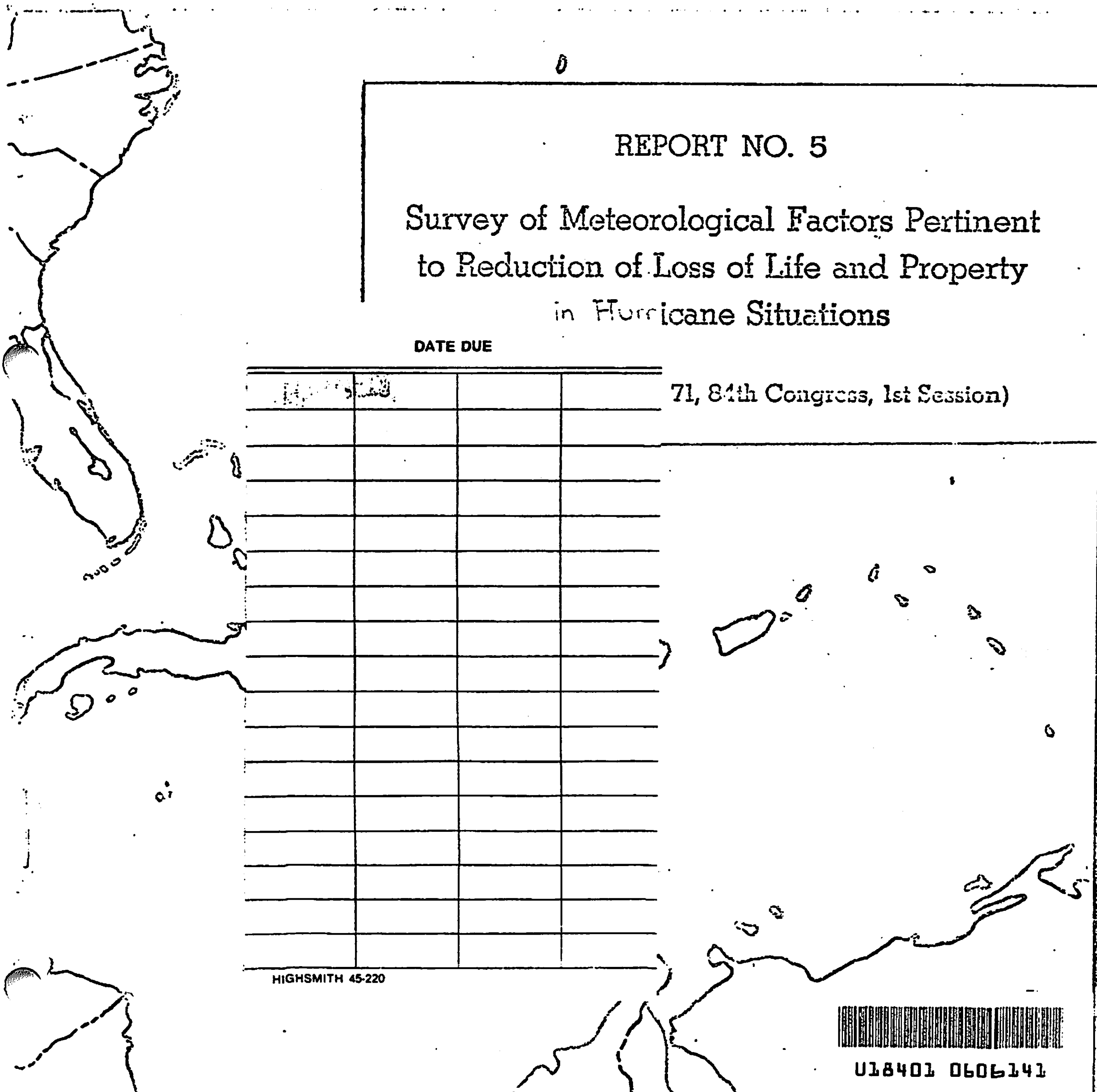
NATIONAL HURRICANE RESEARCH PROJECT



REPORT NO. 5

Survey of Meteorological Factors Pertinent to Reduction of Loss of Life and Property in Hurricane Situations

71, 84th Congress, 1st Session)

U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, Secretary
WEATHER BUREAU
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A Progress Report of Work Accomplished
Under P. L. 71, 84th Congress, 1st Session

Washington, D. C.
March 1957

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Reports by Weather Bureau units, contractors, and cooperators working on the hurricane problem are pre-printed in this series to facilitate immediate distribution of the information among the workers and other interested units. As limited reproduction and distribution in this form do not constitute formal scientific publication, reference to a paper in the series should identify it as a pre-printed report.

Commerce-Weather Bureau, Washington, D. C.

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INTRODUCTION

AUTHORIZING ACT

Public Law 71, 84th Congress, 1st Session reads as follows:

> ...That in view of the severe damage to the coastal and tidal areas of the eastern and southern United States from the occurrence of hurricanes, particularly the hurricanes of August 31, 1954, and September 11, 1954, in the New England, New York, and New Jersey coastal and tidal areas, and the hurricane of October 15, 1954, in the coastal and tidal areas extending south to South Carolina, and in view of the damages caused by other hurricanes in the past, the Secretary of the Army, in cooperation with the Secretary of Commerce and other Federal agencies concerned with hurricanes, is hereby authorized and directed to cause an examination and survey to be made of the eastern and southern seaboard of the United States with respect to hurricanes, with particular reference to areas where severe damages have occurred.
>
> Sec. 2. Such survey, to be made under the direction of the Chief of Engineers, shall include the securing of data on the behavior and frequency of hurricanes, and the determination of methods of forecasting their paths and improving warning services, and of possible means of preventing loss of human lives and damages to property, with due consideration of the economics of proposed break-waters, seawalls, dikes, dams, and other structures, warning services, or other measures which might be required.
>
> Sec. 3. There are hereby authorized to be appropriated such sums as may be necessary to carry out the provisions of this Act.

WEATHER BUREAU SUBPROJECTS

After passage of the law, several conferences between officials of the Corps of Engineers and the Weather Bureau resulted in mutual agreement that the assignment of the Weather Bureau under the provisions of the law should include reports on seven subprojects as follows:

Subproject No. 1: Regional frequencies of hurricanes in coastal areas of Atlantic and Gulf of Mexico.

Subproject No. 2: Study of selected hurricane characteristics and correlation of these with probabilities of occurrence in various regions.

Subproject No. 3: Correlation of hurricane characteristics with excessive rainfall, and development of improved quantitative rainfall forecasting methods for use in connection with general hurricane forecasting activities.

Subproject No. 4: Development of improved methods of forecasting hurricane paths and characteristics.

Subproject No. 5: Development of improved hurricane warning plan, including necessary coordination with other Federal, State, and Local agencies.

Subproject No. 6: Wind analysis associated with development of improved methods of forecasting tidal effects and waves resulting from hurricanes.

Subproject No. 7: Special wind analysis pertinent to determination of wave and tidal effects at specific locations involved in engineering studies, such as Narragansett Bay, R. I.

These subprojects are described in more detail in a memorandum dated 25 November 1955, prepared in the Office of the Chief of Engineers, Civil Works Division, and entitled "Comprehensive Investigations on Hurricanes and Associated Problems."

POINTS OF EMPHASIS

A reading of the law indicates that its main intent is directed to the saving of life and property in hurricane situations. Several points deserve emphasis: (1) Most of the loss of life and the property damage have occurred in connection with only a few of the many hurricanes that have struck the United States during the past century. (2) The places of great loss have been scattered along the whole length of the coast line from southern Texas to New England. (3) No community along the entire coast can consider itself immune from a hurricane disaster. (4) The efficacy of any warning plan depends ultimately on decisions made by individuals who must have the latest information available and who must, largely, have previously-drawn-up plans for action to be taken in various contingencies. (5) The principal cause of loss of life in major hurricanes is drowning (a) in the hurricane surge and (b) in the flooding caused by the excessive rainfall; the next in importance is the force of the wind; and there are various indirect causes of death.

The present report represents the survey of the problem and the results obtained during the first 18 months of the project. Chapters 2 to 6 are interim reports on subprojects 1 to 5, respectively, and Chapter 7 discusses the development of plans for surge forecasting. The main emphasis is directed toward measures to prevent loss of life and reduce property damage in connection with hurricanes. Such measures are discussed in the various chapters of the report. The results presented herein should be regarded as preliminary, subject to revision as the study progresses.

CHAPTER 1 - DESTRUCTIVE FORCE OF HURRICANES

Hurricanes, when fully developed, are the most destructive of all storms. A hurricane is a tropical cyclone, accompanied by winds of 75 miles per hour or higher, occurring over the Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico. Tropical cyclones vary greatly in intensity. Those with winds less than 75 miles per hour are called tropical storms or tropical disturbances to distinguish them from hurricanes.

The winds in a hurricane whirl counterclockwise (in the Northern Hemisphere) with the highest speeds in a circular band beginning at the edge of the "eye" and extending out 20 to 30 miles or more. In the area of the strongest wind, speeds up to 150 miles per hour or more have occurred, with brief gusts to even higher speeds.

While the winds of the hurricane are blowing at great speed around the center, the entire storm may move forward very slowly and sometimes even remain stationary for a short time. This is especially true while the hurricane is in the Tropics, where the forward speed is usually less than 15 miles per hour. As the hurricane moves into higher latitudes, the forward speed usually increases and in extreme cases may reach 50 miles an hour or more.

The winds of a hurricane can do great damage, but the greatest loss of life and heaviest property damage is often caused by the high tides and waves accompanying the hurricane. As the storm moves forward, it often piles up huge waves which cut off or completely cover low-lying beaches and islands. Records indicate that low-lying coastal areas may be inundated to a depth of several feet by wind-driven sea water in a matter of minutes. Small boats are flung high on beaches. Giant waves pound and smash shore buildings, roads, and bridges, and may wash away long-standing sand dunes.

Most hurricanes are accompanied by torrential rains which extend inland and cause additional damage from overflowing streams which may destroy crops, wash out roads and bridges, and flood low-lying communities.

Man can at present do nothing to destroy a hurricane. Much has been done, however, to prevent the loss of life and to reduce property losses through the issuance of advance warnings. Additional steps can and should be taken to reduce further the unnecessary disasters caused by hurricanes.

SOME MEMORABLE HURRICANES

Hurricanes Prior to 1900

The recorded history of tropical hurricanes affecting the continental United States begins with arrival of the explorers from Europe in the 15th Century. Early settlers encountered hurricanes along the Gulf Coast and the east coast of Florida during the period 1559-1566. The recorded history of New England hurricanes begins early in the 17th century. A hurricane did considerable damage there in August 1635.

Records for the first half of the 18th Century are incomplete but devastating storms were reported to have struck at various points including New Orleans, La., in 1722 and 1723; and Charleston, S. C., in 1713 and 1728. The latter two storms produced great inundations from the sea at Charleston. In 1752 a tropical storm completely destroyed the North Carolina town of Johnston. Camp Lejeune now stands near the site of this former seat of Onslow County.

As the nation grew in population and resources during the 19th Century, tropical storms continued to strike our coasts but with much greater losses of human life and property. In 1821 the center of a hurricane crossed western Long Island. At New York more damage was done in two hours than ever before witnessed there. It is reported that the tide rose 13 feet in one hour, overflowing the wharves, the city having been saved from a greater inundation by the coincidence of the hurricane with the time of normal low tide.

The latter half of the 19th Century produced many hurricanes of great intensity. On August 10, 1856, when hurricanes crossed the Louisiana coast, a pleasure resort located on an island south-southwest of New Orleans was inundated by a wave of water from the sea which destroyed everything on the island, now known as Lost Island. On October 2 and 3, 1867, a hurricane passed near Galveston, Tex., with damage totalling $1,000,000, mostly due to flood waters which covered the city. The towns of Bagdad and Clarksville, situated at the mouth of the Rio Grande, were destroyed.

In 1878 a very destructive hurricane moved northward from Cuba, skirted Florida, and entered the United States coast near Wilmington, N. C. The storm maintained its intensity over land destroying many buildings in Philadelphia, Pa., and causing much flooding and other destruction along the coast through New England.

The 1880's brought two severe hurricanes to the coast of the United States. The first, in 1881, killed 400 people in Charleston, S. C., and 335 in Savannah, Ga. The second destroyed Indianola, Tex., on August 20, 1886.

The year 1893 was noted for two hurricanes which brought much loss of life and destruction. In August of that year a hurricane was accompanied by a tremendous wave which overran the coastal islands in the vicinity of Savannah, Ga., and Charleston, S. C., leaving 2,000 dead and damages totalling $10,000,000. On October 1, 1893, another hurricane killed 2,000 people in the vicinity of New Orleans, La., when the accompanying storm wave swept inland over the Mississippi Delta.

Hurricanes Since 1900

The twentieth century opened a new and vastly more destructive era in terms of loss of life and property by tropical hurricanes along the Atlantic and Gulf Coasts and elsewhere in the United States (See table 2, Chapter 2). On September 8, 1900, 6,000 human beings lost their lives when a hurricane accompanied by a storm wave moved over Galveston, Tex. The entire south, west, and east portions of the city were destroyed with total property losses estimated at $30,000,000.

Again at Galveston, in August 1915 during a hurricane the tide reached 12 feet above normal, inundating the business district to a depth of 5 to 6 feet. The highest wind reached 120 m.p.h. The death figure for this storm was 275.

A hurricane which struck Florida in September 1926 caused about one-third the number of deaths caused by the Galveston hurricane of 1900, but property losses were staggering in comparison. Nearly 5,000 homes were destroyed in a belt extending from Fort Lauderdale to Miami and total damage in Florida was $100,000,000. During this storm the wind during one 5-minute period averaged 123 miles per hour, and was sufficient to twist some buildings such as the El Commodore Hotel on their foundations. The September 1926 storm continued across Florida and across the Gulf of Mexico into Alabama where it destroyed property worth $5,000,000.

A hurricane in the year 1928 brought about another great catastrophe in Florida when winds passing over Lake Okeechobee in southern Florida pushed the water out of its normal boundaries drowning 2,000 persons near the south-eastern shore of the Lake.

One of the most violent hurricanes on record anywhere in the world struck Key West, Fla., on Labor Day, September 3, 1935. Four hundred persons, including 200 veterans of World War I, who were temporarily housed in the area, lost their lives. Winds in this storm were estimated to have reached as high as 200 miles per hour.

The year 1938 opened a second phase of hurricane destruction in the present century when a violent hurricane which seemed destined to hit Florida veered northward and struck New England. This hurricane was accompanied by both destructive winds and devastating tidal inundation, bringing ruin to count-less seaside resorts, fishing fleets, and industrial harbors, and carrying with it a vast amount of wind and flood damage to inland areas. Loss of life totalled approximately 600 and property damage estimates ranged from 250 to 300 million dollars.

Six years later in 1944 another great hurricane moved northward along the Atlantic Coast ripping up the boardwalk and smashing the steel pier at Atlantic City, N. J., before entering the southern coast of New England near Point Judith, R. I. 390 lives were lost and damage totalled $100,000,000.

However it was the years 1954 and 1955 which brought the great hurricanes which will long be known in history as Carol, Hazel, and Diane. On August 31, 1954, Carol, a hurricane similar to those of 1938 and 1944, swept across Long Island into southern New England causing the greatest natural disaster until that date. Here again a storm wave flooded low-lying coastal areas and about one-third of the city of Providence, R. I. was under 8 to 10 feet of water for several hours. Sixty persons lost their lives as a result of this storm for which damage estimates reached $460,000,000.

On October 15, 1954, hurricane Hazel moved inland near the North Carolina-South Carolina border ripping up beach areas for a considerable distance. The hurricane maintained its strength over land and gusts as high as 98 miles per hour were reported near Washington, D. C. as the storm center moved northward. The storm brought record-breaking rains as it crossed the border into Canada where 78 persons lost their lives, mostly in the resulting flash floods.

The Canadian experience with hurricane Hazel, however devastating in terms of floods, could not compare with the catastrophe which struck in the Middle Atlantic States and New England in August 1955. The disaster was touched off by hurricane Connie which entered the North Carolina coast and followed a path similar to that of hurricane Hazel of the previous year. The passage of the hurricane was accompanied by heavy rains, which, though producing considerable water damage, served mainly to saturate the ground with water. Then, when hurricane Diane moved inland with its heavy rains a few days later, the earth could not absorb the torrential rains and the runoff floods resulted in the greatest disaster ever to strike the northeastern United States. The Corps of Engineers set the total damage from hurricane Diane at $686,516,000 and the Red Cross reported a total of 180 deaths. Hurricane Diane was no longer a hurricane when the flood rains began. As with most hurricanes the damage and loss of life was not primarily due to wind but to water, this time to torrential rains which the earth could not absorb.

DESTRUCTIVE ACTIONS OF HURRICANES

In the past, hurricanes have caused great loss of life and tremendous property damage in the United States. Most casualties have been caused by drowning, either from storm surges along the coasts or from floods on inland rivers and streams. Likewise, the greatest property damage has been due to the action of water: the action of ocean tides and surges or of floods resulting from torrential rains. Deaths and destruction due directly to the winds are smaller in magnitude, but occur with almost every hurricane that reaches or influences the United States mainland.

Hurricane Deaths

During the period 1900-1956, nearly 12,000 persons lost their lives from hurricanes or tropical storms. Four hurricanes - Galveston 1900 (6,000), Galveston 1915 (275), Lake Okeechobee 1928 (2000) and New England 1938 (600) - account for nearly 9,000 of this total.

The loss of life in a hurricane depends to a large extent on the number of people residing in the area influenced by the storm. A severe hurricane will cause more deaths in highly populated coastal areas than in those relatively sparsely settled. Hurricane floods likewise exact greater death tolls when they occur in heavily populated areas.

While drowning accounts for the largest percentage of hurricane deaths, many other causes contribute to the total loss of life. Among these are: collapse of buildings, flying debris, electrocution, traffic accidents due to poor driving conditions, train and airplane accidents, falling trees, fires in buildings, explosions, heart attacks due to overexertion, diseases resulting from contaminated food or water, and other contributory factors.

Receipt of accurate warnings sufficiently far in advance to permit precautionary actions would aid greatly in reducing the loss of life in future hurricanes. To be of maximum use in saving lives, these warnings must be clearly understood by the persons receiving them, they must not leave room for doubt, and the recipient must have a predetermined plan for safeguarding his life. (See Chapter 6).

Hurricane Damage

The type of damage to property (real and personal) and the amount vary with each hurricane and depend on many factors such as, severity of the hurricane winds, amount of tidal surge, development of floods, urbanization of the affected area, coastal configuration, and others. Each type of damage is described briefly below.

Houses. - These may be partially or totally destroyed due to wind action alone. Houses built according to hurricane-resistant building codes are less likely to be totally destroyed by hurricane winds. When located with waterfront exposure, houses are also subject to severe damage from wave wash and flooding. Houses susceptible to river or stream flooding may also be destroyed or damaged by fresh water flooding.

Farm Buildings. - Barns, poultry houses, sheds, etc., usually are more susceptible to wind damage than well constructed houses due to their generally lighter construction. Being less resistant to wind damage such structures may sustain damage even when located some distance inland from the coast.

Commercial structures. - Warehouses, factories, stores, hotels, etc., rarely are totally destroyed due to wind alone for several reasons: (1) such structures are generally more sturdily built and withstand higher winds with less damage; (2) commercial structures are not usually built on the open ocean front and thus are less vulnerable since hurricane winds decrease rapidly in speed as storms move inland. Such structures however, are subject to damage if located within reach of tidal surges or river floods.

Transportation facilities. - Roads, bridges, railroads, airports, etc., are susceptible to coastal wave and surge action and are also endangered by river and stream flooding.

Ships, Boats, and Small Craft. - Large ocean vessels generally navigate to avoid hurricanes, but action of the wind and sea may cause structural damage even when a ship is not near the center of the hurricane. On rare occasions a ship may be lost if it comes within the dangerous sector of a fully developed hurricane. Smaller boats, such as fishing vessels, sailboats, motor launches, etc., can often be secured in advance so as to avoid complete loss due to the wind. Despite the best mooring, loss or severe damage of such craft may result from the action of storm surges and prolonged storm wave action.

Shipping facilities. - Piers, jetties, wharves, etc., may suffer major damage from the action of the ocean's storm surge and waves. The tremendous force of the ocean driven by hurricane winds may completely obliterate a pier or other waterfront structure. Wind action by itself is not usually violent enough to destroy waterfront shipping facilities although structural damage often occurs.

Coastal features. - The action of hurricane winds on the ocean surface causes abnormally high tides, storm surges, tremendous waves and swells, and abnormal currents which in combination may denude or destroy natural landscape features such as beaches, dunes, and the like. In some cases coastal residents rely on natural sand dunes for protection from the direct effect of the ocean. Loss of these features may lead to inundation and destruction of coastal property in the same or succeeding storms. Seawalls and other man-made protective works are likewise subject to damage or destruction during severe hurricanes leaving coastal residents without protection from the action of the ocean.

Agricultural and Horticultural Crops. - Destruction varies widely depending on maximum winds observed, gustiness, extent of heavy rainfall, resultant floods, and state of crop maturity. Except for immediate coastal regions, crops are not generally susceptible to damage from ocean surge. The encroachment of salt water from the ocean onto farm land not only destroys current crops but often renders the land unfit for farming for several years or until the salt concentration has been leached out by normal rainfall. The occurrence of hurricane winds just as a crop nears maturity often results in almost total crop loss. The combination of heavy rains and strong winds is also destructive to growing crops.

Forests, Trees, and Vegetative Cover. - Wind alone may destroy trees and other forms of vegetative cover. When heavy rains have occurred just prior to the onset of hurricane winds, trees are extremely vulnerable to uprooting. Flash floods on smaller streams and general river flooding may also cause the destructinn of trees, etc. Where trees grow in the vicinity of houses or other buildings they may add to structural damage if uprooted or blown over.

Communication and Power Facilities. - Wind, and to a lesser extent, ocean waves and fresh-water flooding, often cause destruction of overhead power, telephone, and telegraph transmission lines. In addition to blowing over transmission poles, falling trees further disrupt such services. Power failure can contribute to disruption of community life (lack of refrigeration, heat, water, and cooking facilities). Lack of wire communications may result in inadequate facilities to cope with fires, resulting floods, etc.

Attachments to Buildings. - Radio and TV antennas, awnings, shutters, etc. are influenced primarily by wind which can blow down or severely damage such outside fixtures. Not only is damage sustained by the fixtures themselves but when they are blown loose they become destructive weapons endangering life and other property such as windows, roofs, etc.

EFFECTS OF COASTAL DEVELOPMENT AND SHIFTS OF POPULATION

Increased Potential for Hurricane Losses

During recent years there has been a great increase in the population along coastal areas. Most of this increase has apparently been brought about by the migration of individuals to new industries along the coasts, and of retired persons and tourists to homes in the coastal areas. Many of the newer residents in coastal areas have little or no experience with hurricanes, and they, as well as all other coastal residents, should be informed of the potential dangers associated with hurricanes so that they can make intelligent decisions should a hurricane warning be issued for their area. Extreme care must be taken to see that newcomers especially are properly warned in the event of an actual hurricane.

In many of these areas, highways do not have the capacity to handle mass evacuation. Warnings will ordinarily be issued far enough in advance to allow for an orderly exit, but there may be occasions, due to uncertainty of motion or rapid development, when only a short period of advance warnings will be possible.

The Census Bureau has recently completed a revision of the projections of the population of the United States to 1965 and 1975. The new projections yield estimates of population ranging from 186 million to 193 million in 1965, and from 207 million to 228 million in 1975. Some of this increase will be in coastal areas, and this, in turn, will increase the potential for loss of life and property in hurricanes.

All of the above points to the need for an intensive educational program dealing with hurricane danger and protection.

Planning to Avoid Future Hurricane Disasters

With the population along our Gulf and Atlantic coastal areas increasing at a rather rapid rate, coastal areas are more vulnerable to hurricane damage even if there is no change in either the frequency, the intensity, or the distribution of such storms. It is also entirely probable that the most severe hurricane that nature is capable of developing has not yet been experienced by man. Because of this, and because many places on the Gulf and Atlantic coasts have never been struck by a really severe hurricane, it is felt that plans should be formulated and energetic remedial steps taken to avoid future hurricane disasters.

It may well be conjectured that if one of the worst possible hurricanes that has ever occurred on our coasts (such as the Galveston hurricane of 1900) were to cross the coast near a large metropolitan area such as New York City, Norfolk, Charleston, Miami, or New Orleans, in such a way as to re-create the same wind and tide conditions experienced at Galveston, the property damage and loss of life would be appalling.

For maximum safety, adequate local preparations, plans for possible evacuation and rescue work, and other protective measures must be made in anticipation of a destructive hurricane.

It is realized there is a loss in the value of warnings if given too frequently when not required, or if they are too often inaccurate. The U. S. Weather Bureau, as well as other institutions, is actively conducting research in hurricane forecasting, and there is hope that hurricane forecasting will become gradually more accurate and warnings more precise. (See Chapters 5 and 6). When a warning is issued for a populated or highly industrialized area there is much effort and money spent on evacuation of people, rerouting of traffic, shutting down of plants, ferrying out of aircraft, securing of property, and other precautionary measures. If hurricane conditions fail to materialize, people may feel that they have been put to an unjustifiable expense and trouble. In such cases, it may be proper to consider the precautions taken as practice "drills" or as insurance in which the premium becomes gradually lower as forecasting techniques improve.

A casual glance at the loss of life and/or damage caused by any one of the several devastating hurricanes mentioned earlier should make any coastal resident hurricane conscious. Not only is the region where the center of the hurricane crosses the coast in danger, but also the area on either side of the storm center. After the winds have diminished to less than dangerous proportions, there often remains a real threat due to heavy rain and flooding.

CHAPTER 2 - REGIONAL FREQUENCY OF HURRICANES

A destructive hurricane is a relatively rare event at any one place on the United States coast. Yet more than a thousand hurricanes have visited the United States since 1600. Lack of previous hurricanes at a particular place should not lead to a false sense of security. No part of the Atlantic or Gulf of Mexico coasts of the United States is immune to hurricanes. Nor should experiences with hurricanes of only moderate intensity lead a community to overconfidence in the adequacy of its preparedness program to cope with a really severe hurricane. It can be assumed that, during the next hundred years, much of the United States coast will experience moderate hurricanes or the moderate effects on the fringes of more severe hurricanes, some of the coast will escape hurricane experiences altogether, and a few points will be subjected to the violence of the severest part of a really great storm. There is no possibility of knowing in advance where these last places will be, though the probability of such an occurrence does vary somewhat from one region to another. Therefore each coastal community, and each river valley within the reach of hurricane rain, should give attention to what the local effect of a hurricane might be.

