrowing of the warning area. At 0600 EDT (1000 UTC), the official hurricane warning was issued.

Throughout this period, internal contacts between NHC and other NWS units as well as with state and local emergency management officials were taking



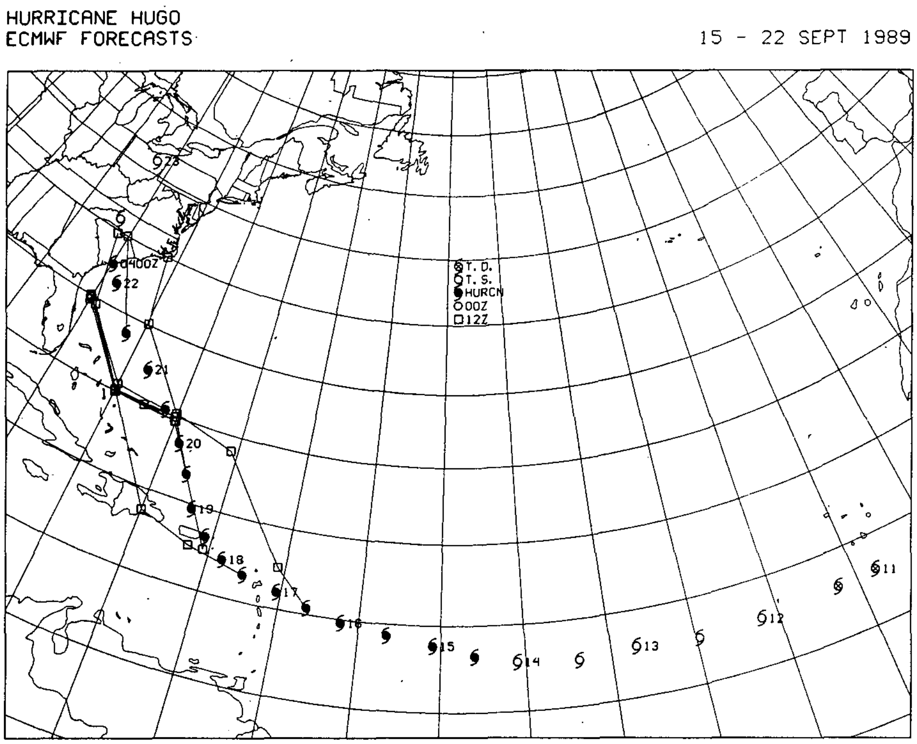


FIG. 19. Track forecasts generated for Hurricane Hugo (1989) by prediction models at the (a) NMC (MRF), (b) ECMWF, and (c) UKMO (courtesy J. Ward, NMC).

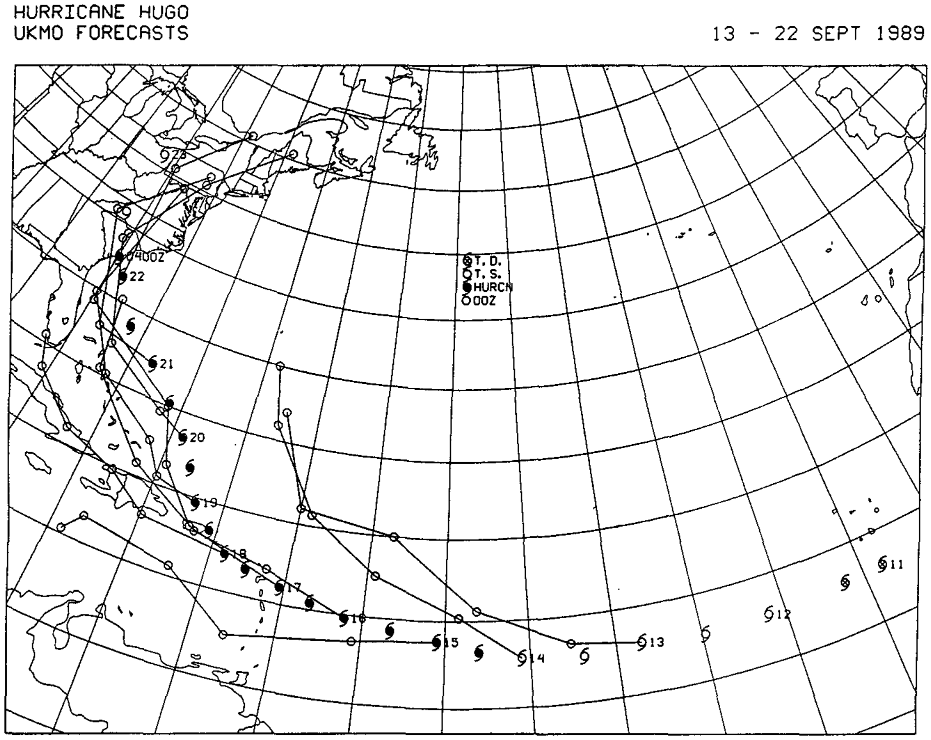


FIG. 19. (*Continued*)

place. Some local emergency management officials started official evacuations before the actual issuance of the warning, but most coincided with the warning. Shortly after noon on 21 September, Governor Campbell contacted the director of NHC to state that more than 90% of the people on the South Carolina barrier islands had been successfully evacuated. The great majority of the remainder were evacuated during the next 2 to 3 hours, well before tropical storm or hurricane conditions arrived on the coast.

During the Hurricane Hugo threat, the electronic media pool at NHC requested that 30–60 sec hourly updates be provided by the NHC spokesperson in addition to the standard issuances of advisories as the hurricane moved toward the coast. These updates were provided nationwide for all stations who desired them. Stations in the threatened area routinely broadcast these updates and frequently followed up with more detailed information from the local NWS offices and their local television meteorologists and weathercasters. Numerous individuals in the threatened area stated that this process permitted them to go about their preparation activities in a calm and orderly fashion, assured that they were being provided the most complete and accurate information available and would be immediately aware of any major changes. Local media, including their meteorologists, also commented on how this process permitted the most up-to-date and accurate information to be made available to their respective audiences. They could follow up with specific applications for their respective areas, motivating people to take the right actions. More than 700 independent telecasts were made directly from NHC during hurricane Hugo. Clearly, the highly coordinated and cooperative efforts of the three groups mentioned earlier resulted in the excellent response for this record-breaking hurricane.

As mentioned earlier, during the afternoon of 21 September, Hurricane Hugo increased in strength. Also the area of hurricane force winds expanded well to the north and east of the center. The result was the potential for hurricane force winds on portions of the outer banks of North Carolina and over Pamlico Sound. Therefore, at 1500 EDT (1900 UTC), hurricane warnings were extended northward from Cape Lookout to Oregon Inlet, North Carolina including Pamlico sound. The extension of these warnings at this late time caused some concern for local officials as it was too late for any major evacuations in this region. However, local NWS officials explained to them that this extension of the warning did not reflect a major change in the forecast track, but was primarily due to the expansion of the region of hurricane force winds; i.e., the area was not expected to experience the core of the hurricane, but could experience hurricane force winds and increased storm surge and wave action. Therefore, no