Whether there is a long-term climatic trend in the paths or the frequency of hurricanes is a matter of great scientific interest. However, there is no reliable means at present of projecting any trend very far into the future. Therefore, for practical planning of hurricane protection, trends should be largely neglected. The past may be taken as a reliable guide to the future, recalling of course that we have only incompletely observed the past. There is no reason to assume that the severest Atlantic hurricane that the atmosphere is capable of producing has been detected during the relatively brief period of observation.

SOURCES OF INFORMATION

Although the history of hurricanes extends back to 1494, the earlier records are fragmentary. As the islands of the West Indies, the shores of the Gulf of Mexico, and the Atlantic coast of the United States became more densely populated, hurricanes were more often mentioned in historical records. The frequency of hurricanes and their intensities and movements vary considerably from year to year. The more important variations in frequency are discussed later in this report.

One of the earliest compilations of hurricane climatology contains the tracks for several hurricanes between the years 1804 and 1835 and was compiled by the American meteorologist Redfield [1]. It is likely that other probably lesser storms occurred in this period since we have no positive indication that Redfield's list is all-inclusive. It is significant that the tracks plotted by Redfield 121 years ago are strikingly similar to the paths of many storms of recent years. The storms of the late 19th and early 20th centuries were studied intensively by Mitchell [2]. His published work contains charts for months or half-months of the hurricane season showing all the hurricanes

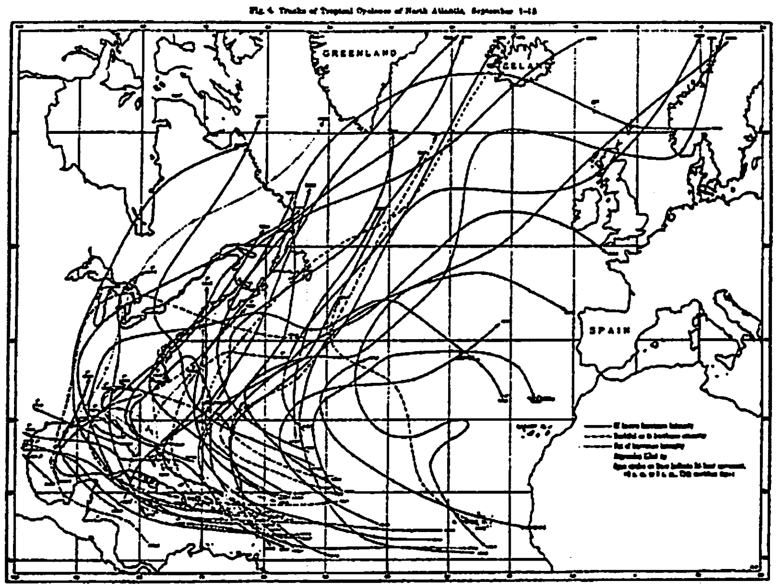

Figure 2-1. - Tracks of tropical cyclones of North Atlantic, September 1-15, 1887-1923. (From [2]).

that occurred during the years 1887 to 1932. Figure 2-1 is an example of such a chart for the first half of September from 1887 through 1923. The Weather Bureau throughout its history has published in the Monthly Weather Review descriptions and tracks of hurricanes passing near the United States. Annual summaries have appeared in the Monthly Weather Review since 1925 and a climatological discussion of each hurricane season has been published in Climatological Data, National Summary, annual issue, each year since 1950. In 1924 and again in 1932 the chronology of hurricanes was organized into more comprehensive studies which were published as supplement No. 24 of the Monthly Weather Review and in the December 1932 issue of the Monthly Weather Review. A comprehensive compilation of all previous studies of hurricanes is given in the book Hurricanes by I. R. Tannehill [3], first published in 1938 and revised periodically since that time. This treatise contains discussions of hurricane climatology and a set of annual tracks for the storms of the 20th century. A statistical study of the direction of motion of tropical storms by 5° squares and by months has been made by Colón [4]. He includes all storms for the period 1887 to 1950 and for each month of the hurricane season, June through November. Other charts portray seasonal shifts in areas of storm inception, seasonal shifts in latitude of recurvature, persistence of motion by 5° squares in each month, and many other elements. A separation of storms according to geographical area and type of path, together with variations and incidence of storms of various categories has been investigated by Willett [5].

The basic information which went into the analyses and compilations mentioned in the previous paragraph, has come from several sources, including logs of ships, newspaper or diary accounts of hurricane damage, synoptic reports and autographic records after the period of establishment of national weather services, and more recently, aircraft reconnaissance and radar. During the earlier days of hurricane reporting, only meager information was obtained when a storm was located some distance from land, and it was not until the reports from ships arrived by mail that it was possible to trace a storm's path with any degree of accuracy. With the establishment of meteorological stations in the West Indies during the Spanish American War, however, and still later with the advent of wireless communication, there was notable improvement in the charting of tropical storms for forecasting purposes. Reconcaissance of tropical storms by aircraft of the U. S. Air Force and U. S. Navy was begun in 1943. It brought the hurricane warning service an excellent new tool for detecting the presence and tracking the centers of tropical storms, as well as for estimating the wind velocities within their circulation. Daytime aerial reconnaissance soon became routine practice, and since 1947 planes equipped with radar have been used for nighttime tracking of storms. Coastal radar stations (military, private, and Weather Bureau) also observe and report on tropical storms. There is an ever-expanding network of these stations along the Gulf and Atlantic Coasts. Our knowledge of the tracks and behavior of hurricanes has increased with each improvement in methods of detecting and tracking these storms.

During fiscal year 1956 the Office of Climatology of the Weather Bureau began a systematic and comprehensive compilation of the tracks of all hurricanes and lesser tropical storms for North Atlantic, Caribbean, and Gulf of Mexico waters for the years from 1887 to the present time. This involves bringing up to date Mitchell's review; in addition several storms of earlier years have been identified that were not previously included. From tracks one can readily determine how many hurricanes have passed any given area, at what seasons of the year, moving in what direction and at what speeds. But one does not know the intensity unless this is included in additional notes. A simple intensity classification is being developed to accompany the tracks. The tracks are to be published both with year-to-year maps and also for 10-day spans of dates for 10 years, for example, September 1-10, for 1931 to 1940. The latter presentation has the advantage of concise portrayal of variations from decade to decade in the seasonal change in hurricane paths.

REGIONS OF FORMATION AND GENERAL MOVEMENT OF HURRICANES

Formation and Initial Motion

Tropical cyclones occur over every major tropical ocean except the South Atlantic. In general they move in the direction of the prevailing winds of the area. The principal regions and general directions of movement for these storms are shown in figure 2-2. Hurricanes are known to develop in the belt of lighter winds south of the main "Trade Winds" of the southern North Atlantic Ocean, western Caribbean Sea, and Gulf of Mexico. It is difficult to treat the formation of these storms quantitatively. Usually, the beginning of a track marks the point where or when high winds began to be observed. In most cases this is not the point of first formation. Generally, the initial disturbance has existed and moved for some time prior to intensification. East of the Lesser Antilles it is common for disturbances, even of storm intensity, to exist for a few days before they are detected. This problem was more serious during the earlier part of the period of record.

Figure 2-3 shows the regions of formation as indicated by the initial point of

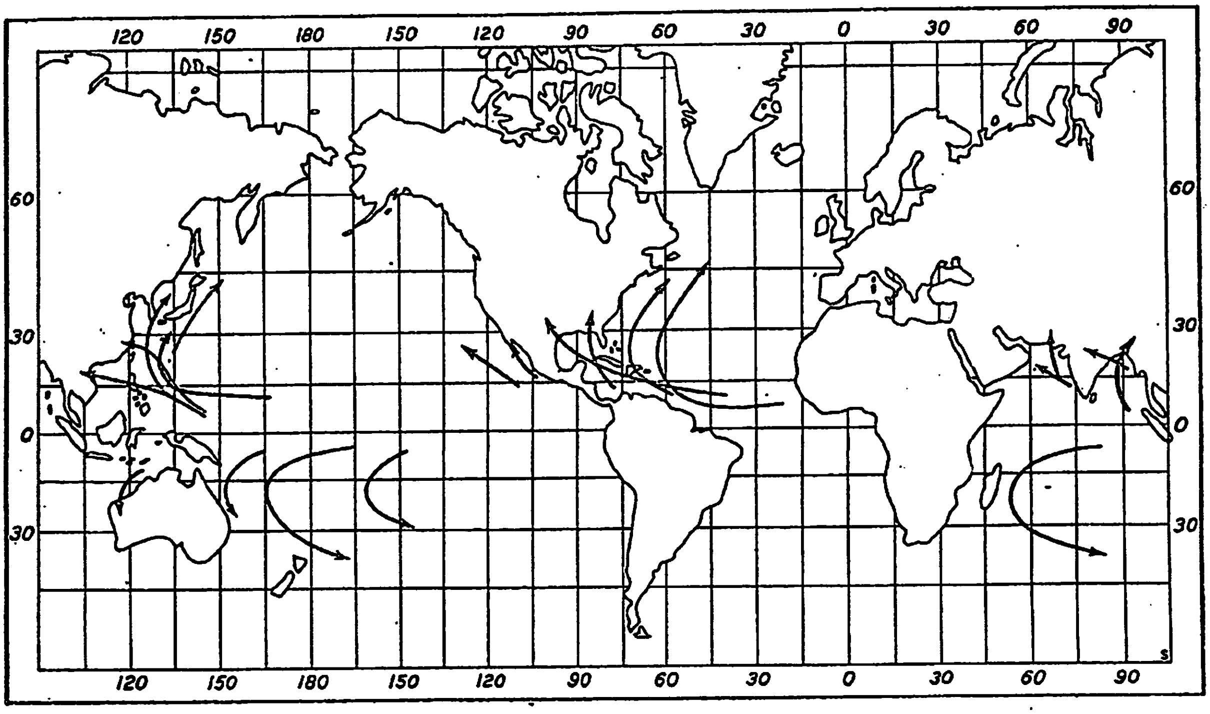

Figure 2-2. - Principal world regions of tropical cyclones. Areas of occurrence and direction of motion are indicated by arrows. (From [7].)

the published storm tracks. In general these charts corroborate statements found in recent literature, in that there are four especially active regions of storm development: the Atlantic east of the Lesser Antilles, the western Caribbean Sea, the Gulf of Mexico, and the Atlantic east of southeastern Florida.

While the cyclonic circulation is being established and the winds are increasing in force, the disturbance as a whole also moves. Thus there are two movements to be considered: (1) the winds directed counterclockwise around and slightly inward toward the center of the cyclone, and (2) the forward movement of the entire wind system. The circulatory movement in the fully developed hurricane is violent, the speeds of the wind near the center approaching and sometimes considerably exceeding 100 miles an hour. The progressive movement of the entire system while in the Tropics averages only 12 to 14 miles an hour. This movement usually increases somewhat as the storm moves to higher latitudes, especially after it has recurved to a more northeasterly direction

Recurvature

Nearly all of the storms that originate in the Cape Verde region first move in a westerly direction over the Atlantic and later recurve in a northerly or northeasterly direction. Some of them reach the West Indies or southern coast of the United States before changing to a more northerly course. Others, which have been first observed in the Atlantic between the West Indies and the African coast, and a few definitely known to have formed in the Cape Verde

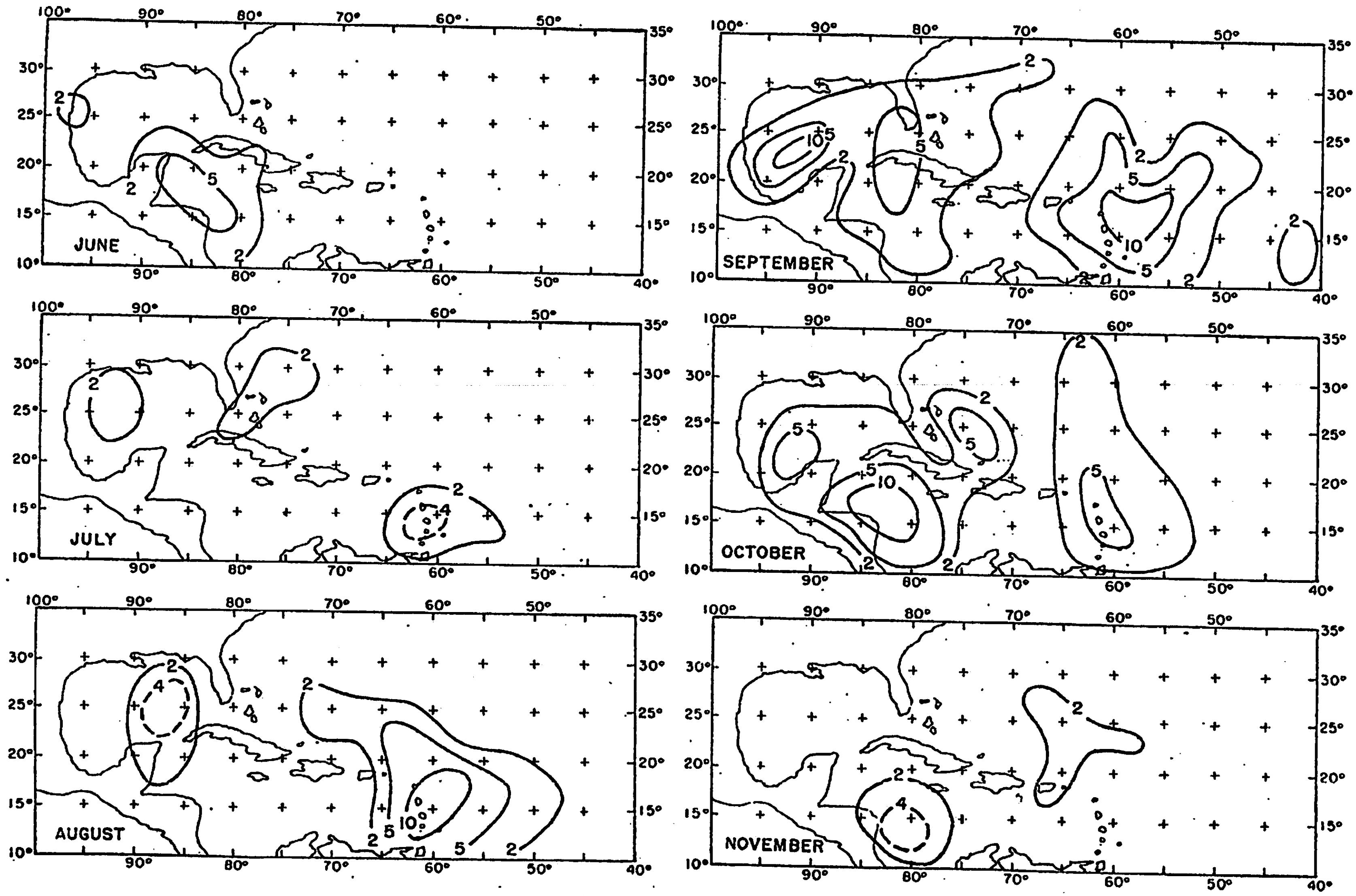

Figure 2-3. - Total frequency of tropical cyclones with tracks starting in each 5° area during the period 1887-1950. (after Colón [4].)

region, continue westward to the coasts of the United States or Mexico, pass into the interior, and finally dissipate without recurving.

During the recurve, many tropical storms move very slowly, and some remain almost stationary for a day or more. After the recurve, which usually takes place at or a little south of 30° N. latitude, the storm generally moves off in a direction between north and east with increasing speed, sometimes at a rate of 40 to 50 miles an hour in higher latitudes.

The movement of individual storms varies greatly. Some travel in a smooth curved path while others change their courses quite rapidly. In general, the path of a hurricane is determined by the wind currents in the layer from the surface of the earth to above 50,000 feet in the area where the storm is located. Characteristically, the storm drifts slightly northward at the same time that it is carried along by the surrounding air currents. As most storms start in areas dominated by winds from an easterly direction, their initial motion is westward and slightly north. After a period of time many will have drifted far enough north to pass out of the area dominated by east winds and approach the regions dominated by west winds (the prevailing westerlies of middle latitudes). The storms are then carried eastward rather than westward as they drift north. The resulting path is often described as parabolic. There are, however, no fixed or preferred paths and each storm follows a path of its own, differing in some or many aspects from the paths of all other storms. Many storm tracks when plotted on a map describe rather long sweeping curves, others are quite irregular with occasional abrupt changes in direction of movement. These changes usually occur as the storm passes through areas of light and variable winds characteristic of the transitional zone between the low-latitude easterlies and the middle-latitude westerlies. Here the storms may come under the influence of disturbances in either the easterly or westerly wind streams and may indeed alternate between the influence of these two major air currents. Such variable influences may result in a number of loops, abrupt turns, and unusual movements, as shown by the examples in figure 2-4.

Seasonal Characteristics

The early-season hurricanes (June and July - 15 percent of the total) are formed entirely on the western side of the Atlantic in the lower latitudes, most frequently in the western Caribbean. They tend to be relatively weak and short-lived, either moving westward and inland to dissipate at low latitudes, or recurving at low latitudes and moving into the Atlantic. Very few of them affect the coastal United States outside of the Florida Peninsula.

The mid-season hurricanes (August and first half of September - 60 percent of total), are formed about as frequently on the eastern side of the Atlantic where the intertropical front is at its farthest north, as on the western side including the central Gulf of Mexico. The mid-season hurricanes tend to form in the more northerly portions of the zone, become relatively intense and long-lived, mostly recurving farther north (close to 30° N. on the average), and they have the longest extratropical history after recurvature. The majority of the mid-season hurricanes affect the Atlantic or Gulf Coasts of the

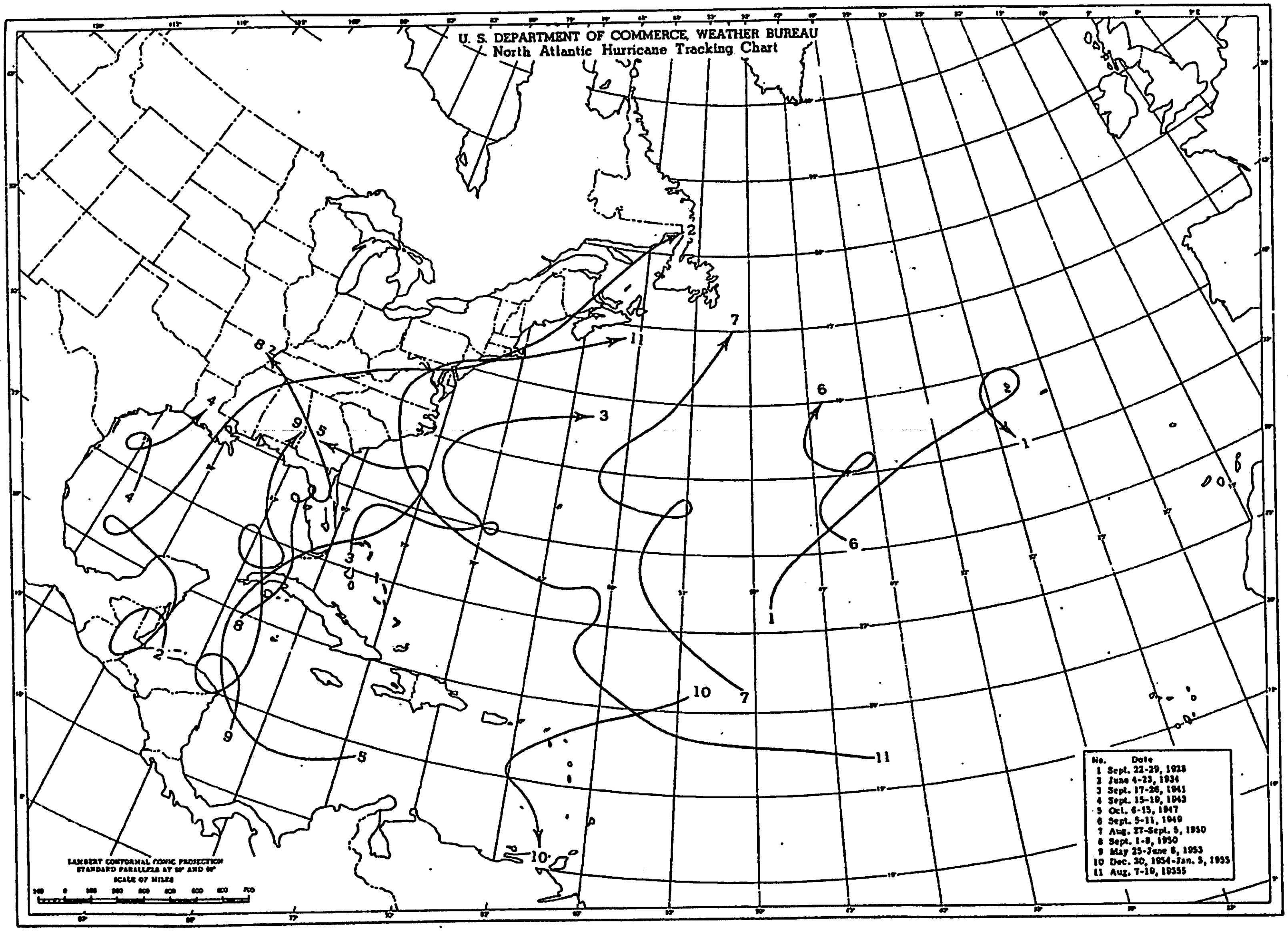

Figure 2-4. - Tracks of some tropical storms exhibiting irregular motion. (From [7].)

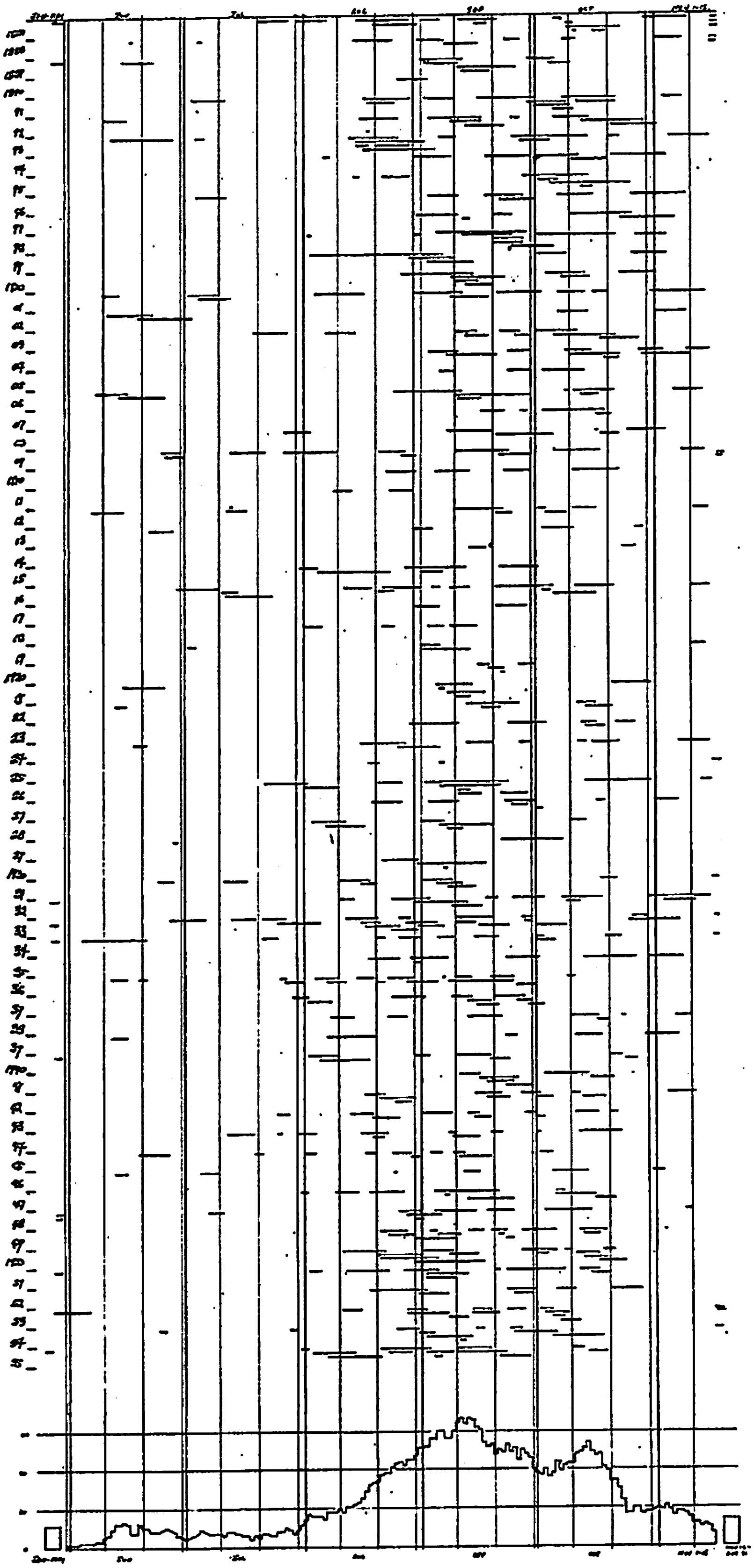

Figure 2-5 - Tropical storm days 1887-1955.

United States, although some recurve northeastward through the western Atlantic without affecting the Coast.

The late-season hurricanes (second half of September through November - 25 percent) return increasingly to the characteristics of the early-season ones and only occasionally affect the United States.

The dates of earliest and latest hurricanes and lesser tropical storms and their period of activity are shown in figure 2-5.

FREQUENCY DISTRIBUTIONS

Frequency within Coastal Sectors

The incidence of tropical storms within the various coastal sections is shown chronologically in figure 2-6. The bar graph at the bottom represents the total occurrence of storms by years over the Atlantic, Caribbean, and Gulf; those that remained at sea as well as those striking land. The solid portion of the bar represents the number of storms which reached hurricane intensity. The time scale extends from 1887 on the left to 1955 on the right. The seven upper bar graphs depict the occurrence of hurricanes and lesser tropical storms in the seven coastal regions shown by the small maps. A storm affecting more than one of these areas is graphed in each.