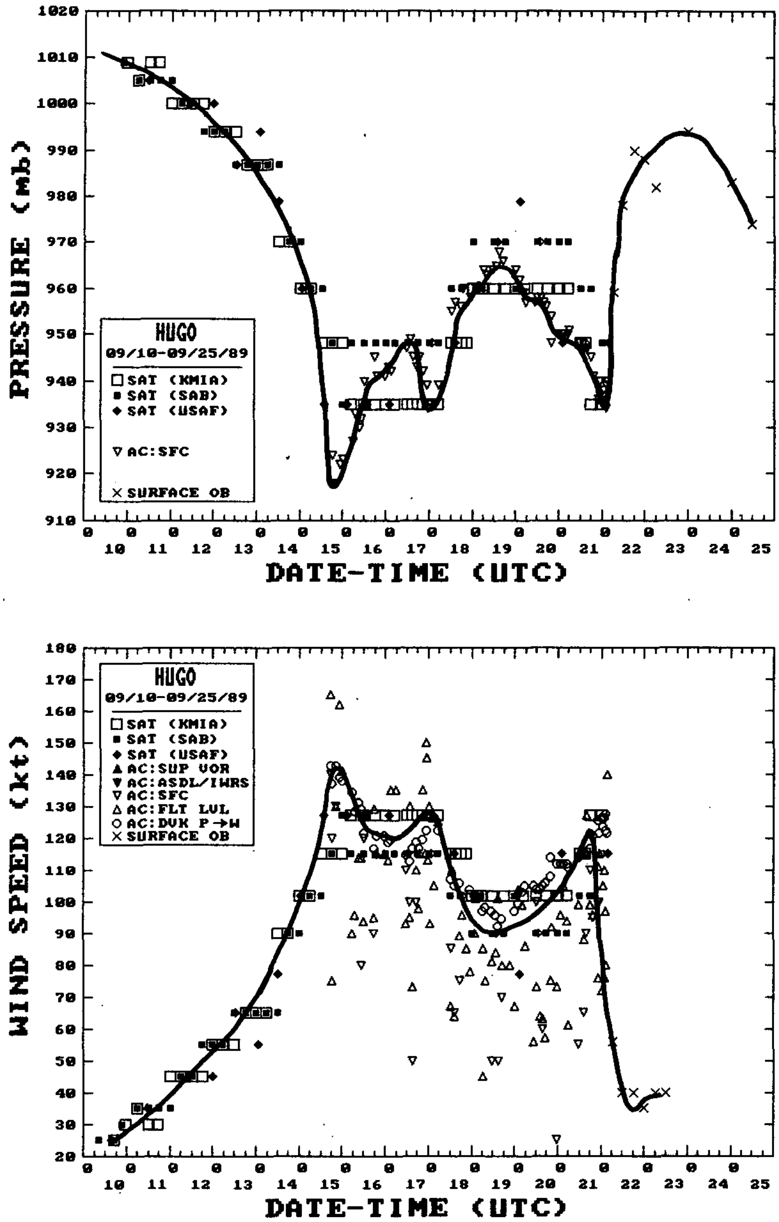


FIG. 20. Hurricane Hugo (1989) (a) minimum sea-level pressures, and (b) maximum sustained wind speeds. The bold solid curve is the "best track" values determined after the fact.

major evacuations off the barrier islands would seem necessary. Increased preparation activities that might be prudent, as compared to activities under the previous tropical storm warning, would be for people who had planned to stay in the first row of houses on the beach to move away from the wave action, people in mobile homes to move to more substantial housing on the island, and those who readily had the materials available and had not done so to board up as weather conditions were just starting to deteriorate. Under these conditions, activities went well and no major problems were encountered in the area.

c. *Conflicting information*

The great majority of private meteorological firms and media meteorologists work very closely with the NWS to provide the best possible services for their specific clients and the public in general. Private meteorological firms closely monitor NHC issuances including meteorological discussions, and frequently call NHC during critical decision periods for their clients. Companies dealing with oil rigs, etc., also frequently provide observations to NHC and other information about vulnerbilities and response times that assist NHC in its responsibilities. In addition, the present satellite communications systems used by the media permits the general public to receive the information directly from the source of the warnings. Although, this has not totally eliminated response problems associated with conflicting information, it has greatly improved the warning and response process as exemplified by the response during Hurricane Hugo. In most cases where problems have occurred, it has been due to an inexperienced person not realizing the impact to the general public of what might seem to be rather innocent remarks. Those cases are usually quickly cleared up with no lasting impacts upon response. However, there occasionally seems to be a lack of sensitivity to the response process, previously described, which required years of work and highly coordinated efforts to protect life and property when a hurricane threatens. Two such cases are illustrated below.

1) HURRICANE BABE, SEPTEMBER 1977

Conflicting information provided to the public during Tropical Storm Babe caused considerable problems for the public and local officials responding to that storm. An Air Force reconnaissance aircraft reported a measured wind of 70 kt (36 m/s) at a flight level of 1500 ft (457 m) and estimated a surface wind of 70 kt—a very subjective process. A private meteorologist in New Orleans who routinely monitored "vortex" messages from the aircraft apparently failed to check out the report or compare it with other information, but immediately went on the air and stated that Babe was now a hurricane. This was contrary to official advisories being issued by the NHC at that time and what local officials were responding to. Such a declaration was almost assuredly inaccurate and caused great confusion in the highly vulnerable New Orleans and southern Louisiana area. The minimum sea-level pressure reported in that same vortex message was 1000 mb. Empirically derived pressure/wind relationships would result in a 45 kt (23 m/s) wind for that pressure. It is highly likely that the reported wind was an isolated value in a convective cell and not representative of the wind field associated with the storm. This assessment is further supported by the fact that the maximum wind speed reported in all other "vortex" messages before or after the 70 kt wind report was 55 kt (28 m/s) or less. However, the on-air statement by a well-known meteorologist in the area caused great confusion for the general population and questioning of local officials' actions.

After consultation with those officials, the director of the NHC decided to officially upgrade the storm to hurricane status so that preparation activities could proceed in an orderly manner. Although the central pressure of the storm decreased to 995 mb during the next 13 hours, it is questionable whether or not Babe ever actually attained hurricane force. The actual maximum sustained winds recorded on the coast were 39 kt (20 m/s) with gusts to 46 kt (24 m/s). There were almost assuredly stronger winds that were not recorded, but even the 995 mb pressure would only support 55 kt (28 m/s) wind speeds, based upon standard pressure/wind relationships.

2) HURRICANE GILBERT, SEPTEMBER 1988

Track forecasts in conflict with official forecasts were issued publicly in the Galveston/Houston area by a private meteorological firm during Hurricane Gilbert. These issuances contributed to some controversial evacuation decisions. At the time, the official forecast track and hurricane warnings were well south of the area. However, a private forecast was issued indicating this powerful storm was

> . . . expected to take a turn more to the northwest and north tonight, and (company name) believes it will go onshore between Galveston and Corpus Christi during the early part of Friday afternoon. Winds in your area (Texas City) will begin to increase later tonight (Thursday), with the worst conditions likely during tomorrow. Most likely wind speeds at your site will average 40–70 MPH during tomorrow with stronger gusts as well. . . .

After the fact, the client who received this message wrote a letter to the firm, stating

> Your 1100 CDT report, received by fax, predicted landfall between Galveston and Corpus Christi. At about the same time, one of your staff stated on radio station (call letters) that he felt that the storm had slowed and had begun movement on a more northly (sic) track. In the radio report, several times he referred to the "worst case scenario . . . landfall at Texas City."

The client then called the meteorological firm questioning the difference between this forecast and the official forecast. He later received a "correction" which stated that the predicted location of landfall was a typographical error and that it should have read between Brownsville and Corpus Christi. In the letter to the company, the client stated

> The written report very well may have been an inadvertent error, but the intent of the radio spot was clear. It appeared someone was too anxious to be the first to call the long predicted turn to the north. As you can see from the attached newspaper article, your actions contributed to Galveston's decision to recommend evacuation. This event heightened the level of fear and concern throughout our area.

Because of the concern for the life and safety of people on Galveston Island, the confusion that was already taking place as a result of the conflicting information, and the potential for impact by this major hurricane the official in charge at Galveston felt the most prudent action was to order an evacuation. Unfortunately, this action was contrary to what surrounding counties were doing based upon NWS issuances. The complex evacuation procedures based upon the SLOSH model studies mentioned earlier were now in disarray. Inland, host counties were not prepared to open evacuation shelters for the barrier island evacuees nor to provide special traffic flow procedures, etc. These actions are quite expensive and these communities were reluctant to take such actions based upon their assessment of the situation. By contrast, the official at Galveston felt he had little choice in the matter.

5. Future hurricane forecast and warning operations

Forecasters and numerical models continue to suffer from the lack of quantitative data over the tropics and subtropics. Therefore, analyses require manual interpretation of qualitative information. The next generation *GOES* series satellites (Shenk et al. 1987) with the first satellite in the series planned for launch during 1991 is expected to provide more accurate and higher resolution "sounding" data than presently available from geosynchronous satellites. Similar improvements are expected from polar-orbiter satellite systems. However, much of the information available to the analyst will remain qualitative in nature. Therefore, it is expected that the best possible analysis for the tropical and subtropical regions will involve a man/computer interactive multiple level analysis scheme with an initial objective analysis modified by the analyst. Although quite difficult, the scheme should contain four-dimensional checks for dynamical consistency. Such a scheme is being pursued at NHC. These new sounding capabilities and this analysis approach should improve initial analyses and forecasts of the large-scale flow patterns over the tropical and subtropical regions. However, it is likely that the accuracy of these analyses and forecasts will continue to lag those at midlatitudes where more quantitative data are available.