The number of hurricane center passages per unit length of coastline of the United States is shown in figure 2-7 and also the frequency for all tropical storms including those of less than hurricane intensity. The period of record for this figure is 1901-55. A modified definition of hurricane is used here such that if the central pressure of the storm was less than 29.00 inches at the coast it was counted as a hurricane regardless of wind speed. Storms are counted only in the sector where the center passed inland across the coast, each sector covering 85 nautical miles. The total length of coastline from Brownsville to Eastport is 3547 miles, not including bays and inlets.

It is seen from figure 2-7 that the coastal region most vulnerable to tropical storms is the southern quarter of Florida where 18 hurricanes were experienced in 55 years, or one storm for each 17.2 nautical miles of coast line. Other of the more vulnerable areas are the Texas coast, the mid-Gulf coast, and the North Carolina coast near Cape Hatteras.

The count of hurricane centers entering the coast does not depict the complete frequency of experiences with hurricanes in the various regions along the coast. For example, a storm entering the coast at one point may produce heavy rain and floods at a great distance from that point even after it has lost its importance as a wind storm. Also, many of the sectors that had no hurricane centers enter the coast during the 55 years experienced hurricane force winds one or more times from storms that skirted the coast.

Frequency of Storms Per Year

The frequency distribution of tropical storms per year is shown in the right-hand panel of figure 2-8. These are for the same storms as in the bottom

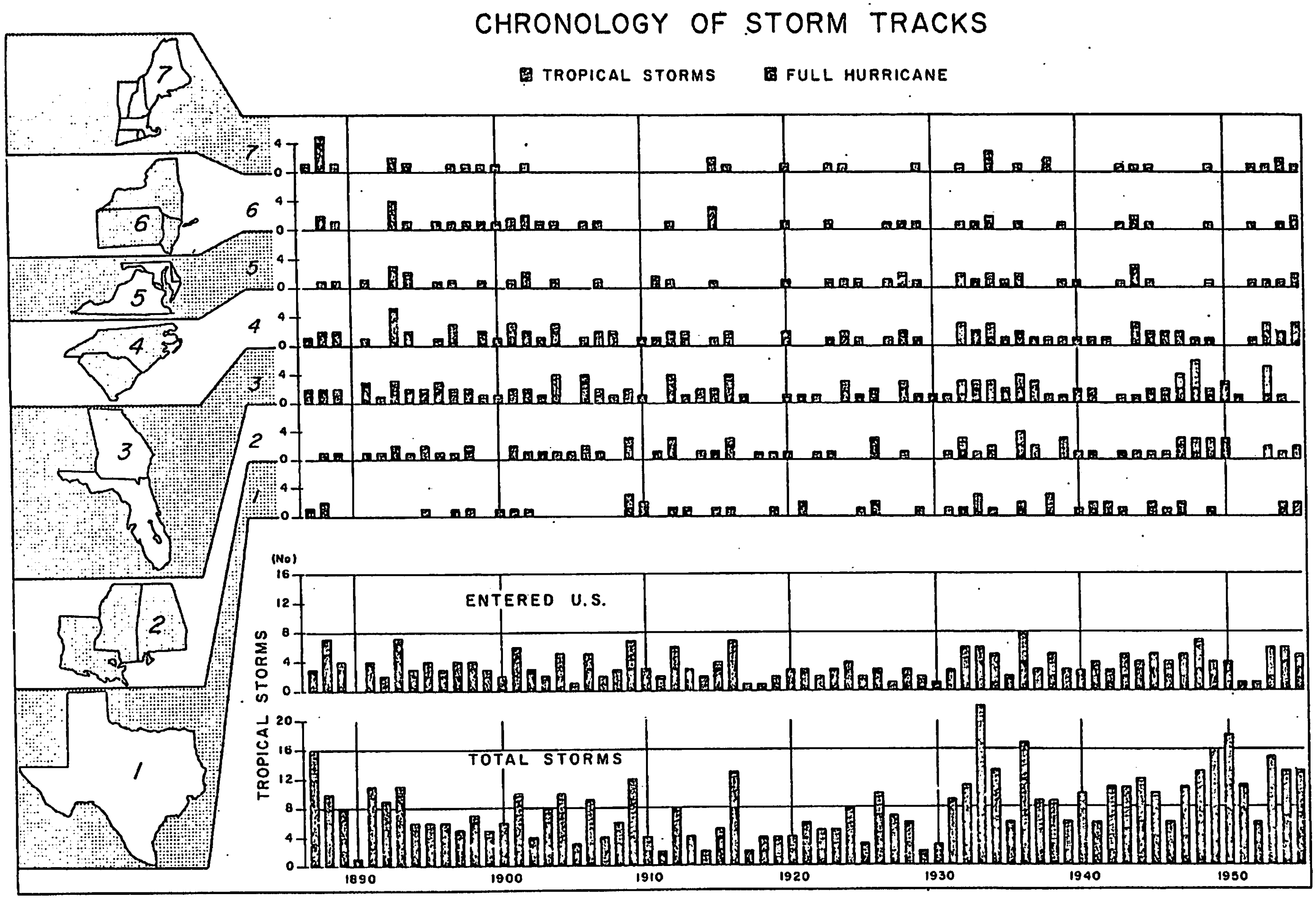

Figure 2-6. - Chronology of storm tracks. The occurrence of hurricanes and tropical storms in the different coastal regions shown at left, and the total occurrence.

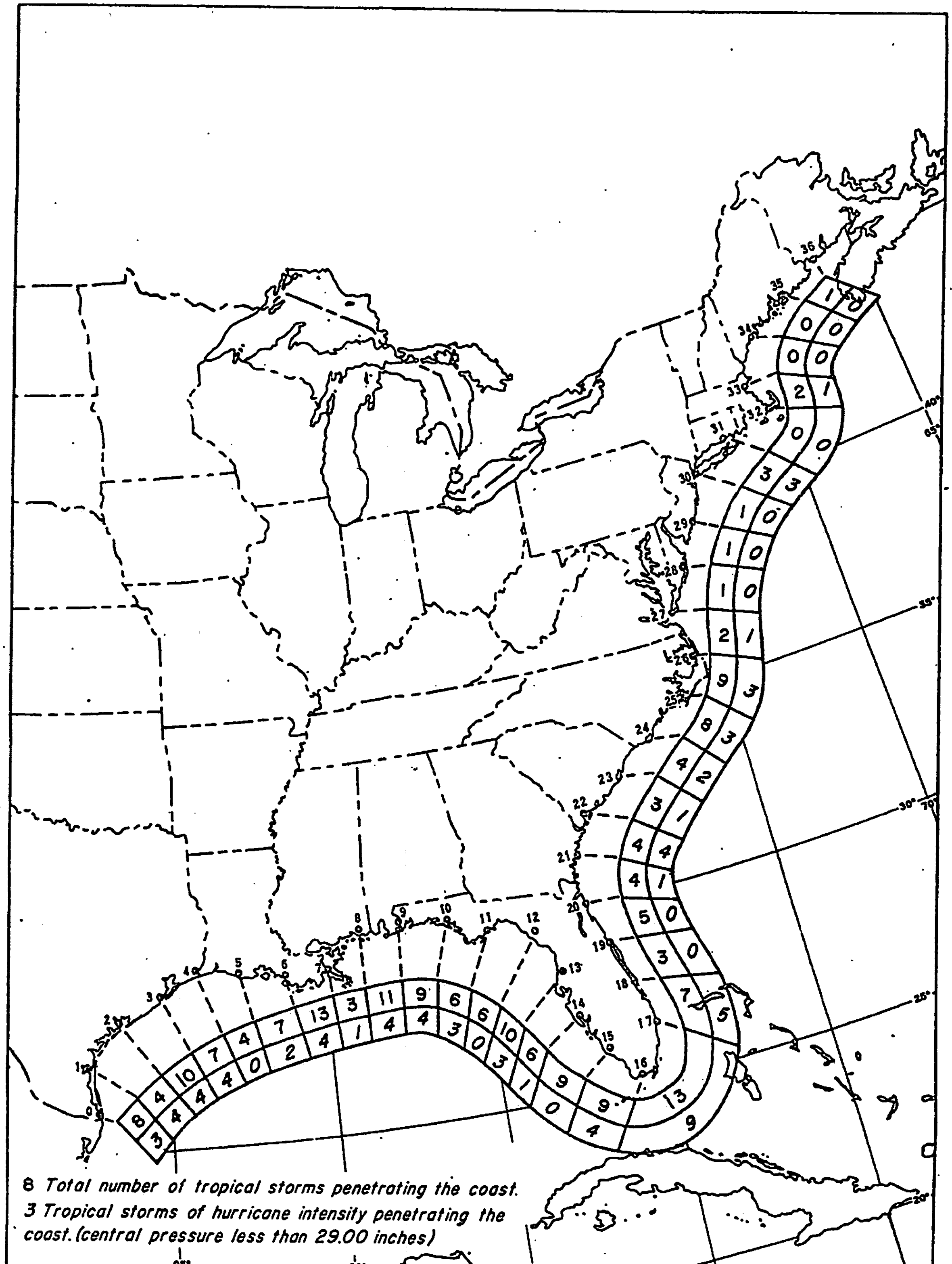

Figure 2-7. - Frequency of hurricanes and tropical storms penetrating the Atlantic and Gulf coasts 1901-1955.

graph of figure 2-6, and include all storms in Atlantic, Gulf, and Caribbean waters. It is seen that the number of storms is highly variable, ranging from only one storm in a season to 21 storms. The number of most frequent occurrence per season is 6.

The frequency distribution of storms grouped according to their track characteristics is shown in the three left-hand panels of figure 2-8. These were constructed to check whether there was any tendency for tracks to be similar in any given hurricane seasons. The distribution labeled group 1 is for the storms which remained always in the easterlies and continued westward through their entire track. That labeled group 2 is for storms which began in the easterlies, recurved, and acquired an eastward component of motion under the influence of the westerlies. The remaining diagram shows frequency distribution for group 3, the storms which had an eastward component of motion during their entire path. A comparison of the actual frequency distribution of the three track categories with two random distributions suggests strongly that the observed distribution is also random; that is, that there is no significant tendency for tracks in a given hurricane season to be alike, so far as the three track characteristics defined here are concerned.

Yearly Frequency By Tracks

Figure 2-9 illustrates the chronological distribution of each of these three classes of storms. The top diagram shows group 3, eastward-moving storms, those always under the influence of the westerlies. The central diagram shows group 2, those which recurved passing from the influence of easterly to westerly circulations. The bottom diagram shows group 1, those remaining always under the influence of the easterlies. It may be noted that the shape of the chronological diagram of all storms (fig. 2-6, bottom graph) is reflected in the most numerous class, group 2; the increase in number of storms since the early thirties is also evident in group 1. The storms whose paths are always in the westerlies (group 3) are infrequent through this period of record, with never more than 3 and usually only 1 or 2 in each year.

Frequency of Recurvature By Areas

An important forecasting decision when a hurricane is approaching is: where will the storm recurve from motion toward the west to motion toward the north or northeast? The climatology of points of recurvature is one considered among others in making this decision. Points of recurvature were tabulated by 5-year periods from 1891 through 1955 for various areas. Here the point along the track where the storm was farthest west was considered as the point of recurvature. A graph of frequencies of storms recurving in each area is shown in figure 2-10. The graphs along the outer edges include storms recurving in the extended latitudinal or longitudinal bands indicated by the arrows. A comparison of the frequency of storms recurving in each area to the number of storms occurring in the area may be obtained by referring to figures 2-10 and 2-11.

FUTURE TRENDS IN HURRICANES

The high frequency of hurricanes on the Atlantic coast north of Florida and

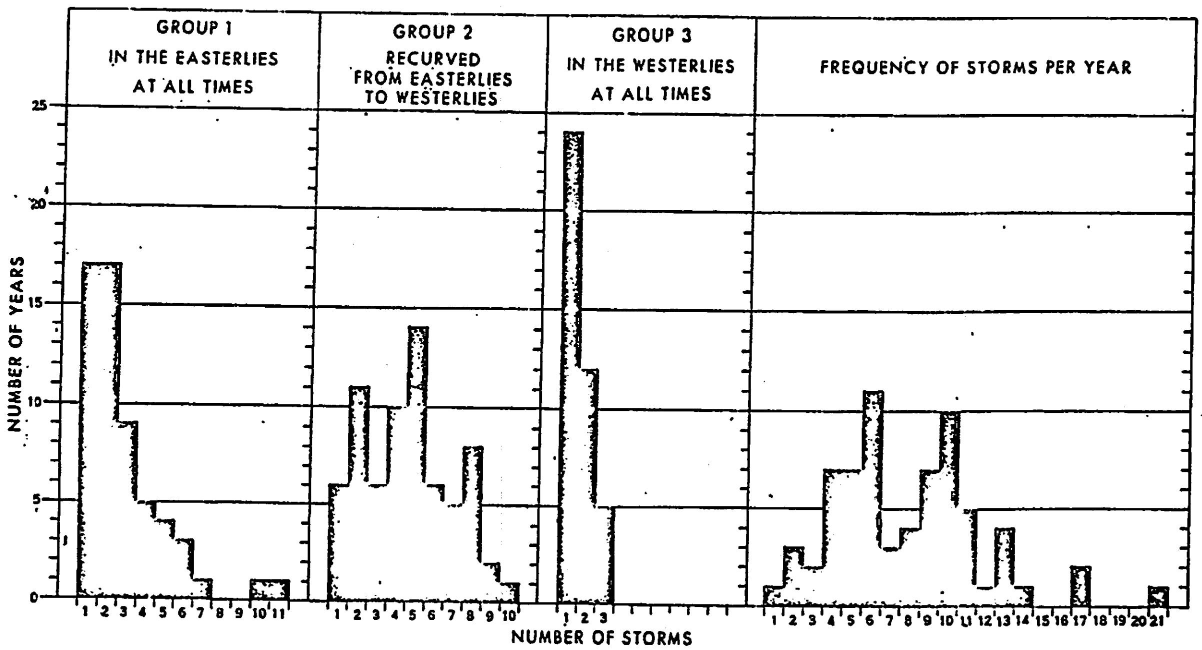

Figure 2-8. - Frequency distribution of number of hurricanes and tropical storms per year, by type.

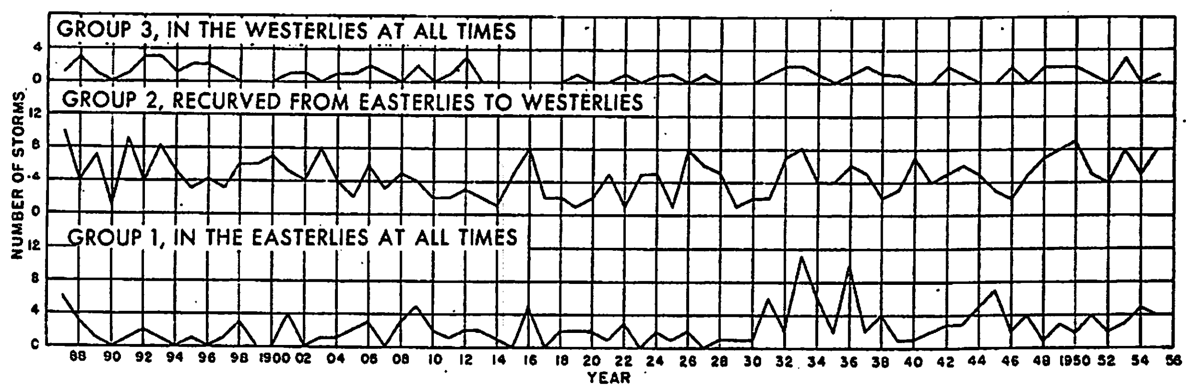

Figure 2-9. - Chronological graphs of number of storms per year by type.

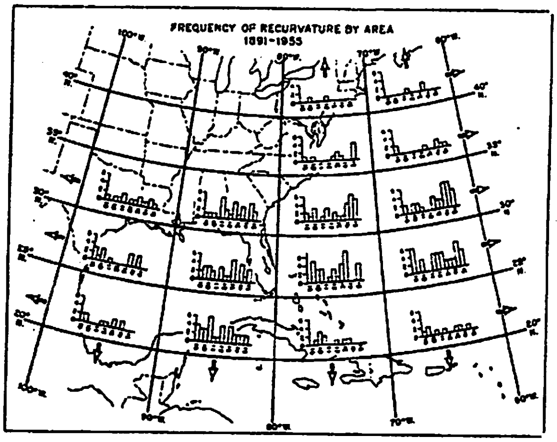

Figure 2-10. - Frequency of recurvature by area.

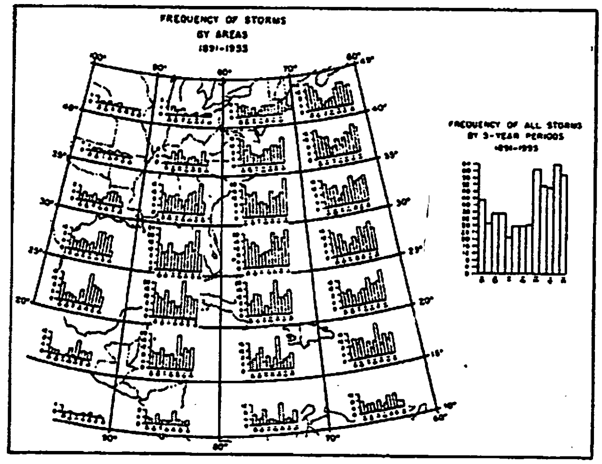

Figure 2-11. - Frequency of storms by area, 1891-1955.

Georgia during 1954 and 1955 naturally led to speculation and serious investigation of whether the climate has changed so as to make this area more vulnerable to hurricanes than had previously been thought and, perhaps, to make Florida and other areas less vulnerable. There have been cycles in world climate, that is, fluctuations between cold and warm, dry and wet, both on global and regional scales. Within historic times glaciers have advanced and receded, timber lines on mountain ranges have changed, and many climatic elements have exhibited clear trends. Hurricanes are not haphazard random occurrences, rather their paths and probably their formation and intensity are intimately related to the general circulation of the atmosphere. They undoubtedly change if the general circulation changes. Some relations of regional hurricane frequency to general circulation anomalies were discussed by Namias [6]. Further investigations along the same lines have continued since that time. Most changes in weather or climate, from periods of a few days up to periods of hundreds of thousands or perhaps millions of years, are fluctuations or oscillations. There is little evidence of continuous trends in one direction. As far as records go back there have been ups and downs in the number of hurricanes and their paths. It can be noted in figure 2-6 that the total number of storms decreased gradually from the beginning of the graph in 1887 to 1930. An abrupt increase in the early 1930's with a sustained higher level of activity since that time, is observed. This suggests that the recent increase is not due solely to increased effectiveness of observational procedures. From these one might expect a gradual increase in the number of hurricanes observed during recent years, but this would not explain either the abruptness of the increase in the early 30's or the decline in activity from the late 19th century to 1930.

The graph immediately above this representation of total storm activity in figure 6 shows the storms that crossed the United States coast line. It reflects quite generally the characteristics of the total curve.

Table 2-1. - Total number of hurricanes and tropical storms and the loss of life and property damage inflicted, by years, 1900-1955.

Year	Total number Tropical Storms*		Total number Hurricanes		Loss of Life		Damage by categories **	
	In all areas	Reaching U. S. Coast	In all areas	Reaching U. S. Coast	Total all areas	In United States	Total all areas	In United States
1900	7	3	3	1	†	6,000	†	7
1901	10	6	4	3	†	10	†	6
1902	4	3	2	2	†	#	†	#
1903	9	2	6	2	†	9	†	6
1904	10	5	2	2	†	#	†	6
1905	3	1	2	0	†	#	†	#
1906	9	6	6	4	†	520	†	7
1907	4	2	0	0	†	#	†	#
1908	6	3	2	1	†	#	†	#
1909	12	7	4	3	†	259	†	7
1910	4	3	3	2	†	13	†	6
1911	2	2	2	2	†	17	†	6
1912	8	6	4	3	†	12	†	6
1913	4	3	2	2	†	#	†	#
1914	2	2	0	0	†	#	†	#
1915	5	4	4	3	†	600	†	8
1916	13	9	10	6	†	107	†	7
1917	2	1	2	1	†	5	†	5
1918	4	1	3	1	†	34	†	6
1919	4	2	1	1	†	287	†	7
1920	4	3	4	3	†	2	†	6
1921	6	2	5	2	†	5	†	6
1922	5	2	3	0	†	0	†	#
1923	5	3	4	2	†	0	†	4
1924	8	4	5	3	†	2	†	3
1925	3	2	1	1	†	6	†	3
1926	10	3	8	3	†	269	†	8
1927	7	1	4	0	†	0	†	#
1928	6	3	4	3	†	1,836	†	7
1929	2	2	2	2	†	3	†	6
1930	3	1	2	1	†	0	†	2
1931	9	3	2	0	†	0	†	#
1932	11	6	6	2	†	0	†	#
1933	21	6	9	4	†	63	†	7
1934	11	5	6	3	†	17	†	6
1935	6	2	5	2	†	414	†	7
1936	17	8	7	3	†	9	†	6
1937	9	4	3	0	†	0	†	4
1938	7	4	3	2	†	600	†	8
1939	5	3	2	0	†	3	†	3
1940	8	4	4	3	†	51	†	6
1941	6	4	4	2	†	10	†	7
1942	10	3	4	2	17	8	7	7
1943	10	4	5	3	19	16	7	7
1944	10	4	6	3	1,076	64	8	8
1945	10	5	4	3	29	7	8	8
1946	6	4	3	2	5	0	7	7
1947	9	7	5	3	72	53	8	8
1948	10	5	6	3	24	3	7	7
1949	13	4	8	3	4	4	8	8
1950	13	4	11	4	27	19	7	7
1951	10	1	8	1	244	0	7	6
1952	6	1	6	1	16	3	6	6
1953	14	6	6	2	3	2	7	7
1954	11	5	7	4	720+	193	9	9
1955	13	5	10	3	1,518+	218	9	9

* Including hurricanes

† Loss of life and damage figures outside United States not available prior 1942

Not reported in literature, believed minor

\+ Additional deaths for which figures are not available

** This is a new form of presentation of storm damage estimates. The Weather Bureau has for some time recognized the fact that without detailed expert appraisal of damage all figures published are merely approximations to fact. Since errors in dollar estimates vary in proportion to the total, storms are placed in categories varying from 1 to 9 as follows:

1	Less than $50	6	$500,000 to $5,000,000
2	$50 to $500	7	$5,000,000 to $50,000,000
3	$500 to $5,000	8	$50,000,000 to $500,000,000
4	$5,000 to $50,000	9	$500,000,000 to $5,000,000,000
5	$50,000 to $500,000		

The seven graphs on the upper portion of figure 2-6 show the incidence of storm centers within various geographical sections of the coastal area chronologically. In each area it may be noted that periods of storm activity are interspersed with periods of inactivity. This is most pronounced in the Texas and New England areas. A periodicity of the data for any region is not evident, nor are trends evident wherein storm incidence shifts systematically from one coastal section to another.

SUMMARY

Early workers in hurricane climatology concentrated on chronological lists and tracks. It is thought that they identified practically all of the hurricanes since about 1650 in Atlantic, Gulf of Mexico, and Caribbean waters from various historical accounts. This chapter shows the latest compilation of statistics on the hurricanes since 1887, including frequencies in various coastal regions and per unit length of coastline, frequencies of total number of storms per year, the dates of the earliest and latest hurricanes each year, a description of the seasonal trend in hurricane tracks, and other material. It is shown that the variation in track characteristics from year to year (east-to-west, west-to-east, and recurving) and in individual hurricane seasons is probably a random affair with little or no discernible tendency for similar tracks to persist in a given season.

The approximate damage caused and lives lost in hurricanes since 1900 are shown in table 2-1.

Since the paths and behavior of tropical storms of less than hurricane intensity are similar to those of hurricanes it is appropriate to study the tracks and frequency of tropical storms of all intensities. Many of the statistical compilations presented in this report include tropical storms of all intensities.

Trends in hurricane frequencies and areas affected are discussed. The conclusions up to this time are that there is a tie-in between hurricane tracks and the character of the general circulation at any particular time, but there is no evidence of a trend in one direction of the behavior of this controlling general circulation or means of predicting it for a season in advance.

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CHAPTER 3

DAMAGE-PRODUCING CHARACTERISTICS OF HURRICANES

Hurricanes threaten the life and property of man and interfere with his activities in three ways. First, the level of the sea rises under the influence of the winds and low pressure of the storm, and floods coastal areas above the usual high tide; the coastal damage is augmented by the pounding of great waves. Second, the torrential rains of the hurricanes swell stream and rivers and produce floods in areas within reach of the stream. Third, the strong winds break up structures, flatten crops, and send debris flying through the air at dangerous velocities. The wind-driven rains also soak into walls causing some damage as does rain falling into buildings which have been unroofed by the wind. Modern buildings, if properly engineered, more readily withstand the ravages of a hurricane than typical construction of 50 or 60 years ago. However, because of increased population and development, the potential for damage by hurricanes has become greater rather than less in many areas. There is a marked trend toward the development and population of coastal areas that are definitely vulnerable to hurricanes but which have not experienced major storms in recent years.

Much of the discussion in this chapter is based upon those elements included in table 3-1 and defined in the footnotes to the table. All of the elements except p_a, lowest pressure actually observed by barometer, are estimates obtained by individual detailed analysis of each storm. Many of the data are carried forward from an earlier report [3] with some adjustments and corrections. Table 3-1 includes all hurricanes whose central pressure reached 29.00 inches or less in the vicinity of the United States coast. For the Atlantic seaboard north of Jacksonville, Fla., and the Gulf coast in or near Louisiana, the data cover the years 1893 to date. For Texas and Florida, the years included are 1900 to 1949.

HURRICANE SURGES (TIDES) AND WAVES

Although the exceptionally high tides which accompany some hurricanes have been responsible for more than three-fourths of the loss of life due to the storms, less is known about this problem than about almost any other important hurricane characteristic. This is due in part to the difficulty of obtaining the information needed to study the phenomenon, and in part to the fact that, while floods from the sea have caused the greatest hurricane disasters, they are the predominant cause of loss of life and of property damage in only a comparatively few storms. This problem is discussed in more detail in Chapter 7. The winds and other hurricane characteristics that cause or affect the surges are discussed in this section.