Modelers indicate that such improved initial datasets in the tropical cyclone, its near environment, and over the general tropical and subtropical belt, will result in significant improvements in tropical cyclone track and intensity predictions. It is the author's opinion that any major improvements in longer range forecasts (36–72 hours) will likely only come through improved dynamical models. Global, hemispheric, and regional models have shown considerable promise in recent years for forecasting storm motion. Figure 19 shows results from three of those models for Hurricane Hugo. Note some excellent forecasts, but also the lack of consistency. These models are presently out performed by statistical/dynamical models through 72-h forecast periods, but have been closing the gap between them in recent years. In addition, these dynamical models often provide the best guidance available for difficult forecast situations.

Statistical/dynamical models will likely continue to be the best performers for tropical cyclone track predictions, for the next several years, through forecast periods up to 36 hours or more. Results from improved versions of NHC83, (to be named NHC90) indicate that tropical cyclone, forecast-track errors might be reduced by as much as 10%–20% through the use of these type of models over the next few years, depending upon the performance of the associated dynamical model.

In addition to the models cited above, mesoscale models such as the new ETA coordinate system model (Mesinger et al. 1988), under development and testing at NMC, are showing great promise. Hopefully, these models and perhaps the regional and hemispheric dynamical models mentioned earlier will start to show some skill in the prediction of tropical cyclone formation and intensity. Such skill is sorely lacking at this time.

Methods for observations in and around tropical cyclones continue to improve. New satellite technology includes the Air Force Special Sensor Microwave/Imager (SSM/I) system aboard a polar-orbiting satellite (Negri et al. 1989). This system shows promise for improved rainfall estimates (Olson et al. 1989) and surface wind estimates outside of high rain rate areas where wind speeds are less than 30–50 kts (Rappaport 1989). The microwave sensor also provides essentially a "smeared" radar image which can help in center locations of tropical cyclones (Veldon et al. 1989). Lightning detection systems are also coming into use for monitoring the convective activity in hurricanes well away from land (Lyons et al. 1989). These systems are being used to track movement of the convective bands and eyewall and perhaps to infer intensity changes. New aircraft capabilities include the Air Force IWRS capabilities using satellite data links mentioned earlier which provide detailed wind fields in real time for operational use in potential storm surge calculations and damage-potential warnings. Also, these systems provide capabilities for improved tropical cyclone tracking using the mass field (Sheets 1986). That system has shown potential for significant improvement in the 12–36-h forecasts.

Present operational reconnaissance aircraft provide valuable data in the core of the hurricane. However, these data are generally limited to along the flight path or below it at infrequent intervals using dropwindsondes (Burpee et al. 1984). These aircraft are also slow. Doppler radar capabilities are now an integral part of NOAA's research aircraft operations. These systems provide entire data fields within several miles

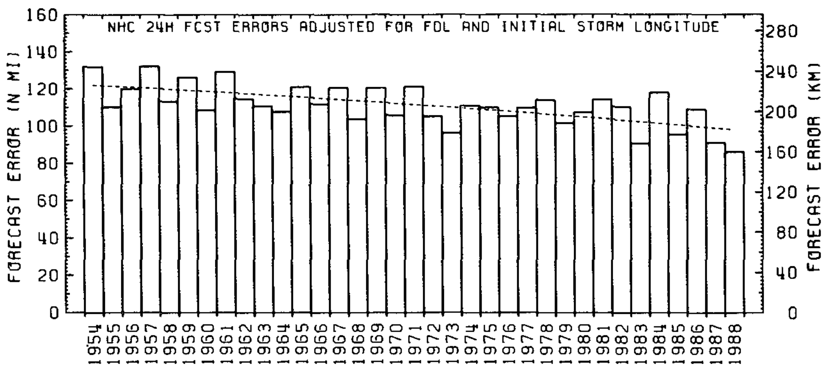


FIG. 21. Atlantic basin "official" 24-h forecast error trends. The forecast errors have been adjusted for forecast difficulty using the CLIPER model (Pike and Neumann 1987) and the initial storm longitude (courtesy of C. Neumann, NHC).