Wind Effects on Tides and Waves

Areal Distribution of Hurricane Winds. - The knowledge of the wind required for estimating the tide and waves that a hurricane can produce is quite different from the knowledge required for estimating wind damage to structures. The sea reacts to the total force of the wind over a large area and an appre-

Table 3-1. - Characteristics of United States hurricanes.

Date	P_0	P_n	P_n-P_0	P_0	P_n	P_n-P_0	R n.mi.		V_{gx}	c	t_c	P_a		Station	r_a
	in	in	in	mb	mb	mb	(a)	(b)	mph	kt	hrs	in	mb		n.mi.
Aug. 28, 1893	28.28	29.61	1.33	958	1003	45	34	25	78	15	4	28.28	958	Savannah, Ga.	2
Oct. 1, 1893	28.22	29.99	1.77	956	1016	60	17		94	7	4	28.65	970	Moss Point, Miss.	13
Oct. 13, 1893	28.33	29.61	1.28	959	1003	44	23		78	21	4	28.33	959	South Island, S. C.	1
Oct. 2, 1898	28.82	30.03	1.21	976	1017	41	32	27	75	11	4	29.12	986	Jacksonville, Fla.	23
Oct. 31, 1899	28.70	30.49	1.79	972	1033	61	110		80	18	4	28.90	979	Charleston, S. C.	50
Sept. 8, 1900	27.64	29.78	2.14	936	1009	73	14		104	10	4	28.48	964	Galveston, Tex.	17
Aug. 14, 1901	28.72	30.16	1.44	973	1021	48	33		83	14	4	29.42	996	New Orleans, La.	45
Sept.11, 1903	28.84	30.12	1.28	977	1020	43	43		76	7	3	29.47	998	Tampa, Fla.	14
June 17, 1906	28.91	29.98	1.07	979	1015	36	26		72	12	4	29.46	998	Jupiter, Fla.	29
Sept.17, 1906	28.98	30.38	1.40	981	1029	48	61		71	16	4	29.50	999	Columbia, S. C.	28
Sept.27, 1906	28.50	30.07	1.57	965	1018	53	57	73	83	16	4	28.50	965	Ship at Scranton, Miss.	5
Oct. 18, 1906	28.84	29.80	.96	977	1009	32	35		67	6	4	29.26	991	Jupiter, Fla.	33
July 21, 1909	28.31	30.27	1.96	959	1025	66	19		99	12	4	29.00	982	Bay City, Tex.	16
Sept.20, 1909	28.94	30.30	1.36	980	1026	46	88		73	11	4	29.23	990	New Orleans, La.	43
Oct. 11, 1909	28.30	30.07	1.77	958	1018	60	24	22	94	10	4	28.36	960	Sand Key, Fla.	7
Oct. 17, 1910	27.80	29.19	1.39	941	989	48	16		84	11	4	27.80	941	S. S. Jean Nr. Tortugas, Fla.	0
*Oct. 18, 1910	28.33	29.77	1.44	959	1008	49	48	62	81	11	4	28.94	980	Tampa, Fla.	45
Aug. 28, 1911	28.92	30.10	1.18	979	1019	40	44	27	73	8	4	29.02	983	Savannah, Ga.	6
Sept. 3, 1913	28.81	29.98	1.17	976	1015	39	41		72	16	4	29.36	994	Raleigh, N. C.	6
Aug. 16, 1915	28.14	29.57	1.43	953	1001	48	32		83	11	4	28.14	953	Velasco, Tex.	4
Sept.29, 1915	27.87	30.14	2.27	944	1021	77	29		106	10	4	28.01	949	New Orleans, La.(Pauline St. wharf)	12
July 5, 1916	28.38	30.03	1.65	961	1017	56	50		81	25	3	28.92	979	Mobile, Ala.	32
Aug. 18, 1916	28.00	30.77	2.77	948	1042	94	35		116	11	4	28.00	948	Santa Gertrudis, Tex.	6
Oct. 18, 1916	28.76	30.20	1.44	974	1023	49	44	19	81	21	4	28.76	974	Pensacola, Fla.	0
Sept.28, 1917	28.48	29.88	1.40	964	1012	48	31	33	81	13	3	28.51	966	Pensacola, Fla.	12
Sept. 9, 1919	27.44	29.73	2.29	929	1007	78	15		108	8	2	27.44	929	Mean of two ships and Dry Tortugas, Fla.	0
*Sept.14, 1919	P_0 near 28.0 inches						-		-	20	4	28.65	970	Corpus Christi, Tex.	-
Sept.21, 1920	28.93	29.90	.97	980	1013	33	28		67	28	3	28.99	982	Houma, La.	10
June 22, 1921	28.17	30.03	1.86	954	1017	63	17		97	11	4	29.37	995	Houston, Tex.	33
Oct. 25, 1921	28.29	29.59	1.30	958	1002	44	18		80	10	4	28.29	958	Tarpon Srpings, Fla.	1
Aug. 25, 1924	28.70	30.33	1.63	972	1027	55	89	34	78	22	4	28.80	975	Hatteras, N. C.	28
*Aug. 26, 1924	28.70	29.62	.92	972	1003	31	55	66	59	29	4	28.71	972	Nantucket, Mass.	12
Oct. 19, 1924	28.70	29.82	1.12	972	1010	38	19		75	8	4	--	--	Nr. Dry Tortugas, Fla.	(b)
*Oct. 20, 1924	28.83	29.62	.79	976	1003	27	25		62	6	4	29.10	985	Miami, Fla.	0
Dec. 2, 1925	28.95	29.90	.95	980	1013	33	49	54	62	14	4	29.17	988	Wilmington, N. C.	35
July 28, 1926	28.34	29.91	1.57	960	1013	53	14		89	8	4	28.80	975	Merritt Island, Fla.	11
Aug. 25, 1926	28.31	30.35	2.04	959	1028	69	27		100	10	4	28.31	959	Houma, La.	3
Sept.18, 1926	27.59	29.99	2.40	934	1016	82	24		110	17	4	27.61	935	Miami, Fla.	4
*Sept.20, 1926	28.20	30.13	1.93	955	1020	65	24	17	98	7	4	28.20	955	Perdido Beach, Ala.	1
Oct. 20, 1926	27.52	29.97	2.45	932	1015	83	21		112	16	4	29.16	988	Key West, Fla.	60
Sept.16, 1928	27.62	30.38	2.76	935	1029	94	28	53	117	13	4	27.62	935	West Palm Beach, Fla.	3
June 28, 1929	28.62	29.97	1.35	969	1015	46	13		82	15	2	29.12	986	Pt. O'Connor, Tex.	13
Sept.28, 1929	28.15	30.08	1.93	953	1019	66	28		98	10	4	28.18	954	Long Key, Fla.	7
*Sept.30, 1929	28.80	29.96	1.16	975	1015	40	58	65	70	6	4	28.80	975	Panama City, Fla.	6
Aug. 13, 1932	27.83	30.11	2.28	942	1020	78	12		108	15	4	27.83	942	East Columbia, Tex.	0
Aug. 4, 1933	28.80	29.96	1.16	975	1015	40	24	25	76	10	4	28.98	981	Brownsville, Tex.	15
Aug. 23, 1933	28.63	29.48	.85	970	998	28	54	36	58	18	4	28.66	971	Cape Henry, Va.	16
Sept. 4, 1933	27.98	29.98	2.00	948	1015	67	13	29	101	11	4	27.98	948	Jupiter, Fla.	0
Sept. 5, 1933	28.02	30.24	2.22	949	1024	75	30	20	105	8	4	28.07	951	Brownsville, Tex.	2
Sept.16, 1933	28.25	29.82	1.57	957	1010	53	42		84	9	4	28.25	957	Hatteras, N. C.	7
June 16, 1934	28.52	29.94	1.42	966	1014	48	37		80	16	4	28.58	968	Jeanerette, La.	0
Sept. 2, 1935	26.35	29.92	3.57	892	1013	121	6		137	9	4	26.35	892	Long Key, Fla.	0
*Sept. 4, 1935	28.71	29.89	1.18	972	1012	40	51		71	-	-	29.18	988	Columbia, S. C.	30
Nov. 4, 1935	28.73	--	--	973	--	--	--		79	-	-	28.73	973	Miami, Fla.	0
July 31, 1936	28.46	30.00	1.54	964	1016	52	19		80	9	4	28.73	973	Valpariso, Fla.	0
Sept.18, 1936	28.53	29.42	.89	966	996	30	34		63	16	4	28.52	966	Mean of two ships off Hatteras, N. C.	0
Sept.21, 1938	27.86	29.52	1.66	943	1000	57	50		83	47	4	28.04	950	Hartford, Conn.	7
Aug. 7, 1940	28.76	29.75	.99	974	1008	34	11		71	8	4	28.87	978	Port Arthur, Tex.	5
Aug. 11, 1940	28.78	30.02	1.24	975	1017	42	26	27	77	12	4	28.78	975	Savannah WBO, Ga.	2
Sept.23, 1941	28.31	29.66	1.35	959	1004	45	21		81	13	3	28.66	971	Houston WBO, Tex.	0
Oct. 7, 1941	28.98	30.19	1.21	981	1022	41	18		78	11	4	29.00	982	Carrabelle, Fla.	0
Aug. 30, 1942	28.07	29.64	1.57	951	1004	53	18		88	14	4	28.10	952	Seadrift, Tex.	4
July 27, 1943	28.78	30.02	1.24	975	1017	42	17	16	78	8	4	28.78	975	Ellington Fld., Tex.	2
Sept.14, 1944	27.88	30.66	2.78	944	1038	94	49	17	113	23	4	27.97	947	Hatteras, N. C.	14
*Sept.14, 1944	28.31	29.39	1.08	959	995	36	26	48	71	30	4	28.31	956	Pt. Judith, R. I.	3
Oct. 18, 1944	28.02	29.80	1.78	949	1009	60	27		93	13	4	28.02	949	Dry Tortugas, Fla.	4
*Oct. 19, 1944	28.42	29.67	1.25	962	1004	42	34	35	77	14	4	28.42	962	Sarasota, Fla.	1
Aug. 27, 1945	28.57	30.13	1.56	968	1020	52	18		88	4	4	28.57	968	Palacios, Tex.	1
Sept.15, 1945	28.09	30.00	1.91	951	1016	65	12	24	99	10	4	28.09	951	Homestead, Fla.(FECRR)	0
Sept.17, 1947	27.76	29.83	2.08	940	1010	70	19	34	102	10	3	27.97	947	Hillsboro, Fla.	8
*Sept.19, 1947	28.57	29.70	1.13	968	1006	38	28	33	72	16	4	28.57	968	New Orleans, WBO, La.	2
Oct. 15, 1947	28.59	29.65	1.06	968	1004	36	13		73	17	4	28.76	974	Savannah, Ga., WBAS	7
Sept.21, 1948	27.62	29.61	1.99	935	1003	68	7		102	8	4	28.45	963	Key West WBO, Fla.	8
*Sept.22, 1948	28.41	29.83	1.42	962	1010	48	16		85	11	4	28.47	964	Clewiston, Fla.	8

Table 3-1. -Continued.

Date	p_0	p_n	p_n-p_0	p_0	p_n	p_n-p_0	R		V_{gx}	c	t_c	p_a		Station	r_a
	in	in	in	mb	mb	mb	n.mi. (a)	(b)	mph	kt	hrs	in	mb		n.mi.
Oct. 5, 1948	28.85	29.77	.92	977	1008	31	27	31	67	13	4	28.92	979	Miami, Fla.	2
Aug. 24, 1949	28.86	30.20	1.34	977	1023	46	24		80	22	4	28.86	977	Diamond Shoals L/S, N.C.	3
Aug. 26, 1949	28.16	30.12	1.96	954	1020	66	22	23	99	14	3	28.17	954	W. Palm Beach WBAS, Fla.	0
Oct. 4, 1949	28.88	30.13	1.25	978	1020	42	28		78	11	4	28.88	978	Freeport, Tex.	0
Aug. 30, 1950	28.92	29.71	.79	979	1006	27	21		64	23	4	28.92	979	Ft. Morgan, Ala.	0
Aug. 30, 1954	28.35	--	-	960	-	-	-		-	24	4	28.35	960	Aircraft Recon.	
*Aug. 31, 1954	28.38	--	-	961	-	-	45	22	-	33	4	28.42	962	Suffolk County AFB, R. I.	
Sept.11, 1954	28.10	29.26	1.16	952	991	39	37	39		40	6	28.10	952	Martha's Vineyard, Mass.	0
Oct. 15, 1954	27.66	29.32	1.66	937	993	56	14	36	92	26	4	27.70	938	Little River, N. C.	4
Aug. 12, 1955	28.57	29.77	1.20	968	1008	40	45		72	7	4	28.64	970	Cherry Point, N. C.	17
Sept.19, 1955	28.51	29.87	1.36	966	1012	46	50		78	9	4	28.63	970	Cherry Point, N. C.	18

Note: All values are estimated except p_a.

p_0 central pressure

p_n asymptotic pressure

p_n-p_0 pressure difference between "outside" of storm and center

R radius to region of maximum wind speed

(a) computed from pressure profile

(b) observed from wind speed record

V_{gx} maximum gradient wind computed from pressure difference by formula p. Maximum wind at 30 feet above open water is on the order of 85 to 100 percent of this value.

c forward speed of the storm

t_c time interval over which storm movement is averaged to obtain c

p_a lowest pressure detected by a barometer

Station - at which p_a was observed

r_a minimum distance from station to track of storm center

* same hurricane as previous line, entering or passing coast at a second point

ciable period of time. Therefore, for each hurricane a complete picture is needed of the wind speeds and directions throughout the storm area, not merely the highest speeds. The general picture of the areal distribution of wind speeds in a hurricane is well known, a vast vortex of winds spiraling inward and turning in a counterclockwise direction (in the Northern Hemisphere), with speeds increasing from the periphery of the storm to the most intense winds near the edges of the eye. From here the wind speeds drop off rapidly and are light or even near calm in the center of the storm.

The quantitative details of the areal wind picture distribution in hurricanes over the open sea are not well known. The hurricane is not a smooth wind whirl, but, rather, contains lines of locally higher or slower speeds, departs considerably from circular symmetry, and varies (in different quadrants) the radius at which the wind speed is a maximum. All this means that considering the spotty observations of speed that are available, there is always the question as to how well an individual observation represents the average wind speed and direction over an area. A major fraction of the effort in the studies described in this portion of the report has been devoted to finding means for estimating, as well as possible, the areal picture of the wind speeds and directions in past hurricanes that have produced major surges. Reconstruction of past storms provides the only method for testing and improving theories of just how the sea, in a particular region with a particular configuration of the sea bottom, will react to a given hurricane wind field. As reaction of the sea is approximately proportional to the square of the wind speed; the need for the best possible definition of the wind speed becomes apparent; for example, a 15 percent over-all error in wind speed may result in an error as large as 30 percent in wind force imparted to the sea. Methods have been worked out for estimating the wind field from the pressure field to amplify the wind data.

Wind speed patterns. - Various composite pictures of wind speeds in hurricanes show that the wind speed field is not symmetrical. Studies by Cline [7] thirty years ago led him to the conclusion that wind speeds in hurricanes are much stronger in general in the half of the storm to the right of the direction of forward motion than in the left half, and that the highest speeds are usually experienced in the right rear quadrant. Hughes plotted wind speed reports from 84 reconnaissance flights into 28 hurricanes in both the Pacific and the Atlantic at their relative positions from the storm centers and thus obtained a composite picture of wind speed over the sea [8]. This pattern, reproduced in figure 3-1, is more or less symmetrical but with a slightly larger area of 80-knot or higher speeds on the right side than on the left. There is a small 90-knot maximum in the right rear quadrant, a placement in agreement with Cline. Sherman [9] has shown by a kinematic analysis of the streamlines of flow in hurricanes that the highest speed should be on the right side of the storm. A composite picture of ship-reported wind speeds in hurricane Flossy of 1956 shows a much larger region of high speeds on the right side of the storm than on the left. Weather Bureau hurricane warnings for storms off the Atlantic seaboard frequently report gale winds extending to greater distances to the front and right of the center than to the left and rear.

All of the foregoing are broad pictures of hurricane wind speed patterns and lack detail in the zone of maximum speeds; it is not yet clear whether there is a characteristic pattern in this zone common to most hurricanes. Figure 3-2 a composite picture of the wind speed in the September 1938 hurricane over a 3-hour period obtained in a recent Weather Bureau study [10], shows at the radius of maximum winds the strongest speeds on the right side of the hurricane. There is other evidence that the wind speeds are not necessarily stronger on the right side of the storm in the maximum speed zone. Analysis of the wind speeds in the storm of September 1944 shows that speeds on the left and right sides of the storm, adjusted for surface frictional differences, are more nearly equal than in the 1938 storm. The left side of the August 1949 hurricane was very vigorous in passing over Lake Okeechobee. It is not known, whether the right side would have been slightly more vigorous if it had been over water also. Intensive analysis of a few of the more recent hurricanes plus theoretical studies give good promise of better definition of the asymmetry of the hurricane wind field at the completion of the Public Law 71 studies than at the time of preparation of this report.

Radius of maximum winds. - The radius of maximum winds, R, is an index to the size of a hurricane. This is an important factor for hurricane tides and waves, because obviously the greater the lateral extent of the storm, the greater can be the total wind energy over an area or along a straight-line fetch. Table 3-2 shows the geographical distribution of the values of R given in table 3-1 for hurricanes of central pressure less than 28.50 inches. R was obtained in two ways. One method was to note the time when a wind-speed reporting station experienced a maximum of wind speed before the slack-off of speed in the eye, and to scale the map distance from the storm center to the station at this time. The other, more indirect, was to compute an R from the

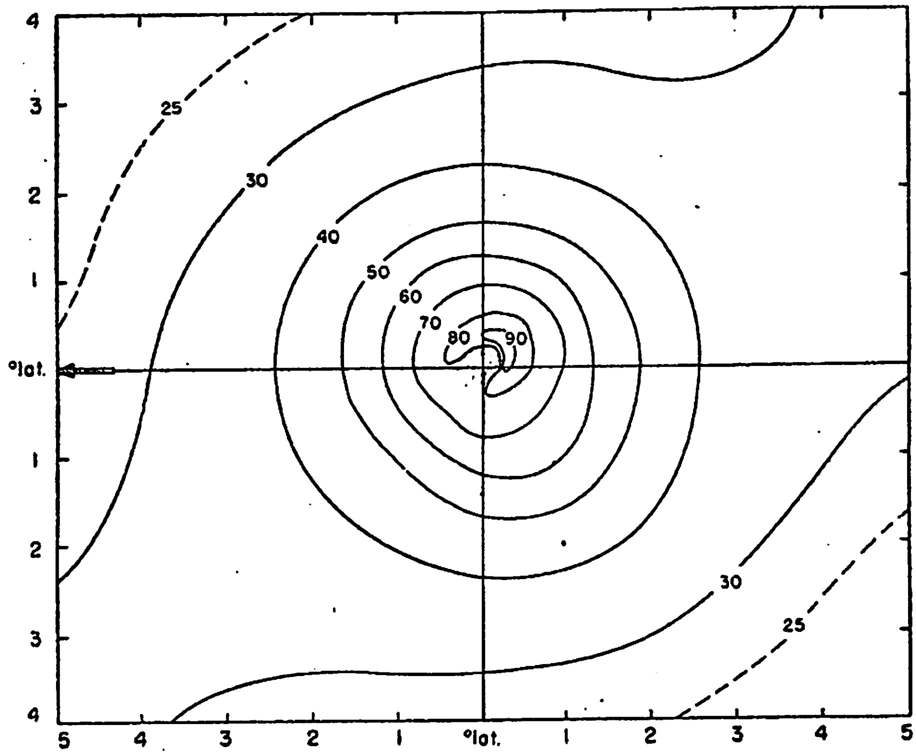

Figure 3-1. - Total wind speed in knots. Arrow indicates direction of storm movement. (From [8].)

pressure field in the manner described in Hydrometeorological Report No. 32 [3]. Table 3-2 reveals a tendency for R to increase with increasing distance from the tropical source region of hurricanes. This is in harmony with the commonly-held concept that hurricanes, as they mature and move out of the Tropics, expand somewhat in size with some decrease in maximum intensity.

Wind direction. - A composite wind direction pattern was derived by Hughes [8] in the same manner as his composite wind speed pattern, and shows deflection angles of about 18° to 28° over the area within 60 nautical miles of the center. The deflection angle is defined as the angle between the wind direction and a tangent to a circle with its center at the center of the hurricane. Hughes considered the inner portion the least reliable because of the sparsity of data. A composite wind direction analysis for the September 1938 and 1944 hurricanes is reproduced from [10] where it is described, and here shown as figure 3-3. On the basis of these patterns and theoretical considerations which suggest that the deflection angle would be less at R than farther out in the storm, the Weather Bureau at present is recommending for design hurricanes over the sea that a deflection angle of 25° be used from Radius R + 10 nautical miles outward, a deflection angle of 20° from R inward, and a transition zone between. The crudeness of the pattern derived from the 1938 and 1944 hurricanes is apparent from inspection of the figure. There are good prospects that better typical wind patterns for the central portion of hurricanes will be obtained before the completion of Public Law 71 studies.

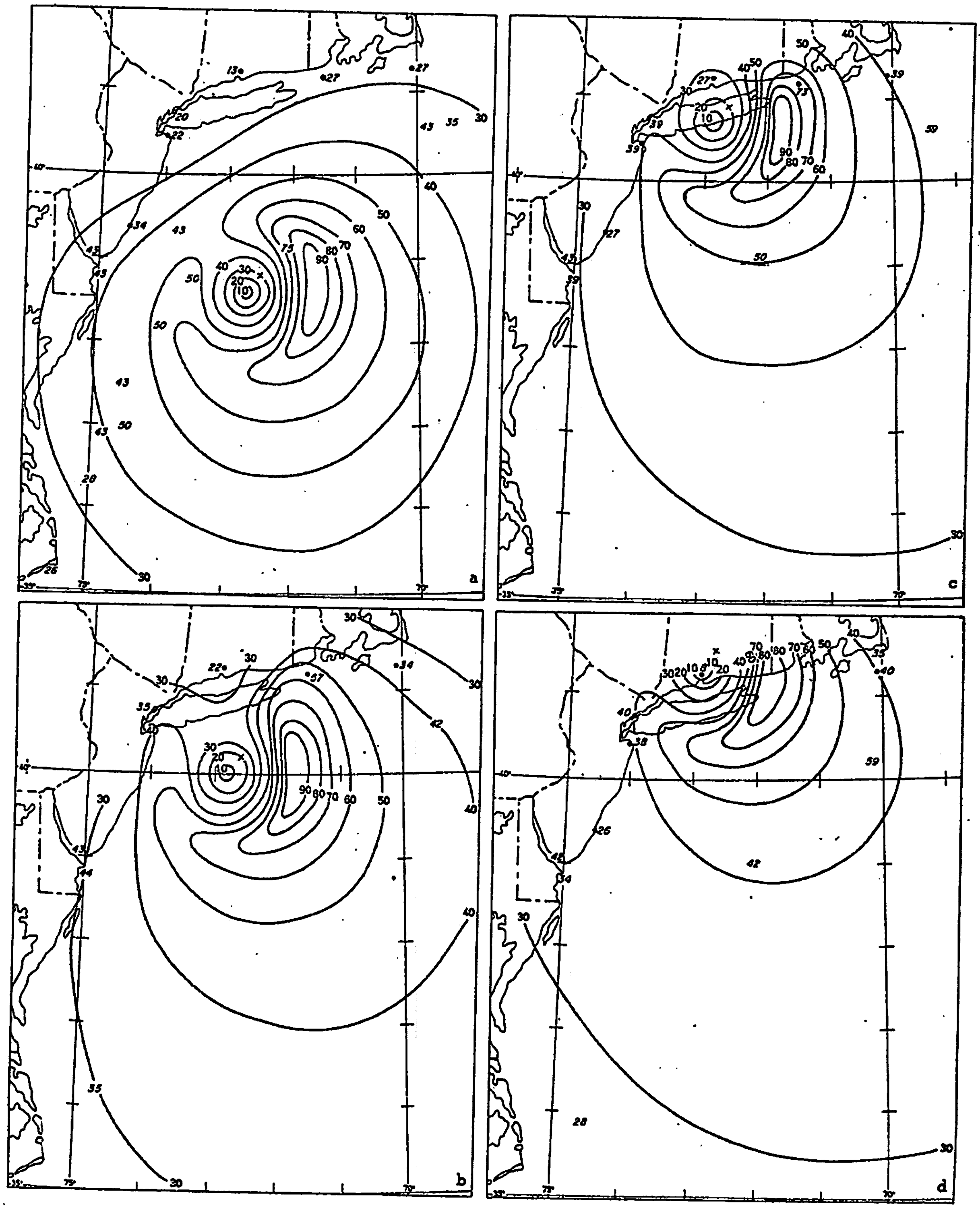

Figure 3-2. - 30-foot wind speeds (m.p.h.) September 21, 1938, (a) 1200, (b) 1400, (c) 1500, and (d) 1600 EST. Data with dot positions are Weather Bureau station observations, reduced to 30 feet. Data without dot positions are ship reports, unadjusted. X shows location of pressure center. (From [10].)

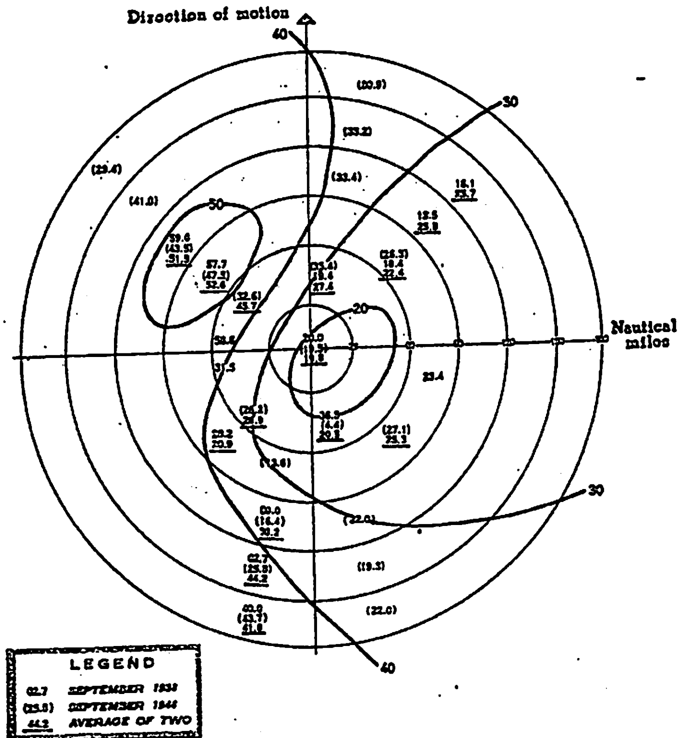

Figure 3-3. - Wind deflection angle (degrees). Data are means of zones outlined and plotted at point of greatest concentration of observations in the zones.

Table 3-2. - Radius of maximum winds (nautical miles) by regions for United States hurricanes with central pressures below 28.50 in.

Texas 1900-1949		Mid-Gulf 1887-1956		Florida Peninsula 1900-1949		Florida Keys 1900-1949		Atlantic (N. of Fla. - S. of Cape Hat.) 1893 - 1955		Atlantic (Cape Hat. and northward) 1893 - 1955	
a	b	a	b	a	b	a	b	a	b	a	b
		50		48	62	28		34		50	
35		31	33	34	35	27		23		49	
32		29		28	53	24	22	14	36	45	22
30	20	24	17	24	36	21				42	
21		21		22	23	16				37	39
19		19		19	34	15				26	28
18		17		18		7					
17				16		6					
14				14							
12				13	29						
				12	24						
Mean 22		27		23		18		24		42	

a = computed from pressure profile
b = observed from wind speed record

Table 3-3. - United States hurricanes with central pressure (p_0) below 29.00 in., by regions.

Texas 1900-1949		Mid-Gulf 1887 - 1955		Fla. Peninsula 1900-1949		Fla. Keys 1900-1949		Atlantic (N. of Fla. S. of Cape Hat.) 1893 - 1955		Atlantic (Cape Hat. and Northward) 1893 - 1955	
in	mb	in	mb	in	mb	in	mb	in	mb	in	mb
27.64	936	27.87	944	27.59	934	26.35	892	27.66	937	27.86	944
27.83	942	28.20	955	27.62	935	27.44	929	28.28	958	27.88	944
28.00	948	28.22	956	27.76	940	27.52	932	28.33	959	28.10	952
28.02	949	28.31	959	27.98	948	27.62	935	28.51	966	28.25	957
28.07	951	28.38	961	28.09	951	27.80	941	28.57	968	28.31	959
28.14	953	28.46	964	28.16	954	28.02	949	28.59	968	28.35	960
28.17	954	28.48	964	28.29	958	28.15	953	28.63	970	28.38	961
28.31	959	28.50	965	28.33	959	28.30	958	28.70	972	28.53	966
28.31	959	28.52	966	28.34	960			28.71	972	28.70	972
28.57	968	28.57	968	28.41	962			28.78	975	28.70	972
28.62	969	28.72	973	28.42	962			28.81	976		
28.76	974	28.76	974	28.70	972			28.86	977		
28.78	975	28.80	975	28.73	973			28.95	980		
28.80	975	28.92	979	28.82	976			28.98	981		
28.88	978	28.93	980	28.83	976						
		28.94	980	28.84	977						
				28.84	977						
				28.85	977						
				28.91	979						
				28.92	979						
				28.98	981						

Pressure effects on Tides and Waves

Central pressures. - The minimum pressure in a hurricane is important both as a partial index of the intensity of the wind and as an index of the magnitudes of the inverted barometer effect in lifting the sea surface. The estimates of hurricane central pressures, p_0, of table 3-1 are listed separately by regions and in order of magnitude in table 3-3. The same information is shown graphically in figure 3-4. It can be noted that the lowest pressures in and near the United States have been experienced in the Florida Keys; that is, the area closest to the hurricane source region. There have been no observed coastal values of less than 27.5 inches outside of the Keys. With increasing distances from the Tropics, the central pressures are higher. Central pressures in the mid-Gulf region are comparable to what may be expected at a somewhat more northerly latitude on the Atlantic Coast, perhaps because large intense hurricanes comprise a bigger percentage of hurricanes in the Atlantic, where there is more room for development, than in the Gulf and Caribbean Sea.

The lowest known central pressure in a hurricane in the Atlantic-Gulf area is 26.35 inches in the Florida Keys in 1935. This is the world's record for a land station. Slightly lower pressures have been reported at sea a few times in typhoons of the Pacific. The lowest pressure reported or estimated in a hurricane in New England from an official Weather Bureau barometer was 28.04 inches at Hartford, Conn., in the 1938 storm, or 27.94 inches at the Bellport Coast Guard station, Long Island, in the same storm (correction on barometer unknown). The central pressure of this storm was estimated in a recent Weather Bureau study [10] as 27.86 inches at the time the center crossed the south shore of Long Island. Texas, the Florida Peninsula, and the Carolina coast have experienced extreme hurricane pressures of about 27.60 inches at least once, as shown in table 3-3. The mid-Gulf extreme is 27.87 estimated in the hurricane of September 29, 1915.

Table 3-4. - Pressure difference, $p_n - p_o$, by regions, United States Hurricanes with central pressures below 29.00 inches

Texas 1900-1949		Mid-Gulf 1887-1955		Florida Peninsula 1900-1949		Florida Keys 1900-1949		Atlantic (N. of Fla. S of Hat.) 1893-1955		Atlantic (Cape Hat. and northward) 1893-1955	
in	mb	in	mb	in	mb	in	mb	in	mb	in	mb
2.77	94	2.27	77	2.76	94	3.57	121	1.79	61	2.78	94
2.28	78	2.04	69	2.40	82	2.45	83	1.66	56	1.66	57
2.22	75	1.93	65	2.08	70	2.29	78	1.57	53	1.63	55
2.14	73	1.77	60	2.00	67	1.99	68	1.40	48	1.16	39
1.96	66	1.65	56	1.96	66	1.93	66	1.36	46	1.08	36
1.86	63	1.57	53	1.91	65	1.78	60	1.34	46	0.92	31
1.57	53	1.54	52	1.57	53	1.77	60	1.33	45	0.89	30
1.56	52	1.44	49	1.44	49	1.39	48	1.28	44	0.85	28
1.43	48	1.44	48	1.42	48			1.24	42		
1.35	46	1.42	48	1.30	44			1.20	40		
1.35	45	1.40	48	1.28	43			1.18	40		
1.25	42	1.36	46	1.25	42			1.17	39		
1.24	42	1.16	40	1.21	41			1.06	36		
1.16	40	1.13	38	1.21	41			0.95	33		
0.99	34	0.97	33	1.18	40						
		0.79	27	1.12	38						
				1.07	36						
				0.96	32						
				0.92	31						
				0.79	27						
Mean											
1.68	57	1.40	47	1.49	50	2.15	73	1.32	45	1.37	46

Pressure differences. - The wind strength of a hurricane is roughly proportional to the square root of the difference between the peripheral pressure p_n and the central pressure p_o. The regional variation of the pressure difference is similar to that of the central pressure (table 3-4 and fig. 3-4b). Several regions have experienced pressure differences slightly in excess of 2.5 inches. The maximum gradient winds in table 3-1 are computed from the pressure difference for each hurricane*. Fletcher [19] gives a formula for estimating maximum anemometer-level winds from the pressure difference.

*The maximum gradient winds are computed from

$$V_{gx} = 73 \sqrt{p_n - p_o} - R(0.575 f)$$

where V_{gx} is the maximum gradient wind speed in m.p.h., $p_n - p_o$ is the pressure difference in inches, R is the radius of maximum winds in nautical miles, and f is the coriolis parameter in units of $hour^{-1}$. Approximate values of 0.575 f are 1/8 at 25° N.; 1/7 at 30° N.; 1/6 at 35° N., and 1/5 at 40° N.

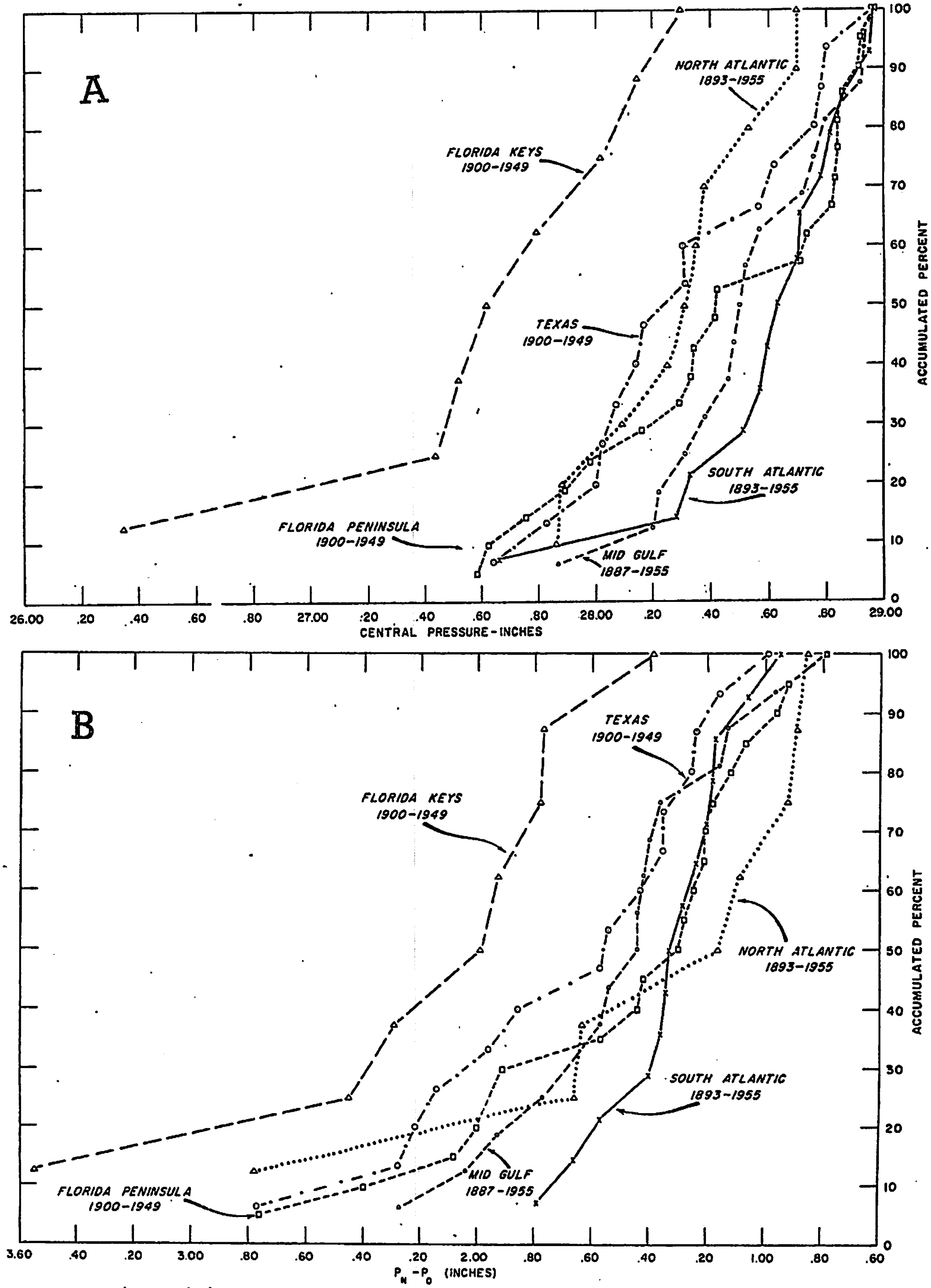

Figure 3-4. - (A) Accumulated frequency of occurrence of hurricane central pressures p_o by regions. (B) Accumulated frequency of occurrence of specific pressure differences $p_n - p_o$ (inches) by regions.

Table 3-5. - Average forward speed (knots) 2 hours before and after entering the coast, by regions. (United States Hurricanes with central pressures below 29.00 inches)

Texas 1900-1949	Mid-Gulf 1887-1955	Florida Peninsula	Florida Keys	Atlantic (N. of Fla. - S. of Hatteras) 1893-1955	Atlantic (Cape Hat. and northward) 1893 - 1955
4	6	6	8	7	16
8	7	6	8	9	18
8	7	7	9	9	22
8	9	8	10	12	23
10	10	8	10	14	24
10	10	8	11	15	29
11	11	10	13	16	30
11	11	10	13	16	33
11	14	10	16	17	40
11	16	11		18	47
12	16	11		21	
13	16	11		22	
14	21	11		26	
15	23	11			
15	25	12			
	28	13			
		13			
		14			
		14			
		17			
Mean 11	14	11	11	16	28

Interrelation of Central Pressure and Radius of Maximum Winds. - The most critical hurricane for causing an uplift of the sea is one that is both intense (with a low central pressure p_o and large pressure difference $p_n - p_o$) and of great lateral extent (as indicated by a large radius R of maximum winds.) The climatological list of hurricanes (table 3-1) shows that the hurricane of September 1935 had by far the lowest p_o and also the smallest radius of maximum winds, only 6 nautical miles. On the other hand, all the storms with R in excess of 50 nautical miles had only modest depressions of the pressure. This suggests an inverse relationship between R and p_o, an important consideration in design studies. Figure 3-5 shows plots of R versus p_o for various regions. An envelope has been constructed in each figure, that is, a line has been drawn through the points lying farthest to the upper right side of the figure. For the near-tropical regions, this envelope probably has more physical significance than for the more northerly regions, particularly the Atlantic Coast north of Hatteras. Closer to the Tropics, a tendency for maturing hurricanes to expand horizontally with the rise of the central pressure can be detected. Once hurricanes have assumed a definite northerly

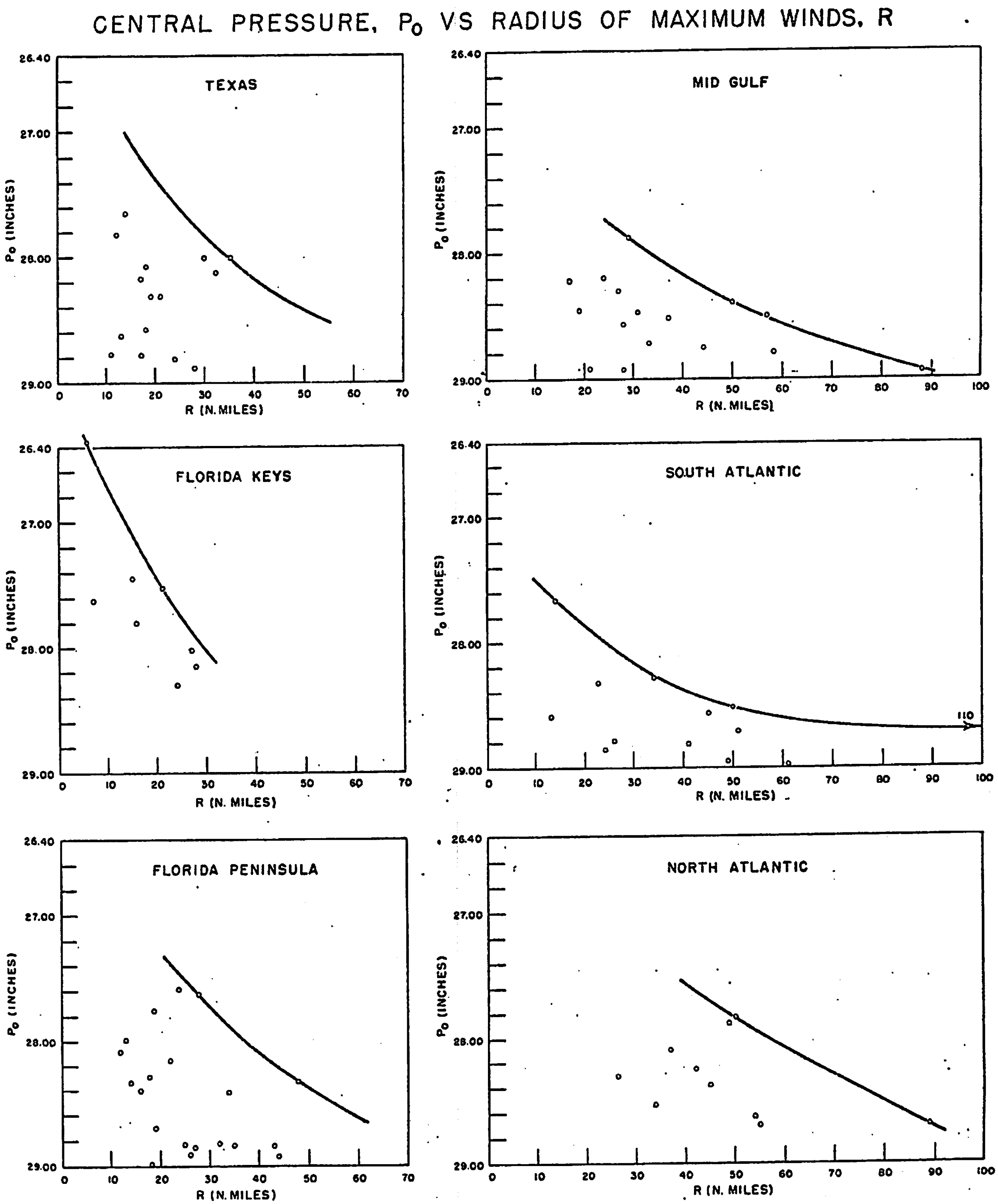

Figure 3-5. - Radius of maximum wind R plotted against central pressure p_o, by regions.

course and have reached the latitude of Cape Hatteras, it seems probable that this type of internal adjustment of the storm is no longer effective; here it is as reasonable to suppose that a hurricane will become smaller as the depression of central pressure weakens as that it will become larger. For example, the September 1944 hurricane became both weaker and smaller during its transit from the latitude of Cape Hatteras to the coast of New England.

Movement Effects on Tides and Waves

Speed of Forward Movement. - There is a marked regional variation in the speed of forward movement of hurricanes. This is shown in table 3-5 for the storms listed in table 3-1. In the Tropics hurricanes most frequently move toward the west at a moderate speed of some 10 m.p.h. This is most characteristic of hurricanes in the Atlantic, east of the West Indies. Motions in the Caribbean Sea are more haphazard in their arrangement. Eventually westward-moving hurricanes either strike land or swing in an arc to a direction more toward the north. After this recurving process they become engulfed in the more vigorous wind currents in middle latitudes and usually pick up speed, sometimes attaining speeds of 50 to 60 m.p.h. in their forward translation. The average speed of forward motion of hurricanes north of Cape Hatteras was 28 knots as compared with 11 knots for the area of the Florida Keys and for the Texas coast. The forward speed is critical for two reasons. First, it determines how long a hurricane will remain in a given area and therefore how much energy can be imparted to a water surface in a given length of time, and second, certain forward speeds are thought to be critical in producing the most effective possible continued build-up of reinforcement and a hurricane surge over certain configurations of the ocean bottom and certain depths of water.

Direction of Movement. - Directions of motion of hurricanes can be readily studied from tracks only without resort to detailed analysis. Over the years there have been various summaries of the directions of motion of storms; references are shown in the bibliography. The Weather Bureau is preparing a revised edition of all hurricane and tropical storm tracks in Atlantic, Caribbean, and Gulf waters since 1887 that will be published early in 1957. Regionally, these tracks show that south of the latitude of Savannah, Ga., hurricanes most frequently approach the Atlantic Coast from the southeast, but any direction from east through south, is common. North of Savannah practically all hurricanes will have recurved and will most often be moving from the south or south-southwest, or, for the outer part of New England, from the southwest, when making a landfall. South-southeast is also an admissible direction about as far up the coast as New York City. Most storms reach the west coast of Florida from the south or southwest. For the remainder of the Gulf coast directions from southeast through southwest are common, except for southern Texas, where the quadrant from east through south is the critical one.

A special study was made of direction of motion of hurricanes reaching the stretch of coast from Jacksonville to Cape Hatteras, a zone in which hurricanes that have not recurved and hurricanes that have recurved are mixed. Results are shown in table 3-6.

Table 3-6. - Breakdown into categories of direction of motion (in degrees) of hurricanes at the time they crossed the coast between Jacksonville, Fla. and Hatteras, N. C. (180° = from south). Dates of severe hurricanes are underlined.

180°-210°	150°-180°	120°-150°	90°-120°
Sept. 1804	Aug. 1893	June 1873	Aug. 1881
Sept. 1821	Oct. 1893	Aug. 1911	Sept. 1906
Aug. 1830	Oct. 1898	Aug. 1913	Oct. 1947
Sept. 1876	Aug. 1952	Aug. 1940	
Oct. 1878	Aug. 1955		
Aug. 1879	Aug. 1955		
Sept. 1883	Oct. 1899		
Aug. 1885	Oct. 1954		
Oct. 1893	Sept. 1955		
Nov. 1925			
Aug. 1944			
Aug. 1953			
Totals			
12	9	4	3

Any general relation between direction of motion and surge in area of landfall is probably complicated by local coastal features and has not been isolated.

HURRICANE RAINS

Rain is the life of a hurricane in the Tropics. The converging moisture-laden air rises, is cooled by adiabatic expansion, becomes saturated, and releases its copious moisture as rain. The water vapor of the air in condensing to moisture, releases great quantities of heat, and this heat supplies much of the energy required to drive the hurricane. The release of heat into the atmosphere is equal to the amount of heat that would be required to boil all the rain into steam. As hurricanes move out of tropical regions they derive part of their energy from the interaction of cold and warm air masses and rain is not quite so essential an ingredient. As hurricanes may reach the United States in any stages of their life cycle they may or may not be associated with copious rains. The speed of forward motion also has much to do with the amount of rain falling at a particular location. A very fast-moving storm, such as Hazel of 1954, during its first 12 hours over land, does not remain long enough at one place to develop a severe local flood from rainfall. (Flooding from the sea in Hazel was severe, and from rain in later stages over Canada).

Another important aspect of precipitation characteristic of hurricanes is that the rain may, and often does, begin long before the actual major wind-storm arrives and may extend over areas not affected by severe wind speeds. Attention is being given to determining what are the conditions most favorable for heavy pre-hurricane rain. A third important aspect is the orographic release of precipitation in hurricanes. Slopes of mountains or hills can produce great updrafts and both increase the total quantity of rain and concentrate it over one drainage basin.

Rainfall is not closely correlated to the intensity of the wind circulation. Weak tropical storms and decaying hurricanes are at least equally as threatening as vigorous hurricanes in producing floods. The precipitation in the best known United States hurricanes and tropical storms has been portrayed in a report under Public Law 71, National Hurricane Research Project Report No. 3, "Rainfall Associated with Hurricanes." This shows what hurricanes in general have done and can do. Investigations are now proceeding to devise means of predicting what a particular hurricane will do in the way of producing floods. These investigations and other characteristics of the precipitation in hurricanes are described in Chapter 4.

HURRICANE WINDS

Preceding sections have discussed wind characteristics related to waves and rises in water levels. This section deals with characteristics related to direct wind damage. Wind characteristics have received the greatest attention from climatologists over the years, and as there is no extensive new information to report, the discussion here is limited to a brief review of some of the well-known characteristics affecting wind loads on structures.

Damage of an object, such as a building or a tree, by the force of the wind is related to the maximum sustained wind to which the object is subjected, to the peak gust speeds that strike the object, and, in a complex way, to the character of the gustiness, such as the range of speed from lull to peak of a gust, the timing of the gust as compared with the natural vibrational period of the object, and the lateral and vertical extent of individual gusts. The variation of wind speed with height, and over frictional surfaces of differing resistence to the wind flow, must also be taken into account in relating the windiness at a building site to the windiness measured at the nearest weather station.

A really satisfactory climatological description of wind in the hurricane zones of the United States for the purpose of the design of structures would have as its first element, probabilities of occurrence of various high wind speeds at a standardized height above the ground and over a standardized frictional surface. This would be much more than a recital of winds that have been observed in past hurricanes, and would include interpolation between wind-observing stations on the basis of meteorological principles and extrapolation beyond the record in regions that have not had a severe hurricane experience during the period of record by virtue of chance rather than for any basic meteorological reason. Standardization of old wind records from downtown city locations of Weather Bureau Offices is a major study in itself, if indeed it is possible. The buildings around the anemometer site make the effective height of the anemometer above the underlying surface uncertain and difficult to estimate.

Table 3-7. - Maximum wind speeds observed in hurricanes, at United States Coastal Stations

Station	Fastest mile (mph)	Date
Brownsville, Tex.	106	9/5/33
Corpus Christi, Tex.	110	9/14/19
Galveston, Tex.	91	8/17/15
Houston, Tex.	84	7/23/43
New Orleans, La.	98	9/19/47
Mobile, Ala.	98	7/5/16
Pensacola, Fla.	91(b)	10/18/16
Apalachicola, Fla.	67	9/17/47
Tampa, Fla.	84	10/19/44
Key West, Fla.	91	9/10/19
Miami, Fla.	123(a)	9/18/26
Jacksonville, Fla.	76	9/29/96
Savannah, Ga.	90	8/11/40
Charleston, S. C.	73	8/28/93
Wilmington, N. C.	82	10/15/54
Cape Hatteras, N. C.	110(b)	9/14/44
Cape Henry, Va.	134	9/14/44
Norfolk, Va.	78	10/15/54
Baltimore, Md.	78	10/15/54
Atlantic City, N. J.	91	9/14/44
Philadelphia, Pa.	73	10/15/54
New York, N. Y.	113	10/15/54
New Haven, Conn.	62	9/16/03
Block Island, R. I.	100	8/31/54
Providence, R. I.	95	9/21/38
Nantucket, Mass.	60(c)	9/11/54
Boston, Mass.	86	8/31/54

(a) Five-minute maximum
(b) Estimated
(c) 91 m.p.h. on 3/1/14 in winter storm

Maximum wind speeds

The basic climatological factor in assessing wind loads on structures is maximum sustained wind speed. Maximum wind speeds observed at first order Weather Bureau stations in coastal areas from Brownsville, Tex., to Boston, Mass., are shown in table 3-7. All of these maximum winds occurred in hurricanes, except at Nantucket, Mass., where the maximum took place in a winter storm. The speeds in this table are the "fastest single mile;" that is, the fastest one-minute average for a wind of 60 m.p.h., the fastest one-half minute average wind at 120 m.p.h., etc. All observations are by cup-anemometer connected electrically to a recorder which indicates the passage of successive miles of wind by marking on a time graph. The maximum winds in table 3-7 have not been standardized for height, for distance from the sea, or for character of the terrain. It should be noted again that these are the highest winds observed at a Weather Bureau Office, and not necessarily the highest winds within the individual hurricanes. Indeed higher winds were likely present in the majority of these storms.