of the path of the aircraft (Jorgensen 1984; Marks and Houze 1987). Even though remote-sensing technology continues to advance, the use of satellite-based sensors in the core of the hurricane is rather limited, partially due to the poor resolution provided from orbital altitudes of 400 miles or more. Perhaps these same sensors could be adapted for use on fast, high-altitude jet aircraft. The result could be a comprehensive dataset provided by the aircraft flying through the storm and satellite surveillance of the storms environment. Also, single or orthogonal passes through the tropical cyclone could quickly provide entire data fields. This would permit more time for near-environment sampling for model use and assist in calibration of the coarse satellite data. Shorter response times for the faster aircraft would reduce the number of flights cancelled after deployments due to later data. The combination of all these factors would not only mean that data coverage would be greatly improved, but that perhaps four or five specially equipped aircraft could meet the Atlantic basin operational data needs as compared to maintaining large reconnaissance squadrons with aging aircraft.

The addition of doppler capabilities (Doviak and Zrnic 1984) for the next generation NWS radar (NEXRAD) systems will add a new dimension to hurricane warning capabilities. These systems are scheduled for installation along the Gulf of Mexico and Atlantic coasts of the United States during the early and mid-1990s.[15] The doppler capabilities will provide much needed information on tropical cyclone wind fields and their changes as they move inland (Wood and Marks 1989). These and other capabilities will permit more refined warnings during hurricane events. It is envisioned that there will be warnings within warnings; i.e., hurricane warnings will be issued for a broad area of the coast, as they are today, to provide time for evacuations and other preparations, well in advance of the arrival of strong winds and heavy rains on that coast. The NEXRAD system will then be used by local NWS offices to provide short-term warnings as rainbands, high winds, and possible tornadoes move toward specific locations. This will permit incomplete emergency preparations to continue in safety until more extreme conditions approach.

In addition to the wind and storm surge problems normally associated with hurricanes as they approach the coast, heavy rains and flooding frequently occur over widespread areas extending well inland. The NEXRAD system should aid in improving rainfall forecasts and permit better warnings for inland river flooding such as that of hurricane Agnes in 1972.[16]

Improved observing systems and anticipated improvements in analysis, forecasting and warning programs require efficient accessing, processing and analyzing of large quantities of different types of data from numerous sources. These data also provide the opportunity for improved forecasts from numerical models. The class VII computer scheduled for the National Meteorological Center at Suitland, Maryland will permit operational implementation of next generation hurricane prediction models. Finally, products must be provided to users which optimize desired responses. The Advanced Weather Information and Processing System (AWIPS) (AWIPS-90 1985) will be the primary tool for accomplishing this task. Critical meteorological information required by local, state and federal officials and private industry, can be displayed graphically and either accessed or transmitted to users. For example, warning areas, predictions of coastal flooding, expected

[15] The first systems are due at Melbourne, Florida and Washington, D.C. in 1990.

[16] The remnants of Agnes caused major flooding from North Carolina through Pennsylvania and New York with the loss of 122 lives and $2 billion in damage.

rainfall, maps of probabilities, etc., would be generated and made accessible to users. Providing a uniform product for these users should then minimize chances of confusion and result in a more effective warning and evacuation process.

6. Concluding remarks

Tropical cyclone track forecasts have been improving at a slow, but steady pace for at least the past three decades (Fig. 21). Advancing technology is providing the opportunity to greatly increase the rate of improvement and to provide better warning products along the coast and inland. However, the rates of forecast improvement will continue to be much slower than the rate of population growth in hurricane-prone areas. Unless adequate means of evacuation and/or places of refuge are provided for residents in existing and planned communities, on barrier islands and in other vulnerable coastal communities—which keep required evacuation times to less than 24–36-hours—greater overwarning will be required. Such increased overwarning could result in a significant increase in the loss of life due to hurricanes.

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