Another compilation of maximum wind speeds in hurricanes is shown in figure 3-6. This diagram presents the return period in years of certain maximum wind speeds at a standardized level of 100 feet for the Gulf and Florida coasts. These speeds are computed entirely from the pressure fields of hurricanes experienced during the period 1900-1949. Further discussion of the basis of this diagram is contained in Hydrometeorological Report No. 32 [3] in which it first appeared. The frequencies indicated by this diagram are comparable to a table of frequencies of hurricane force winds at coastal cities compiled earlier by Norton and Gray [16] of the Weather Bureau, except Norton and Gray show higher probabilities of hurricane force winds at Pensacola, Fla., than figure 3-6 shows for the mid-Gulf area.

The maximum gradient winds, computed from the pressure fields of individual hurricanes, are shown in table 3-1. The maximum surface wind speed is 80 to 100 percent of this value.

Gust Factors

The gust factor is the ratio of the maximum wind gust speed to the average speed as commonly recorded by meteorological instruments. A precise defini-

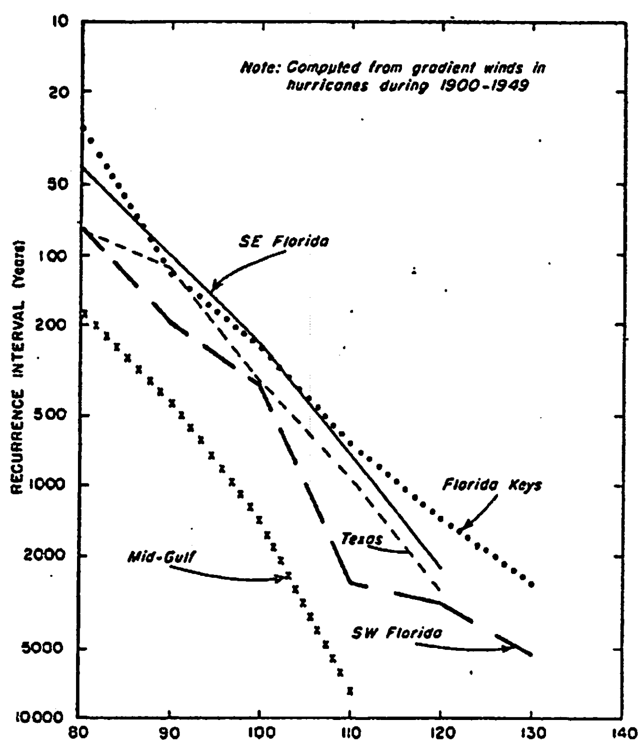

Figure 3-6. - Average recurrence interval at various points along the coast of various 15-minute average off-water wind speeds 100 ft. above the ground.

Table 3-8. - Mean gust factors observed at Brookhaven National Laboratory during hurricanes Carol and Edna of 1954 (From [1].)

Height above ground (ft.)	Gust Factor Carol	Edna
37	1.43	1.45
75	1.38	-
150	1.28	1.29
355	1.22	-
410	-	1.18

$$\text{Gust factor} = \frac{\text{Maximum 2-second speed}}{\text{1-min. mean speed}}$$

tion includes specifications of the time interval over which the gust and the average speed are averaged. These might be, for example, one-second and one-minute periods. At 30 feet above the ground the gust factor is on the order of 1.5. It is doubtful if there is any appreciable regional variation in gust factors. Gust factors obtained in hurricanes Carol and Edna of 1954 at the Brookhaven National Laboratory [1] are included in table 3-8. Other references to gust factors are listed in the bibliography.

Other more complicated relations of wind gustiness to wind loading on structures and the effect of the import of wind-driven rain are important engineering and micrometeorological problems which are not treated in this report.

Variation of Wind Speed with Height

The only known instances of hurricanes passing over a site instrumented to measure the wind speed at more than one level are the passages of hurricanes Carol and Edna of 1954 over the Brookhaven National Laboratory site referred to above. The average variation of wind speed with height for a 2-hour period in each of these two hurricanes is shown in table 3-9, from [1]. There is reason to believe that at locations more exposed to open water there is less variation of the wind speed with height. A number of investigations have been made throughout the world on the variation of wind speed with height. Some that contain specific data are listed in the bibliography.

Variation of Wind Speed with Surface Friction

The wind observations in hurricanes passing over Lake Okeechobee, Fla., recorded by Corps of Engineers meteorological stations on the shore of the Lake and on pylons within the Lake, have been analyzed to determine the variation in wind speed, other conditions being equal, for the three frictional categories of over-water (at the pylons within the Lake), off-water (from lake to land at the shore), and off-land (from land to lake at the shore.)

Table 3-9. - Variation of wind speed with height, Brookhaven National Laboratory, during hurricanes Carol and Edna of 1954. (From [1])

Height above ground (ft.)	Wind Speed (mph) Carol Mean	Carol Max. 1-min.	Edna Mean	Edna Max. 1-min.
37	32.4	51	26.4	38
75	41.8	65		
150	53.9	80	45.4	58
355	65.2	96		
410			57.9	69

This analysis is described in [17] and [3].

On the average the off-water wind speed was 89 percent of an over-water wind speed. A recent unpublished study made in the Weather Bureau of the behavior of wind speeds at Nantucket Island, Mass., confirms this as a reasonable figure. Off-land winds are a lower and more uncertain fraction of the over-water wind, depending on the character of the land. The ratio probably varies with wind speed and location. At Lake Okeechobee, the off-land wind averaged 60 percent of the over-water wind when the latter was 50 m.p.h., and 74 percent when the latter was 80 m.p.h.

FREQUENCY OF HURRICANE CHARACTERISTICS

Frequency Information Needed

After the characteristics of past hurricanes in any particular region have been determined, the second step is to consider the frequency of these characteristics. For protection of all kinds the greatest interest is not in average values for hurricanes, but in the most severe values. Answers are needed to such questions as the following which pertain to the severity of hurricanes: What is the frequency of hurricane central pressures below 28 inches in a given region? What is the return period in years of the lowest central pressure of record; or the highest wind speed of record? What are the frequencies or return periods of certain values of central pressure lower than any observed or of wind speed higher than any observed? Similar questions may be posed with respect to the radius of maximum winds, the speed of forward motion, etc. In some instances the slowness of forward motion that a hurricane may exhibit is a critical characteristic. This is true at Lake Okeechobee, Fla., and at Lake Pontchartrain, La. The longer a hurricane remains over either Lake, up to a considerable number of hours, the larger will be the build-up of water on the windward shore.

Obtaining frequencies of the factors listed above is surrounded by certain difficulties. First, the characteristics of greatest interest are not directly observed by meteorological instruments and are obtained in a particular hurricane only by intensive analysis. This includes central pressure, representative values of maximum wind speed, radius of maximum wind, and, to some extent forward speed. Therefore, even a small amount of data is obtained only with considerable effort. Second, hurricanes in a given region are relatively rare events, and extremely severe hurricanes are even more rare; therefore the total amount of data obtained, even by a large processing effort, may be meager. The appropriate design hurricane for some proposed protective works is usually a hypothetical hurricane more severe than any of record. This poses the usual uncertainties of extrapolating beyond the record.

Approach to Frequency Problem

The most feasible approach to the frequency problem for design purposes is to assemble the available meteorological data on hurricane characteristics pertinent to a particular region. Design engineers can then make subjective judgments as to the appropriateness of particular hurricane characteristics for design criteria or related purposes, with the help of such interpretation of the data as a meteorologist can furnish. This has been done under the Public Law 71 program to date, specifically for southern New England, the Carolina coast, and the New Orleans area. A study of the Chesapeake Bay area is in preparation.

Another aspect of the frequency problem is in computing economic benefit from a project under consideration. In some instances, it may not be feasible to compute economic benefits on the per-year basis applied to flood control projects, because the return period of various categories of hurricanes cannot be estimated with sufficient reliability. One alternative approach to an estimate of economic benefits is based on the idea that if the protective works prevent a hurricane-induced inundation from a hurricane of certain specified characteristics just once, a complete return on the investment is obtained.

OUTLOOK

1. Coastal observations of winds, pressures, and tides should be increased in future hurricanes in order to obtain adequate descriptions of the hurricanes for wind-tide investigations and planning protective works. Some degree of success has been obtained in reconstructing past hurricanes through indirect analysis from sparse data, but this type of analysis will always be inferior to direct observation. Projects which are planned or are in progress for improving these data are outlined below.

(a) A cooperative hurricane reporting network of non-recording wind and pressure stations, to report on-call to forecast centers, will be installed in 1957. Special low-cost equipment has been designed and is being manufactured for this purpose. The primary purpose of this network is for forecasting, but the records will also contribute considerably to the post-analysis of hurricanes. About 75 stations are planned.

(b) About 40 additional automatic wind-recorders are planned for Weather Bureau coastal stations. These are essential for research and post-analysis.

The wind field in a hurricane is too complex to obtain an adequate record from visual observations alone.

(c) Twelve remote-indicating recorders have been attached to Coast and Geodetic Survey tide stations during the past year so as to indicate the current stage of the tide in Weather Bureau Offices. It is planned to extend this network to an additional 12 gages during the coming year. For the last two years the Weather Bureau, with the cooperation of the Coast and Geodetic Survey, has sent an observational team into the vicinity affected by hurricane surges to make a detailed survey of the high water marks left by the storm as promptly as possible after each hurricane's occurrence. This has produced much useful data that would have been lost if the survey had been deferred for even a few weeks. It is planned to continue this policy in the future.

The instrumental programs are supported by other than Public Law 71 funds.

2. One of the greatest gaps in knowledge of hurricanes pertains to surges and waves. The following projects are planned to partially fill-in this gap:

(a) Under the Public Law 71 program the winds and pressures observed over the sea in one or more major surge-producing hurricanes will be reconstructed for each principal section of the coast line. These will form a backlog of meteorological data for study of wind-surge relationships under Public Law 71 and other programs and in years to come. Hurricane Hazel of 1954 is being analyzed in this way at the time of preparation of this report.

(b) The storm surge, the difference between observed sea level and that predicted by astronomical considerations, is being analyzed for a large number of hurricanes. Basic data for this study are obtained from the records of the Coast and Geodetic Survey, and a great deal of valuable supplementary data are being obtained from the records of the Weather Bureau, the Corps of Engineers, the Geological Survey, and other organizations. Post-hurricane surveys made by the Weather Bureau in cooperation with Coast and Geodetic Survey, by the Corps of Engineers, and by some private oceanographic organizations, will contribute further to the available data.

3. Better models of surface wind fields in hurricanes are required.

(a) Dynamic studies on a modest scale are being carried on to integrate into consistent models the meteorological data in hurricanes on the one hand and the basic equations of motion in the atmosphere on the other, and data and theory of turbulence in the surface layer. If these studies develop useful relationships as expected they should be expanded.

(b) Winds and pressures in the severest past hurricanes should be reconstructed again as better models become available through better theories and more data from later hurricanes.

4. An important characteristic of hurricanes for estimating potential severity at such locations as Chesapeake Bay, New York City (from a hurricane passing inland over New Jersey), Lake Ponchartrain, La., Houston, Tex., etc. is the filling (weakening) over land. Empirical studies of filling are being

made under the Public Law 71 program; however, knowledge of how much filling a hurricane can be expected to undergo is still vague and qualitative. The empirical studies will be continued under the Public Law 71 program as needed for particular projects or investigations. Complete solution of this problem will probably have to await better understanding of the three-dimensional energy balance of hurricanes.

5. Field investigations and theoretical studies of the variation of wind speed from open coast to anemometer sites a few miles inland should be amplified as a second phase of the increased wind-speed reporting network. This is required for proper interpretation of the wind data. Studies of this nature have been made under the Public Law 71 program in upper Chesapeake Bay, at Nantucket Island, and at other locations.

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CHAPTER 4 - HURRICANE PRECIPITATION

Rain is an integral part of hurricanes - millions of tons of it over thousands of square miles. Rain formation, which in the atmosphere is a heat-releasing process, is the primary source of energy for hurricanes. After transit to northerly latitudes there may be occasional exceptions. The copious hurricane rains are in general beneficial to agriculture, and in fact to anyone who needs water. But the heavy rains bring their attendant problem - floods. Almost all hurricanes passing over land areas produce some flooding, frequently quite local and inconsequential, but many hurricanes produce severe floods.

There are both permanent and temporary defenses against hurricane rain floods. The permanent defense is to build protective works to the extent consistent with the value of the property and the risk from floods in the particular area, or to limit land use in flood plains by zoning. The corollary temporary defense is to evacuate people and movable property and to place temporary barriers to the water at the time of a flood, acting according to a pre-determined plan. The permanent defense requires from the meteorologist an evaluation on the magnitude of the hurricane flood risk in the particular locality. The temporary defense requires, in addition to this, specific forecasts of precipitation amount as the hurricane approaches. Hurricane precipitation forecasts will attain a really high measure of success only when the internal mechanics of hurricanes are more fully understood. Development of this understanding is receiving impetus under present federal programs.

CHARACTERISTICS OF HURRICANE PRECIPITATION

Intense hurricanes are easily identified meteorologically and probably have more characteristics in common with one another than do most other meteorological phenomena. This similarity from storm to storm probably also applies to hurricane rainfall, but there are still wide variations of rainfall with particular storms. Most intense storms may produce copious rainfall while others with similar characteristics may produce only minor rainfall amounts.

Some of the most intense rainfall over fairly large areas of the United States has occurred either directly or indirectly in connection with hurricanes. Extremely heavy rains have occurred over areas where a hurricane has entered the decadent stage; e.g., the Thrall, Tex. storm of September 8-10, 1921. Other heavy hurricane-rain situations have resulted from the combination of a decadent hurricane with an added orographic influence, as in the case of the Altapass, N. C. storm of July 13-17, 1916, and two or more flood-producing storms over the Rio Grande Valley; viz., the Pandale, Tex., storm of June 24-28, 1954, the Montell, Tex., storm of June 22-30, 1913, and others.

Heavy hurricane rains have occurred in connection with weaker tropical disturbances and hurricanes, and at times several hundred miles from the hurricane itself because of warm moist air flowing poleward around the eastern side encountering cold air along a pre-existing cold front; e.g., the

Ewan, N. J., storm of September 1, 1940, and other similar storms of lesser extent.

Another factor contributing to flood conditions is the occurrence, in rapid succession, of two or more hurricanes or tropical disturbances over the same geographical region, as was the case of hurricanes Connie and Diane of August 1955 and other similar situations.

Although rainfall of the intensity of the aforementioned cases is not necessarily the rule, it has occurred frequently enough to be of importance in any general forecasting activity. The most important ideas in this connection, accepted by meteorologists for many years, are:

1. Heaviest rainfall occurs in particular localities in connection with slower-moving hurricanes because of a longer period of rainfall accumulation.

2. Heaviest rainfall occurs to the right of the path of the hurricane.

It is not unreasonable to assume that these two ideas have a justifiable basis in observation; however, exceptions have been noted.

The principal published works pertaining to these rules are Cline's Tropical Cyclones [1]; the work of Depperman in the Philippines, in particular the publication, "Some Characteristics of Philippine Typhoons" [2]; and some of the storm studies that have been made under the Storm Study Program of the U. S. Corps of Engineers [3]. These rules have been used for most of the precipitation forecasting in connection with hurricanes.

METHODS OF ATTACK ON THE PROBLEM

It is planned that two general means of attack on the problem of hurricane precipitation will be used, one of which might be called the gross-feature method and the second, the physical-approach method. As the first phase of the gross method it was decided to record the precipitation that has occurred in connection with hurricanes and other similar storms in the past. The publication was planned to provide: a climatology of hurricane rainfall; a guide to forecasters as to the rainfall amounts that can be expected in individual hurricanes; basic guidance information to officials charged with design and rescue responsibilities; basic information for research workers on hurricanes. This is important not only for rainfall *per se* but since much, if not most, of the energy for the hurricane probably comes from the release of latent heat, it provides quantitative information for many problems.

This first phase of the gross attack has been completed, published, and distributed as National Hurricane Research Project Report No. 3. [4]. This report consists of a survey of rainfall characteristics in hurricanes and other tropical disturbances during the first half of the 20th century. Since a complete list of hurricanes and tropical disturbances was not available, a separate list was determined by consolidation of available information contained in various publications; i.e., [1, 5, 6]. All tropical disturbances selected were given equal weight, and isohyetal maps were plotted and analyzed for 24-hour periods that would cover not only hurricane rainfall but also pre-hurricane and post-hurricane rainfall. Twenty-four-hour rainfall centers meeting a criterion of 5 inches or more were selected for portraying significant isohyetal patterns of tropical disturbances. After 24-hour isohyetal maps had been prepared and selected according to the 5-inch-center criterion, total storm maps were prepared for all the storms. Here again the 5-inch criterion was used in the selection of pertinent isohyetal patterns. The storms that did not have a 5-inch rainfall center in either 24 hours or over the total storm period were included without isohyetal maps in separate sections of the publication. Storms of tropical origin that were worked up in the Corps of Engineers' Storm Study Program were treated in the same manner, except that the maximum average depth of rainfall in inches and the duration of rainfall in hours at the maximum station were included. In obtaining the 414 isohyetal patterns contained in Report No. 3 approximately 1000 isohyetal maps were plotted and analyzed.

The manner of presentation was attacked along the line of expediency. Since it was not possible to make a detailed study of each tropical disturbance, general meteorological summaries were attempted. Although inclusion of tracks for each of the disturbances was considered necessary, it was not practical to include them at the time of publication. Future plans include presentation of the track of each disturbance.

The moisture flow measured quantitatively around hurricanes is another gross feature that is being used to give an indication of subsequent hurricane rainfall. Cross sections of moisture transport to the right of hurricane paths are being constructed and are being compared with downstream isohyetal patterns. It is anticipated that a report of this will be prepared early in 1957.

The basic data compiled for Report No. 3 will be used in studies of the relationship of hurricane rainfall to the various aspects of the hurricane path; i.e., velocity and acceleration, angle of approach to a coast line, and other gross features of hurricane movement. The relationship of rainfall to the intensity and areal extent of the hurricane will also be correlated.

The physical approach method utilizes the hydrodynamics of atmospheric flow investigated both mathematically and synoptically to predict hurricane rainfall at some time in the future by use of the particular characteristics of the flow that are observed from the weather map at the present time. In the past most methods using this approach have been kept very simple. This was necessary in order to complete the computations and resulting forecast in a minimum amount of time from the instant the data were observed and transmitted to the analyzing station, so that it could be issued in time to be of practical value to people making decisions as to actions to prevent loss of property or life. With the advent of fast computing procedures, and in particular of high-speed electronic computing machines, it now appears that it is possible to undertake solutions of much more ambitious equations describing the physical processes than were formerly thought possible.

A general approach to the forecasting of atmospheric motions has been developed in a concentrated effort over the past few years. It is now in operation at the Joint Numerical Weather Predictions Unit located at Suitland, Md. This unit is a joint enterprise of the Weather Bureau, Air Force, and Navy. The method used gives an implicit forecast of the vertical motion for any time for which a forecast of the horizontal motion of the atmosphere is made. These forecasts are now prepared on a daily basis and are being used by a few Weather Bureau offices for guidance in preparing rainfall forecasts. The method described in an article by J. Smagorinsky and G. O. Collins [7] has given promising results. The method may be capable of giving the large-scale vertical motions for the rainfall over large areas but may not be able to forecast the rainfall over smaller areas, especially the more intense rainfalls that contribute to cloudburst-type floods.

Another approach to the problem of quantitative precipitation forecasting has been suggested by workers in the Hydrometeorological Section of the Weather Bureau, in particular in an article by James F. Appleby [8]. This method assumes that heavy rainfall will occur in areas where there is a strong inflow of warm moist air as compared to surrounding areas. A forecast is made of such an area of relatively strong inflow and promising results are found qualitatively in relating this area of strong inflow to the concurrent and/or subsequent rainfall.

Recent further developmental work in the Hydrometeorological Section in connection with Subproject No. 3 has suggested the possibility that the rainfall will not occur exactly where this area of relatively strong inflow has occurred, but that it will occur somewhat later and downwind from this area. The developmental work has further suggested that fairly accurate analysis of the surface pressure field would be necessary. Over many parts of the country the network of surface pressure-observing stations is not at present dense enough to allow such a detailed analysis, and it will probably always be a problem over the ocean areas since pressure observations at sea, particularly in areas of strong wind such as accompany hurricanes, are a very difficult problem.

Formulas relating the growth of divergence to the rate of change of the geostrophic vorticity with time have been derived on the basis of the equations of atmospheric motion. Considerable effort has been expended on the determination of the most accurate and reliable numerical method for solving the divergence formulas, and their possible application to quantitative precipitation forecasting will be exploited to the fullest extent. In future studies results of the finite difference numerical method will be illustrated by a number of graphs, and the functional relationships assumed for the solution of the formulas will be compared with relationships extracted from given meteorological situations known to be conducive to rainfall. A research report on this work is now being prepared.

SUMMARY

1. A study of the excessive rainfall in hurricanes reveals that, in a general way, it follows patterns, but these patterns show pronounced variations.

2. Very little organized study has been done in the past on these patterns.

3. It is planned, during the immediate future, to intensify the study of these patterns and their relationships with other features of hurricanes.

4. Studies will also be made on the dynamics of air motion in connection with precipitation forecasting.

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CHAPTER 5 - HURRICANE FORECASTING

The hurricane forecast problem, quite similar to the forecast problem at higher latitudes, is complicated by the fact that events critical to hurricanes occur over regions where weather data are insufficient. An important effort toward improving hurricane warnings therefore, must be directed toward improving observations.

Within the last decade great strides in observing techniques have been made by the advent of the intense aircraft reconnaissance of hurricanes and the application of radar to hurricane tracking, and both of these techniques are being expanded under present plans. The Weather Bureau is in the process of expanding the high-powered radar network, and the National Hurricane Research Project represents the most concerted effort in history to collect research-type data on hurricanes. Land station networks are being improved and the number of ships cooperating in the ship observation program at sea is being increased.

Only recently advances have been made in objective hurricane forecasting, and further research effort toward this goal is now being carried out at several places, along with the increased attention to hurricane research at many Weather Bureau offices, universities, private corporations, etc. Verification statistics which reflect both deficiencies of method and insufficient data, show some improvement in recent years, partly due to the improved tracking methods. Significant improvement in forecasting hurricanes and producing more efficient warnings can be anticipated only as a result of basic research now under way.

STATEMENT OF THE PROBLEM

The purpose of this chapter is to define the hurricane forecast problem as it relates to storm damage and peril to life, to describe recent advances, and to review current efforts for further improvement of forecasts in order to reduce the loss of life and property from hurricanes.

It has long been known that a major part of hurricane motion is due to the large-scale circulation in which it is imbedded. The general flow in hurricane regions of the Atlantic is largely a reflection of the dominant Bermuda anticyclone, so the hurricanes move around its southern portion and turn northward on its western limb. Although this knowledge of the climatology of storm tracks provides a base for all hurricane forecasts, by itself it is of limited utility. Rather, the forecast problem is that of predicting the day-to-day changes in the large-scale circulation patterns which are brought about by the smaller-scale transient systems. The hurricane forecaster is faced with the same problem as the forecaster in other regions, but many of the events critical to hurricanes occur out over the subtropical ocean where observations are at best sparse. In addition, a hurricane forecast, if it is to be of any value, must specify the track with great accuracy, for a difference of a few tens of miles is frequently the difference between severe damage and no damage at all. The formation of hurricanes, as well as early detection, is also a forecast problem because the area of genesis is always over the sea. Where formation is distant from populated areas the storm's presence is revealed as it approaches shipping lanes, but the Gulf of Mexico is a region of formation that is critical because storms may form there very near the coast and develop high winds and move into populated areas within one day.

The observations needed for the solution of the forecast problems can be divided into two classes: (1) those necessary to locate the storm and delineate its size and intensity, and (2) those necessary to forecast its future state. Since location is primarily a problem when a storm is at sea, the observations of the first category are those provided by ships, reconnaissance aircraft, and island and coastal stations.

Radar is the most recent contribution to this type of observation, but it has not provided a complete solution because the range is limited and land-based equipment can track a storm only when it is within 100 to 200 miles. Reconnaissance of storms by aircraft is perhaps the greatest single contribution to improved hurricane observing during the last decade because it is the only method presently available to provide precise storm tracking over many oceanic areas.

Observations for forecasting hurricanes must be no less precise but must cover broad areas - from the Pacific to Europe, from low to high latitudes, and throughout great depths of the atmosphere. These observations are provided by all of the meteorological facilities, including aircraft, ships, and stations taking upper-air soundings.

It is, therefore, obvious why such a great effort must be directed toward the observation part of the general forecast problem.

OBSERVATIONS

Observations for Tracking

Locating and tracking of a hurricane are made possible by the following types of observation:

1. Surface weather station reports of the atmospheric pressure, pressure tendency, and wind speed and direction.

2. Ships' reports of pressure, wind direction, and speed.

3. Land-based radar scanning.

4. Aircraft reconnaissance reports of pressure, wind speed and direction, and data from airborne radar.

<u>Surface weather stations</u>. - Although complete surface weather observations are routinely taken at a vast number of stations, precise storm location is provided by these data only when the hurricane lies inside a network of stations. At that time it has already entered a populated region and usually

the critical forecast time has passed. At such a time, however, very accurate storm fixes may be obtained by surface pressure data, as long as the stations' instruments and communication lines are not disabled by the hurricane.

Ship observations. - Precise storm location by ships' reports is possible even if an estimate of the wind is the only observation - providing the ships are located very close to the storm center. The improved warning and communications facilities of the past decade or two have enabled ship captains to avoid the ring of maximum winds, however, and reports from this area are relatively rare.

Ship reports are extremely valuable even when they are 100 miles or more from the storm because they are frequently the only observation available to the forecaster and furnish enough information to make useful estimates of position. For this reason, the ships that routinely take observations every six hours are requested to transmit weather data more frequently when they are in the vicinity of a hurricane. These special observations are also particularly useful when they are requested because a storm is believed to be forming.

Radar observations. - The highest winds of the hurricane are found in the ring of well-developed precipitating clouds surrounding the eye, which makes possible the application of radar to storm tracking. Large water droplets are good radar targets so the motion of the precipitation areas can be followed continuously as long as they are within radar range. Since the radar beam travels essentially along straight lines the curvature of the earth is one factor limiting the range; the more distant the target, the higher it must be in order to be "seen" by radar. Because maximum water content of hurricane clouds is in the middle and low troposphere the hurricane eye is seldom delineated on the radar scope when the eye is more than 200 miles distant.

The utility of radar tracking is unsurpassed when a hurricane is approaching our coast at a small angle or with small but variable speed. Under such conditions a line of radar stations along the coast could keep the storm under constant surveillance during the critical period when it is yet too distant from the coast to make accurate position estimates from conventional meteorological observations.

Under favorable circumstances the center of the ring of heaviest precipitation about the eye can be fixed with an accuracy of $\pm$ 5 miles when the eye is within 150 miles of a high-powered radar. It should be pointed out, however, that at this distance the radar is showing an echo that lies 10,000 to 12,000 ft. above the surface.

Aircraft reconnaissance. - Aircraft reconnaissance is the best method of hurricane location currently available for many areas. Fixes of the storm location are made by two methods: (a) Penetrating into the eye and obtaining a navigation fix of the plane while it is in the eye, (b) Flying as close to the maximum wind ring as convenient and obtaining a fix on the ring of precipitation by airborne radar.

In addition to tracking the storm by obtaining center fixes at frequent intervals, the complete aircraft observation includes, among other things, observation of the central pressure (a good measure of the storm's intensity), the wind speed, and the area covered by the high winds.

Accuracy of aircraft-fixed hurricane position depends upon such a complex combination of many factors that any single number representing the average accuracy would be meaningless. Basically, the errors are of two kinds: (a) uncertainty in location of the aircraft due to navigation errors, and (b) location of the exact center of the storm relative to the aircraft. The greatest part of the total error is frequently due to the latter.

Navigation accuracy varies with distance from radio navigation aids and with conditions affecting radio signals. When an aircraft is some 700 miles southeast of Bermuda, for example, it is not likely that the radio navigation fixes (LORAN) are more accurate than ± 20 or 30 miles, especially if there is radio interference. On the other hand, if an island is within range of the airborne radar, or if the aircraft is within a few hundred miles of a pair of LORAN stations, the error decreases to a few miles. During night missions, celestial navigation fixes are more accurate than the LORAN fixes taken under adverse conditions but less accurate than radio or radar fixes with optimum conditions.

Location of the storm center depends upon the definition of the term. For example, the center to the view of an observer inside the eye would be the geometric center of the cloud walls surrounding the eye. If these clouds contained a uniform distribution of liquid water, the radar center would coincide with the visual center but this is not always the case. The lowest pressure observation as the aircraft flies across the eye might also be defined as the center, but the pressure profile of the eye is frequently quite flat with the minimum sometimes close to one of the cloud walls. The center of the wind circulation might equally well be called the center, but more often than not it is displaced from the other "centers." The open eye is frequently poorly defined (no sharp walls) and 20 to 30 miles across, so it is obvious that a single point cannot be reported as the "center," even if the navigation error were zero. The type of center reported is frequently determined by the conditions and circumstances at the time. The Navy reconnaissance missions at night depend upon radar surveillance from outside the maximum wind ring and, consequently, they report the radar eye approximately at their flight level. During the day, an aircraft inside the eye may determine the center visually from the surrounding cloud walls or by observing the surface of the sea which reveals the center of the surface wind circulation. During night missions, the Air Force crews frequently locate the minimum height of the 500-mb. pressure surface (about 18,000 ft.) to identify the center, which may be a somewhat different point from the surface position of the minimum pressure center.

Aircraft reports are usually the only data obtained on the storm's intensity until it enters a network of land stations. The minimum pressure inside the eye is measured in two ways; by extrapolation of the flight-level minimum pressure to sea level by use of the hydrostatic relation, or by dropping a parachute-borne instrument (dropsonde) to measure pressure, temperature, and humidity of the atmosphere as it descends. The instrument transmits signals to the aircraft where they are recorded and the significant data transmitted to forecast centers along with other weather observations. The former method becomes less satisfactory with increased flight altitude, but when the aircraft is below 10,000 feet the method is fully as accurate as the dropsonde. While the dropsonde yields valuable information, especially when it is dropped from great altitudes, the accuracy of the surface pressure is believed to be about ± 8 mb.

Accuracy of wind speed and distribution data is variable depending upon the method of observation and flight conditions at the time of the observation. Surface wind speed is estimated by visual observation of the state of the sea; an experienced observer can usually estimate the surface wind speed within ± 10 percent so that satisfactory data on distribution of high winds are thus obtained.

Observations for Forecasting

Observations obtained primarily for tracking hurricanes are of direct application to forecasting for short periods (6 to 18 hours) because one of the most successful methods of producing a short-period forecast is to extrapolate the storm's motion along the same smooth path it has moved in the past 12 to 24 hours. (See discussion of forecasting). For that reason the advances in tracking techniques have contributed significantly to improving the accuracy of forecasts for periods up to 24 hours.

Prediction in any field of science depends upon knowing the initial state of the system, so it is obvious that measurements of the atmosphere must be accurate and placed in such a way that the atmosphere is sufficiently sampled in three-dimensional space and in time. The measurements that are required for a forecast that takes into account changes in the existing circulation pattern must be taken over a large part of the Northern Hemisphere, but the method of integrating them into a forecast exceeds the scope of this report.

In addition to those already discussed, the observations necessary for forecasting are:

1. Surface weather stations' reports of wind, pressure, cloud distribution, temperature, humidity, precipitation, etc.

2. Complete ship reports of these same elements.

3. Aircraft reports of pressure, wind, and cloud distributions over their entire flight area (in contrast to the data in the immediate storm area).

4. Upper-air soundings of wind speed and direction, temperature, humidity, and heights of standard pressure surfaces.

The oceans comprise a large part of the globe that is insufficiently sampled. The oceanic surface and upper-air observation program from fixed weather ships operated by the United States and other maritime nations, along with the merchant ship observation program, provides most of the sampling.

Accurate measurement of pressure, temperature, and circulation of the upper air is a critical problem because technical difficulties introduce errors that are particularly troublesome where the data network is inadequate - the very regions that spawn tropical storms. Wind observations obtained at surface stations with radio equipment which tracks free balloons are, in most cases, sufficiently accurate for synoptic analysis. Visual tracking of a balloon by use of a theodolite (an adaptation of the surveyer's transit) is less satisfactory in the Tropics because low clouds prevent observation of the high troposphere and the variable vertical currents introduce large errors.

In low latitudes airflow is more delicately balanced against the horizontal pressure gradient than in high latitudes. Therefore small errors in upper-air pressure measurement are more serious than in temperate latitudes. At the same time tropical conditions such as intense daytime heating and a large diurnal pressure wave make representative observations a more difficult problem than in high latitudes.

Improvements in Observations

The intensified effort on the hurricane problem has been directed along several channels. One of the most important is observations, for every type of observation discussed has been expanded.

Surface weather stations. - Stations that were recently open only 12 to 16 hours per day are now open a full 24 hours. Full operation obviously provides a more complete coverage of routine observations but in addition furnishes better warning service to the public. At some stations the quality of wind observation has been improved by the installation of modern wind measuring equipment. At other stations in the Tropics and subtropics a special program of observing cloud movement is being inaugurated in order to provide observations of upper-air motions where there is no upper-air sounding program.

The establishment of a Cooperative Hurricane Reporting Network of substations along the Atlantic and Gulf Coasts is now in the preliminary stages. Substations would be located fairly close together, near the coast, ready to make reports upon call from forecast centers or other interested offices. Tentative locations have been suggested for these installations, taking into consideration such factors as the nature of the coast line, proximity to large cities, availability of suitable exposures, reliable telephone facilities, and satisfactory observers. It is planned that reports would be entered on regular weather reporting circuits by the particular supervising office. Equipment will consist of wind speed and direction instruments and a non-precision aneroid barometer.

These substations are being established especially to obtain current reports when needed, and it is planned that most of these substations will be installed by the next hurricane season.

Ship Observations. - A large number of merchant ships transmit weather observations at 6-hour intervals and special observations if unusual weather

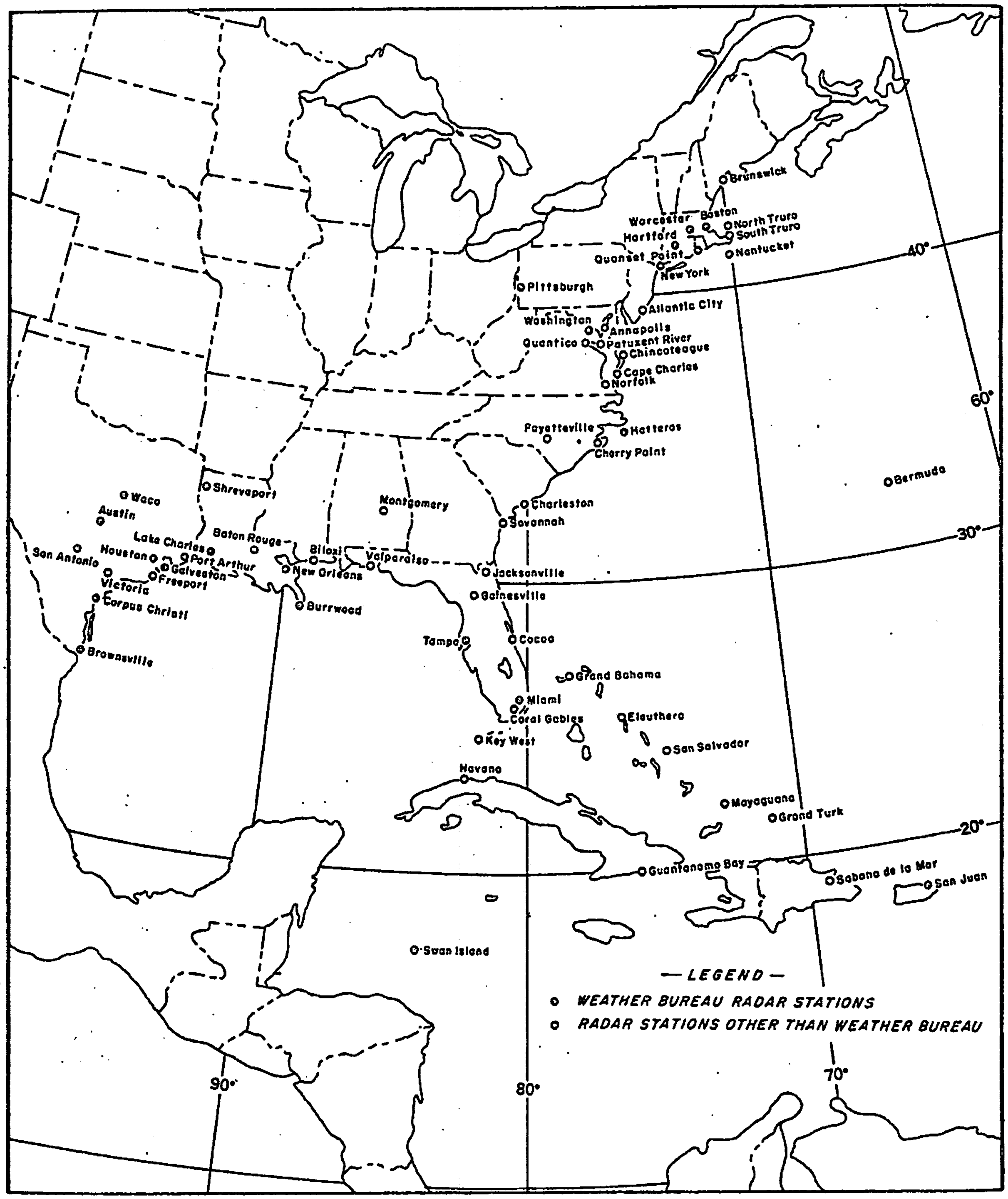

Figure 5-1. - Radar stations for hurricane detection.

is encountered, and the number of these ships has been increased. Because the hurricane forecaster can request special observations at shorter intervals, he can maintain a careful surveillance of a suspicious area and interpret subtle changes that a single ship observer would not recognize as significant.

Radar observations. - Radar sets with capabilities for tracking hurricanes 200 miles distant were installed at Cape Hatteras, N. C., in 1955 and at Nantucket, Mass., and San Juan, P. R., in 1956. Additional weather radar sets are on order and will be installed at about fifteen stations along the Atlantic and Gulf Coasts from Maine to Texas within the next three years. (Figure 5-1).

When a hurricane is moving along the coast it is usually within range of the radar equipment in only one locality at any one time. In order to be most useful, radar data must be available from many stations at the forecast center and to this purpose routine and special messages are sent from the radar sites to forecast centers. These messages give eye positions and speeds and other pertinent details of storm structure as long as the storm is within range.

During the 1956 season an experimental picture transmission system was tested from Hatteras, N. C., to Washington National Airport. The radar scope was photographed with a Land camera; the picture was developed in 60 seconds, and transmitted to the forecast office in Washington on a standard radio-photo transmitter. This system will be expanded to the Boston-Nantucket and Burrwood-New Orleans links before next hurricane season.

Aircraft Reconnaissance. - From the first sporadic flights in 1943 the aircraft reconnaissance of hurricanes has increased until now the location of a going storms is fixed at regular intervals throughout the day and night. When a hurricane is within two or three days' movement of our coast, every effort is made to obtain fixes at 0300, 0900, 1500, and 2130 EST and more frequently as the storm approaches the coast.

During the 1955 and 1956 seasons both the Air Force and Navy increased the time and space coverage of their reconnaissance. Navy reconnaissance has been made more effective by the installation of powerful 10-cm. radar on long-range aircraft. The Air Weather Service during the 1956 season replaced the B-29 with the B-50 aircraft, which, besides having increased range, are equipped with automatic navigational equipment. Navigation fixes no longer depend entirely upon LORAN or celestial fixes. Even more important, the equipment computes flight-level winds furnishing the observer with continuous readings of flight-level wind speed and direction which were never available before except under special circumstances. Having continuous wind readings available makes it easier to locate the storm center and enables the observer to furnish the forecast office with much valuable forecast information.

A more concerted reconnaissance effort for the purpose of research was begun during the 1956 season by the National Hurricane Research Project, using three aircraft - two B-50's and one B-47 - furnished and operated by the Air

Weather Service. These aircraft have been specially instrumented for hurricane research. For example, all three aircraft are equipped with devices to record measurements of various parameters such as wind speed and direction, temperature, pressure, humidity, etc., as frequently as at one second intervals, if desired. Present plans are for all three of these planes to be flown simultaneously at different levels into several hurricanes, collecting and recording data in detail previously impossible, in order to construct an accurate description of the complete three-dimensional structure of the hurricane. Analysis of this description, it is believed, will indicate which particular features of the storm are most important to the forecaster, as well as provide basic data for research into the fundamental nature of the hurricane life cycle. While all three aircraft were operational before the end of the 1956 hurricane season, no storms occurred when three simultaneous flights were possible. Several flights were made during the season, however, and valuable wind data were collected which were of use, not only to the forecaster, but will be valuable as a basis for planning flights during the 1957 season. The National Hurricane Research Project data are to be collected primarily for research use, but at the same time the observations are made available to forecast offices for use in forecast and warning work.

Upper-Air Observations. - Progress in forecasting will depend upon accurate observations of the atmosphere in three dimensions, for the significant large-scale motions are only poorly reflected at the surface.

One of the more important improvements in the upper-air program has been extending the station network into the West Indies as described in the National Hurricane Research Project Report No. 1 [1].

There has also been a program to replace pibal (visual) upper wind observing methods with radio balloon-tracking equipment, and where the visual method is still used, soundings with larger balloons have been inaugurated in order to obtain higher and more reliable runs.

A regular routine of checking radiosonde runs has long been in effect. Starting with the 1956 season the National Hurricane Research Project began a detailed error analysis of these data, which has resulted in a more intensive effort to improve the quality and accuracy of the upper-air observations.

Special Observations. - Two novel projects have been launched that have great potential, and their practicality will be tested within the next one or two hurricane seasons.

Rocket Photography of hurricanes from altitudes of about 100 miles has already been demonstrated [2]. The value of such data lies in the broad instantaneous picture that is secured of cloud and weather distribution throughout the hurricane which is not obtainable by any other means because routine analysis depends upon observations taken at isolated points, so the complete field of interest must be interpolated by analysis. A moving picture taken by a rocket ascending in the vicinity of a hurricane will yield data from which cloud and weather distribution are visible and much information about the field of flow can be deduced, particularly when upper-air measurements made from surface stations and by reconnaissance are available at several points.

The Hurricane Beacon consists of a balloon set to float in the air at a constant-pressure level, and bearing a radio transmitter which will emit signals for radio direction-finding. Observations and theory have provided evidence that an altitude-controlled balloon launched in a hurricane eye may remain inside the eye thereby providing a means of continual tracking. The beacon is conceived as an economical and efficient method of tracking hurricanes. At this writing the technical development is in its last stages and tests will be held in the 1957 hurricane season. If this system proves reliable it will provide a convenient tracking method, and free reconnaissance aircraft for the important task of collecting data in the peripheral regions about the storm which are so important to forecasting hurricane motion.

The Navy is also sponsoring a beacon project and development has proceeded to the point where it will probably be tested during the next hurricane season. The Navy beacon consists of a super-pressure balloon which floats on the sea surface. Preliminary tests have shown that the floating beacon responds to the air motions rather than the currents or waves of the water so the floating beacon may also remain in the hurricane eye.

FORECASTING

Every hurricane forecast starts with consideration of the past path (12 to 24 hours) and climatology; that is, what has been the behavior of other hurricanes in past years, in this position, and this particular time of year? From that base, the forecaster determines the present large-scale flow pattern, because it has been shown that a large part of the motion is controlled by these large-scale patterns [3]. The fact that hurricanes move around large oceanic Highs is a good forecast tool, for an analyzed map of subtropical regions reveals where the motion will be toward the west and where curvature toward the north is likely to commence.

The high-level steering method developed largely by the late Grady Norton at the Weather Bureau Office in Miami was used quite successfully at that office for forecast periods up to 18 hours. Regardless of just what method is regarded as best by any forecaster, all too frequently there are insufficient data available to him, but he must make the best forecast possible with whatever data and indications are available when the deadline is reached. For that reason comparison of storm motion with that predicted in hurricane advisories is not a measure of any one prediction system, but is a measure of the final product of the current forecast endeavor.

Verification of Motion Forecasts

Tables 1, 2, and 3 list some verification statistics based on 274 advisories for a 4-year period. The speed and direction forecast in a given advisory was laid out in a straight line from the current position given in that message and the forecast position compared to the position reported in the advisory 12 hours subsequent.

Table 5-1. - Percent frequency of distance in nautical miles between forecast and actual positions (12-hour forecast from time of issue)

Years	No. of cases	Distance (nautical miles) 0-29	30-59	60-119	120-179	>179	Average error (Naut. Mi.)
1952-1953	80	9 %	33 %	40 %	13 %	5 %	83
1954-1955	194	21 %	37 %	33 %	7 %	2 %	63
All years	274	18 %	35 %	35 %	9 %	3 %	69

Table 5-2. - Percent frequency of angular departure between forecast and actual paths

Year	No. of cases	Angular departure <22 1/2°	22 1/2° - 44°	>44°
1952-1953	80	66 %	33 %	1 %
1954-1955	194	73 %	20 %	7 %
All years	274	70 %	24 %	6 %

Table 1 shows some improvement from the period 1952-53 to the period 1953-54. The breakdown of the forecasts into speed classes (table 5-3) indicates the total distance error increased with storm speed and that the direction error was relatively larger with the slower-moving storms. There is little doubt that the improvement in recent years is partly due to the increased accuracy of storm tracking methods by aerial reconnaissance and radar.

The hurricane forecast for periods up to 24 hours is largely an extrapolation of the recent path and trends that are apparent, adjusted insofar as possible by incorporating circulation changes that are indicated by the forecast. The procedures just mentioned are all, however, quite qualitative in nature. Real progress in hurricane forecasting can be achieved only through evolving quantitative methods that integrate all past and current data into a precise forecast.

Forecast Usefulness

The utility of a given hurricane forecast depends upon the use to which it is put. For example, the forecast that an intense storm will enter the coast near a low-lying city within 24 hours is sufficient, for evacuation would be started as soon as necessary. If the track was 10 or 20 miles in error it would make little difference, for the low-lying parts of the city would prob-

Table 5-3. - Percent frequency of forecast errors (274 cases)

Storm speed		Distance (nautical miles)					Angular departure		
Kt.	No. of cases	0-29	30-59	60-119	120-179	>179	< 22 1/2°	22 1/2°-44°	> 44°
<10	108	23%	40%	30%	7%	0%	61%	25%	14%
10-19.9	132	17%	36%	40%	6%	1%	75%	24%	1%
20-29.9	20	0%	25%	45%	30%	0%	85%	15%	0%
≥30	14	0%	7%	7%	22%	64%	86%	14%	0%

ably be inundated anyway. For that purpose then, the forecast would be completely effective; on the other hand, suppose an industrial plant were located on an inlet such that onshore winds produced high water while high winds from other directions had little effect. In such a case, a difference of ten miles in the point of storm entry would be the difference between no damage from offshore winds or flooding from onshore winds.

Usually an accurate warning 6 to 8 hours before high winds is sufficient for home owners to take precautionary measures. By contrast, shipping concerns, manufacturing plants, and Air Force Bases usually require two or three days to complete their evacuation or to take other appropriate action. The final decision to take a given action in the face of an approaching storm is, of course, not made by the meteorologist, but in order for a forecast to be effective for a wide range of uses it must contain all the pertinent information and at the same time must be brief and concise so that it can be easily understood. To a certain extent, these requirements are mutually exclusive, because a forecast that contains all the information needed by all the users is too long and detailed to be forceful and understood by the general public. The problem of disseminating forecasts is considered in another chapter, but it is pertinent here because the forecaster must explicitly state all useful information.

One of the approaches being investigated is the objective determination of probability forecasts. For example, when the storm is about three days offshore, it may be possible to specify a considerable part of the coast which has a probability of being affected by the storm within 72 hours, but for any one point the probability would be quite low. As the storm approaches within in 48 hours, 36 hours, and 24 hours, the portion likely to be struck could be made smaller, and the probability increased, while the adjacent areas would have assigned to them ever-decreasing probabilities. The various users could then decide at what point in the increasing probability and decreasing time they should take action for their particular purpose.

CURRENT RESEARCH

Objective Quantitative Methods

A semi-objective, quantitative hurricane forecast procedure has recently been developed and tested, and has already been used in most forecast offices [4].

Briefly, the procedure involves simple arithmetical computations on the 500-mb. analysis to obtain an index of the large-scale flow surrounding the hurricane. The index is then related to a 24-hour displacement of the storm, which relationship has been statistically established from several years of hurricane tracks. The method, although quantitative and objective once the 500-mb. analysis is obtained, is in fact only semi-objective because the data coverage at 500 mb. in critical areas is seldom sufficient to eliminate subjective analysis of the initial data. The system produced errors of 60 nautical miles or less for 24-hour forecasts in about 70 percent of the cases when tested by the authors. Many other hurricane forecasters have tested the method on independent analyses and while, in general, they did not report 70 precent of the cases falling within the 60-mile circle, there is agreement that it is one of the best procedures presently available when a reliable 500-mb. analysis is on hand.

Research is proceeding on other approaches to quantitative methods that have shown promise.

Numerical Weather Prediction

Numerical weather prediction, a new and expanding branch of meteorology, has made great strides and during the past year has been especially applied to hurricane forecasting. Beginning in 1955 a few experimental forecasts of hurricane motion were made by the Joint Numerical Weather Prediction Unit in Washington and the results suggested that the standard numerical models devised for mid-latitude forecasts should be applied to hurricane forecasts. Consequently, forecasts were made on the electronic computer for fourteen independent storms from the years 1951 to 1954. The results, reported in National Hurricane Research Project Report No. 2 and Supplement [5], although not of satisfactory quality, suggested the direction in which numerical weather prediction of hurricane motion should proceed, and a modified procedure has already been programmed by the Joint Numerical Weather Prediction Unit. Although the tests have not been completed, first indications are very encouraging.

Groups at the University of Chicago and Massachusetts Institute of Technology are also doing research on the problem of numerical weather prediction of hurricanes and the next few years should see results from these workers.

Statistical Methods

An objective, statistical method is being investigated by the Weather Bureau, and through Air Force contract work at the Travelers Insurance Research Center.

The statistical methods being investigated by the Weather Bureau deal with forecasting those hurricanes which threaten the heavily populated areas along the central and north Atlantic coast. Past storms which have affected these areas during recent years are being studied by correlating the circulation patterns of the atmosphere through a considerable depth with a number of mathematically described surfaces. The degree of correlation with these surfaces is then related to the subsequent 24-hour movement of the storm. The practicability of expressing these hurricane forecasts in terms of the probabilities of the hurricane affecting specific areas is being investigated.

A contract for the development of a somewhat similar statistical forecasting procedure has been let out to the Travelers Weather Research Center by the Air Force. In this investigation also, hurricanes which have affected the middle and north Atlantic coast are studied. By statistical means a series of decreasingly effective forecasting parameters are chosen from the surface charts to indicate the subsequent 24-hour components of the motion of the storm center.

Most of the research underway is aimed at improving forecasts for about a one-day period. There is a need for forecast improvement for periods both longer and shorter than 24 hours (see discussion of forecast effectiveness), and research is proceeding along these lines as well.

Longer-Period Forecasts

The longer-period forecasts being sought are those for 72 hours and for very long periods of a month or a season.

In the Extended Forecast Section of the Weather Bureau, a study is being conducted of departures from the mean seasonal flow in order to relate those anomalies to hurricane occurrence and to hurricane tracks. Some useful results have already been obtained and the problem is being studied further. The utility of long-range forecasts, although they will have to be couched in general terms, lies in their use as a guide in making plans for pouring concrete , entering critical stages of building construction, etc.

Shorter-Period Forecasts

Despite the successful extrapolation for short-period forecasts, a great deal of basic research remains to be done. Detailed track data - especially the fine detail provided by radar - brings peculiar problems. It has been suspected from scattered data and demonstrated theoretically that the hurricane does not move along regularly; rather it moves in a series of oscillations about the average smooth path. The oscillations, while small in themselves, could be the indirect cause of significant changes in the hurricane path by diverting the storm toward or away from a strong carrying current. The oscillations are a disconcerting feature when the storm is on the verge of recurvature away from a critical populated area and the oscillations produce numerous false starts toward the curvature, only to have the hurricane swing back on its original path just when the observer has decided that recurvature has started.

Theory suggests that the oscillations are caused by internal forces of the storm but detailed observations suitable for the study have never been collected. It is the aim of the National Hurricane Research Project to collect this type of detailed data.

Other Research Problems

Research on the internal forces in the hurricane is only one of the many basic tasks that must be completed before there can be any real progress in hurricane forecasting. For example, basic research projects are underway at the National Hurricane Research Project for studying (1) hurricane circulation and structure, (2) energy processes and the hurricane energy budget, (3) dynamics of hurricane movement, and (4) physics of hurricane clouds and precipitation. (See National Hurricane Research Project Report No. 1).

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CHAPTER 6 - HURRICANE WARNINGS

Even a perfect hurricane warning is of little value unless it results in intelligent and well-conceived protective measures.

First, there is a communications problem. The forecaster must get his thoughts across to the public in general and to civil authorities in particular; he must be intimately familiar with the points of vulnerability and the time required for various protective actions to be placed into effect, must integrate the necessary information into his warning, and communicate the sum total to his audience in terms they readily understand.

Second, each community and area must have well-thought-out and widely-accepted plans for action for successively more severe and/or more certain contingencies. This includes evacuation routes (and possible alternates), flood protection plans based on anticipated water height, shelter areas and supplies, emergency communications and power, and the multitude of other activities embodied in any comprehensive civil defense program.

HURRICANE WARNING SERVICE

One of the basic responsibilities of the Weather Bureau is to provide advance warning when hurricane conditions are likely to occur along coastal areas. The Bureau attempts to provide full and complete information on the conditions likely to occur in connection with a hurricane, such as the expected wind speed, the extent of abnormal high water (usually called storm tide), and the amount of flooding along the coast and along inland waters which is caused either by the rise in the level of the ocean associated with the hurricane or the rise in rivers resulting from the torrential rains over inland drainage basins.

It is not a responsibility of the Weather Bureau to order the evacuation of the public from any area. But to assist local, state, and national civic authorities, the Civil Defense Agency, and the American Red Cross in carrying out evacuation measures, the Bureau tries to advise these agencies fully so that they may more accurately and intelligently discharge their responsibilities to the public.

To discharge its responsibility, the Weather Bureau maintains a Hurricane Warning Service. Efficient organization of the service, access to facilities for locating and tracking tropical storms, a comprehensive advisory program, and means for disseminating hurricane information are required to make the service effective. These aspects of the hurricane warning service are discussed in the following sections.

Weather Bureau Organization

The hurricane warning service of the Weather Bureau is carried on through five hurricane warning centers located at San Juan, P. R., Miami, Fla., New Orleans, La., Washington, D. C., and Boston, Mass. Each hurricane warning center has a specific geographical area of responsibility and originates all

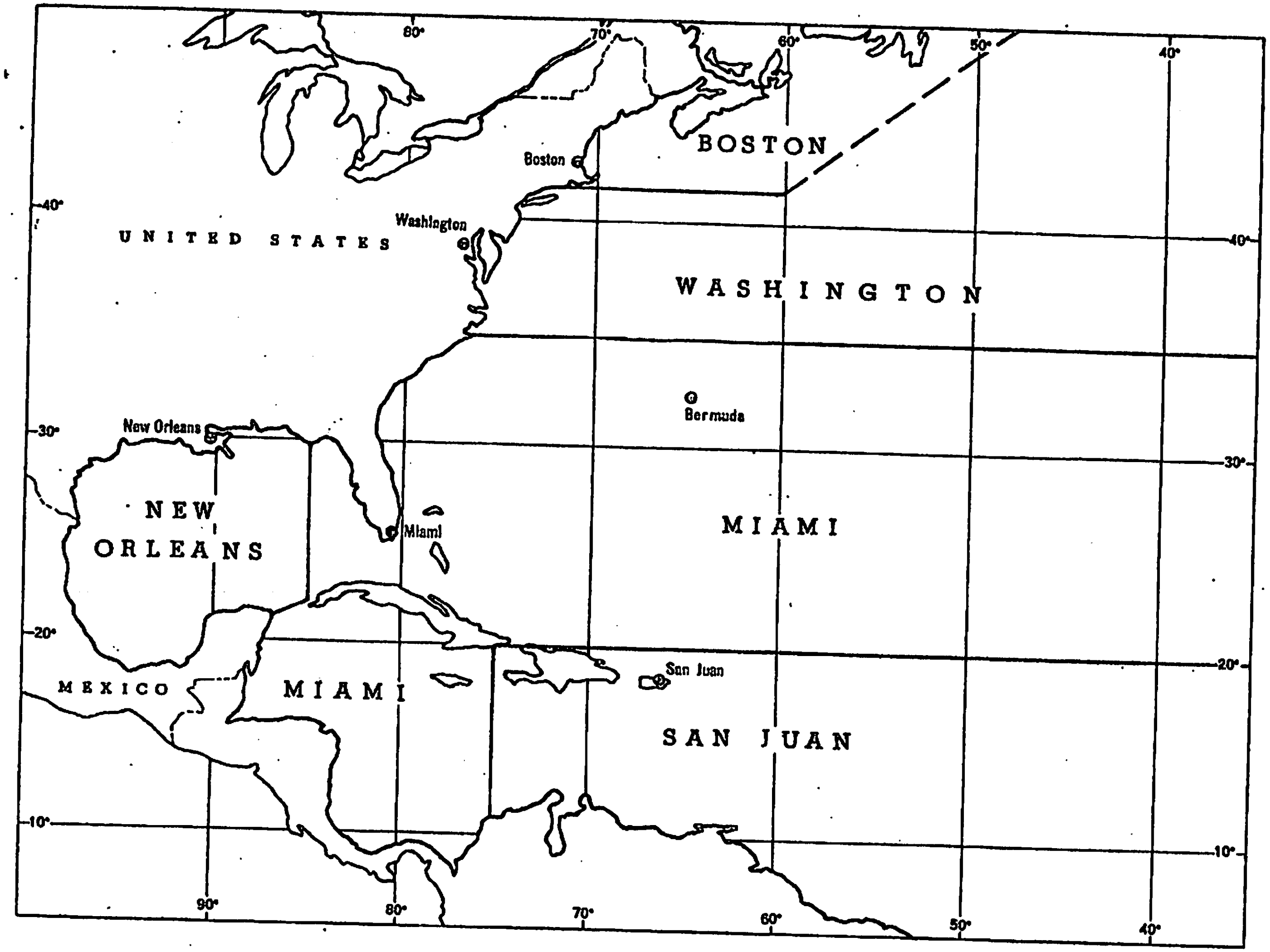

Figure 1. - Weather Bureau hurricane forecast centers and the area of responsibility of each.

advices and warnings regarding a tropical storm in that area. Figure 1 shows the geographical areas for which each hurricane center is responsible.

Liaison with the military services (Navy and Air Force) is carried on through a joint hurricane warning center at Miami in which the Meteorologist in Charge of the Weather Bureau hurricane warning center at Miami serves as the Weather Bureau representative. Through this arrangement plans are coordinated for: (1) aircraft reconnaissance of ocean areas where a tropical storm is in existence or suspected, (2) special upper-air observations, and (3) other aspects of the interdepartmental hurricane warning program.

Facilities for Locating and Tracking Tropical Storms

The first indication that a tropical storm may be forming often comes from weather reports received from merchant ships on the oceans. Weather reports are received at 6-hour intervals throughout the year from a large number of merchant ships of all nationalities. During the hurricane season provision has been made for obtaining special weather reports on request from ships at periods in between the regular 6-hour reporting times.

The greatest aids to locating a storm and to forecasting its future course after it has once developed, and while it is beyond the range of land-based radar, are the reports received from Navy and Air Force reconnaissance flights into the area of the tropical storm. These flights are made at various levels and provide extensive meteorological data for use by the hurricane forecasters. On receipt of tropical storm or hurricane advisories merchant ships alter their courses so as to avoid the hurricane; it often develops, therefore, that the reconnaissance flight reports are almost the sole source of information regarding the storm when it is located over the open ocean away from land areas.

In addition to the normal upper-air reporting program, provisions have been made for obtaining special upper-air soundings during periods when hurricanes are in progress. These provide valuable information at times when there would otherwise be little upper atmosphere data available.

When a hurricane moves within range of land-based storm detection radar installations it is constantly tracked by experienced radar observers. In addition to locating the center of the hurricane, radar storm detection data provides an indication of the extent of heavy rain areas.

Issuance of Advisories and Bulletins

When a tropical storm has been located and when, in the opinion of the forecaster, the storm may later develop hurricane characteristics, the storm is given a name and numbered advisories are issued. Advisories are released at 6-hour intervals until the hurricane either dissipates, moves inland and no longer is a threat to life or property, or moves into the Atlantic beyond the range of United States Weather Bureau forecasting responsibility. The normal release times for hurricane advisories are 5 and 11 a.m. and p.m. Eastern Standard Time.

In addition to the heading of the advisory which gives the name of the storm, the advisory number, and the date and time issued, each advisory gives information on the following points in the order listed: Areas for which hurricane warnings or a hurricane watch have been issued; areas for which gale warnings have been issued; location, direction, and speed of movement of the storm; a description of the storm including estimated highest winds near the center and area covered by winds of gale force; lowest barometric pressure in the center; a forecast of expected future movement and changes in intensity of the storm; abnormal tide conditions expected in the area over which the hurricane will move; a statement of precautions to be taken; the time at which the next advisory will be released; the signature of the forecaster and office preparing the advisory.

In between the regular 6-hour advisories the Weather Bureau releases bulletins for press, radio, and television whenever a tropical storm or hurricane threatens any coastal area of the United States. These intermediate bulletins supply additional details and up-to-the-minute information on the hurricane, but they do not alter the area for which hurricane warnings or a hurricane watch are in effect. A change in the area for which a hurricane warning or hurricane watch has been issued is covered by a new hurricane advisory and such special advisories may be issued at any time.

Types of Warnings

Advice to small craft. - Although the Weather Bureau normally issues small craft warnings when wind and sea conditions along the coast are such as to endanger the operation of small boats, such warnings are not issued in connection with tropical storms. Experience has shown that the hoisting of small craft warnings has at times in the past led to a false sense of security on the part of boat operators in that they may assume there is danger only to small craft without appreciating the fact that at a later time warnings of more severe conditions may be necessary. To meet this problem the Weather Bureau includes statements in advisories indicating that small craft in specific areas of the coast should remain in port.

Storm warning. - These indicate that winds of 32 miles an hour or more are expected over waters adjacent to the coast or, in the judgment of the forecaster, the wind or combination of wind and/or waves and tides is expected to become dangerous to shipping and boat operations and warnings are required.

Hurricane watch. - A hurricane watch is announced for specific areas when a hurricane (or an incipient hurricane condition) off the coast poses a threat. On receipt of a hurricane watch notice all people in the indicated areas should take stock of their preparedness requirements, keep abreast of the latest advisories and bulletins, and be ready for quick action in case a warning is issued. Otherwise the usual daily activities need not be interrupted.

When a hurricane watch is announced, the potential danger should be interpreted as a possibility and not a certainty. At the time the watch is announced hurricane conditions are not expected for at least 24 to 36 hours.

This is a flexible time interval, however, and may be altered as deemed necessary for greatest guidance to the public.

Hurricane warning. - A hurricane warning is issued in connection with tropical storms to indicate areas where winds of 75 miles per hour or higher are expected within the next 24 hours; however, hurricane warnings may be issued when dangerously high water, very rough seas, or other critical conditions justifying emergency action are expected to occur with winds as low as 60 miles per hour. It is not always possible to issue warnings as much as 24 hours in advance with sufficient assurance to serve as a basis for complete implementation of all protective measures. More often the dependable range of hurricane warnings is 12 to 18 hours in advance of the onset of hurricane conditions, and there may be times when, due to extremely erratic or indefinite storm behavior, warnings cannot be issued with confidence more than 6 hours in advance.

Methods for Dissemination of Hurricane Information

Each advisory is distributed to news agencies, radio stations, television stations, and other interests that assist the Weather Bureau in passing the information on to the general public. Various means of communication are used, including telephone, teletypewriter, telegram, short wave radio, and printed bulletins.

When an actual warning is included in an advisory, Weather Bureau offices take the initiative in assuring that distribution of the warning is made to all public distributors. Each Weather Bureau office maintains a "warning list" of individuals and agencies to be notified when a warning is issued. In addition to the news agencies, warnings are sent to local, state and national Civil Defense organizations, Red Cross chapters, local and state police, municipal and state government officials, other federal agencies such as the Corps of Engineers, and others.

In addition to the distribution of hurricane information to residents on land, there is widespread distribution of this information to ships at sea. All advisories and warnings are furnished to the United States Coast Guard which in turn broadcasts the information from its land-based radio stations. Advisory information is also included in the weather broadcast messages prepared at 6-hour intervals for distribution to merchant vessels on the oceans. Land-based commercial radio stations which handle traffic between ship and shore are also furnished advisories so that they may provide the information to shipping interests.

Also, there are radio broadcasts from Weather Bureau offices. Most Weather Bureau field offices cooperate with commercial radio stations in their area in broadcasting weather information several times each day over microphones placed in the Weather Bureau office. In times of a hurricane emergency the frequency of broadcasts made by Weather Bureau meteorologists is increased greatly. This permits the Weather Bureau to disseminate hurricane information and hurricane warnings to the public in the area served by the radio stations and provides a valuable means of reaching large numbers of the public. In addition to broadcasts of this type, several extensive emergency broadcasting networks are used during a hurricane emergency. Examples are the radio networks which have been established in Texas, Florida, North Carolina, and New Jersey where the broadcast direct from the Weather Bureau office each hour is carried by practically all commercial AM and FM radio stations in the areas concerned. In areas where such emergency networks exist a resident has only to tune to his local radio station and listen for the latest authentic up-to-the-minute hurricane information, broadcast direct from the Weather Bureau office.

PROBLEMS IN PROVIDING ADEQUATE WARNINGS

Limitations on Accuracy

While accuracy of hurricane warnings continues to increase from year to year as new forecasting techniques are developed and as better reporting information is obtained, it will probably not be possible in the foreseeable future to assure 100 percent accuracy in hurricane warnings. To be of maximum usefulness, hurricane warnings must be issued hours before actual hurricane conditions commence. The forecast accuracy is limited by the inherent difficulties in forecasting movement and changes in the intensity of the hurricane circulation between the time the initial warning is issued and the time that the hurricane conditions reach the coast line. This poses an important consideration for those concerned with hurricane precautions. Extensive efforts have been made over the past several years and will be continued to fully apprise everyone concerned of the limitations to hurricane forecasting.

In general, the farther in advance a warning is issued, the less accurate it is likely to be. The forecaster is therefore faced with two opposing considerations: (1) issue the warning sufficiently far in advance to provide ample time for people to make all necessary preparations and (2) issue warnings which are nearly 100 percent accurate. Considerable judgment and experience are required in order to issue the warning sufficiently far in advance to achieve maximum benefit, yet not so far in advance that the accuracy is so diminished that many people are alarmed needlessly and as a result the public's confidence in hurricane warnings decreases to the point where protective measures are neglected in spite of warnings.

The requirement for advance warning of a hurricane varies considerably with the geographical area concerned. In regions such as the delta of Louisiana, low-lying islands along the Texas Gulf coast, etc., it is necessary that hurricane warnings be issued as much as 18 to 24 hours in advance if the warning is to be fully effective. The requirement for advance warning may even extend to 24 hours or more under certain local conditions. A special problem exists in connection with congested or resort areas during holidays. In such cases large numbers of people congregate in regions where the normal transportation and evacuation facilities are inadequate to allow escape to be accomplished in a matter of a few hours, and yet it is necessary that evacuation be completed in advance of the onset of dangerous sea and wind conditions, which in some cases reach dangerous proportions even before the onset of hurricane winds.

Dissemination Problems

The Weather Bureau relies to a major extent on the normal news dissemination agencies for the distribution of hurricane warning information. Warnings are provided by direct telegraph, telephone, or teletypewriter circuit to designated public officials, newspapers, radio and television stations. The general public relies primarily on press, radio, and television for receipt of hurricane information. Cooperation from news broadcasters and other news media in general has been good, although in the past there have been some isolated instances of dissemination of inaccurate information. State and national associations of press, radio, and television are cooperating fully, however, toward eliminating such occurrences.

Examples of the types of confusion which have occurred are: First, some news personnel "play up the news" hours and sometimes days in advance of the realization of dangers associated with a particular storm. Second, difficulty has occurred when a newsman used an out-of-date advisory or bulletin, and has broadcast or published it as the latest word on the storm. The recipient has then been confused by two and sometimes more versions of the hurricane conditions. Third, difficulty has been encountered with warning broadcasts originating on a national radio or television network from a point far distant from the specific area threatened. Finally, there have been instances where Weather Bureau warnings or broadcasts have been edited by the person disseminating them to include personal ideas or interpretations. As indicated above, however, state and national news agencies are providing whole-hearted support toward tracking down and eliminating these.

FUTURE PLANS AND SUGGESTIONS

A warning of impending dangerous weather, be it of hurricanes, tornadoes, floods, or other phenomena, is only of value if it is disseminated to the people in the threatened area so that they may take precautionary actions. The most accurate warning is rendered valueless if it is not quickly distributed. A warning given in terms not easily understood by the recipient may lead to misinterpretations and, in some cases, panic.

While much has been done in the last few years to secure more widespread distribution of hurricane warnings, there remains much that could be done to improve warning services. The following is a list, with discussion, of some steps that could be taken to make the Hurricane Warning Service more effective in preventing loss of life and in reducing property damage.

Local Public Weather Teletypewriter Circuits

Local weather circuits which make it possible for the Weather Bureau to transmit rapidly the exact text of hurricane advisories and bulletins to any interests wishing to maintain a drop on the circuit are at present in operation in 18 Gulf and Atlantic Coast cities (on or within 100 miles of the coast). Service of this type should be installed in an additional 20 to 25 of the large cities along the coasts to permit relay of complete hurricane information to all news agencies, Civil Defense, Red Cross, municipal agencies, and the like. Arrangements should also be made to connect cities on or near the coast, and which do not have Weather Bureau offices, to the existing circuits to permit immediate receipt of the vital warning information in these locations also.

State-Wide Emergency Radio Networks

In four coastal states arrangements are in effect to carry radio broadcasts direct from Weather Bureau offices over most commercial radio stations. Broadcasts are made hourly during a hurricane situation by an official of the Bureau giving full details on the hurricane plus precautions considered necessary. Similar emergency networks should be organized in all coastal states to permit more rapid and widespread distribution of warnings.

Public Hurricane Educational Program

For the last several years the Weather Bureau has stepped up its effort to provide information to the public on the nature of hurricanes, operation of the warning service, and precautions that should be taken when warnings are issued. More could and should be done along this line. Additional educational movies, slides, and filmstrips would be helpful, and additional leaflets and descriptive material should be prepared and distributed.

Studies of Effects of Hurricanes

Studies of the effect of various magnitudes of hurricane elements on different areas and communities should be continued. These include wind velocity, height of tide, wave height, and rate of precipitation. A knowledge of the range and probable maximum value of each of these elements as they might affect each coastal community would allow definite preventive plans such as construction of protective works, sand bagging and boarding up when threatened, or actual evacuation if extensive flooding or structural damage is indicated.

It has been established, for instance, that a storm surge of approximately 13 feet above mean high tide would be sufficient to flood the subways of New York City. Knowledge of this fact should serve as a basis for planning for this eventuality. Contour maps have been prepared for Providence, R. I., and should be prepared for other cities so that areas of inundation to be expected with different tide stages can be determined.

Public Survey of Warning Service

In order to assure that future decisions in regard to changes in the warning service are based on known facts, a program of public opinion surveys, conducted by competent analysts, would be valuable. These surveys would assist by: a) providing facts as to the present degree of knowledge regarding hurricanes and the warning service on the part of people living in various coastal sections; b) determining if terminology used in advisories and bulletins is well understood; c) determining how various segments of the public now receive hurricane warnings, how much delay is involved, and weaknesses in distribution methods; d) finding out whether people living on or owning property in hurricane vulnerable areas understand the extent of the danger involved; and e) securing information on how far in advance warnings must be issued to permit ample protective action to be taken in each instance and locality. Results of surveys of this type are essential in planning future improvements in the warning service.

Hurricane Emergency Plans

At present an effort is made to render technical assistance to Civil Defense agencies (state and local), but expansion of this program would be beneficial in improving the readiness of the public to cope with hurricane situations.

Other Suggestions

The preceding discussions do not necessarily exhaust the possibilities of attack on the problems inherent in the hurricane warning and rescue services. There are many other avenues that might be profitably explored.

For example, most states have laws that give the Governor power to declare "martial law" during periods of emergency to insure the public safety, and this has in fact been used to prevent looting and restore order after the occurrence of major hurricane catastrophes. Never, to our knowledge, has this been done before the hurricane struck. It has been suggested that coastal states make some arrangement whereby the Governor, or one of his aides, be notified immediately when an approaching storm shows signs of unusual damage-producing capacities. This would allow state and local officials to get a head start in putting pre-arranged plans into operation.

These plans could include such items as ordering operators of public transportation vehicles to make their equipment available to aid in evacuation, imposing of certain restrictions on public communication facilities, and other steps which may be legally assumed by the state or local authorities only in case of emergencies.

As a corollary, studies should be made by state and local authorities to determine the adequacy of roads and streets leading out of coastal areas which are potentially susceptible to hurricane disasters. Where road systems are inadequate remedial steps should be taken to make possible the rapid evacuation of residents during hurricane emergencies.

CHAPTER 7

HIGH WATER SURGES FROM HURRICANES[1]

More than three-fourths of the loss of life associated with hurricanes in the United States has resulted from inundations from the sea and inland lakes. The abnormal behavior of the tides in hurricanes thus must be recognized as a major aspect of the hurricane disaster problem.

The lateral extent of the peak storm tide due to a hurricane is generally quite small, and extensive damage due to this cause may not occur if the main coast line is protected by barrier reefs or steep shores in the region of highest tides. The more intense hurricane can produce surges as much as 20 feet above the normal tide, thus overtopping the protecting reefs and shores, and presenting an appalling potential for destruction. Weather Bureau hurricane warnings have long included qualitative warnings of excessively high tides and the suggestion for particular caution in low-lying coastal areas. Starting with the hurricane season of 1956, more specific statements of the magnitude of possible surges have been incorporated in Weather Bureau warnings and will continue to be issued in the future.

The factors which govern the magnitude of a hurricane surge are very complex. A difference of only a few miles in the point of entry of a hurricane on the coast line may mean the difference between a destructive storm surge and even a below-normal tide at certain localities. Because of this complexity the magnitude of probable rises in the sea level is usually stated in terms of broad ranges, for example, "from four to eight feet above normal." Considering the undeveloped stage of surge forecasting methods up until 1955, considerable progress has been made in the year and a half during which particular effort has been channeled in this direction, but this is only the beginning of a necessarily long-term program.

NATURE OF THE PROBLEM

Tidal floods appear to be the least understood aspect of hurricane damage. Although fewer than one dozen storms account for three-fourths of the hurricane deaths reported since the Weather Bureau was established, these disasters were due largely to coastal flooding. The fact that most hurricanes produce only minor damage due to this cause, together with the difficulty of obtaining information of the actual level of the sea in a severe storm and of separating the effects of the storm from those of the normal astronomical tide, probably accounts for the limited attempts that have been made in the past to understand the storm surge problem.

The present trend toward the development of residential, industrial, and recreational areas on the coastal islands and nearby low-lying sections of the mainland greatly increases the potential dangers from coastal flooding by hurricanes and other storms and adds to the urgency for an understanding of the problem.

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1 Most of the work reported in this chapter was accomplished from regular Weather Bureau appropriations and not from Public Law 71 funds. It is being reported here because of its close relationship to other projects included in this report.

There are at least three prominent and nearly independent factors which lead to changes in sea level as the hurricane approaches land. These are the wind-driven waves and swell, astronomical tides, and the storm surge. This chapter is concerned primarily with the latter but a brief discussion of the other two is important to an understanding of the problem. The study of the winds causing the waves and surges is discussed in Chapter 3.

In the following discussion, the term storm surge will be used to identify the effect of the storm as distinct from the astronomical tide, and the term storm tide to specify the combined effects of the storm and the astronomical tide.

GROUND SWELL AND WAVES

The most obvious of the effects of a storm on sea level are the waves formed by the high winds near the center of the storm. These move outward from the storm and may break on shores as much as a thousand miles from the storm center and in regions which are never reached by high winds of the storm. The period of an individual wave of this type at one point is generally much less than half a minute. Such waves are generally the most destructive feature of the storm at the water's edge, but their effects do not often extend very far from the water line.

The high waves and swell associated with hurricanes carry a small amount of water shoreward. The first evidence of an approaching hurricane is sometimes provided by a slight increase in the sea level of one or two feet near the shore. The increase is due to the transport of water by the waves and is often referred to as the "forerunner" of the storm. The forerunner, however, does not necessarily appear before a more rapid rising sea level associated with the storm, nor when present is it always followed by the appearance of any other important hurricane characteristics.

IMPORTANCE OF THE ASTRONOMICAL TIDE

Under normal weather conditions the tide is controlled almost entirely by the position of the sun and moon with respect to the earth. The forces which generate the normal tide are well known and can be predicted from theoretical considerations many years in advance. However, the response of the sea to these forces cannot be determined from the theory alone and must be determined from a series of observations, made over a period preferably longer than a year, and taken at the point for which predictions are desired. Since the tide prediction formulas depend on observational data, they include the average meteorological effects for the period on which the predictions are based. This has little practical importance for most applications, but it does imply that a complete separation of the astronomical and meteorological effects on the tide is impossible.

However, the stage of the normal tide has no appreciable effect on the movement of the storm. While the presence of the storm has no appreciable effect on the normal astronomical tide on the open coast, the increase in water level associated with a hurricane or other severe storm does have a detectable effect on the speed with which the normal tide wave propagates up rivers and through long channels.

The normal tide has only a minor effect on the processes by which the storm surge is generated in the open sea, but a great deal of effect on the importance of the surge generated by the storm. For example, the New England hurricanes of 1944 and 1954 produced nearly the same storm surge. However, the 1954 storm, Carol, produced several times as much damage in New England because it went inland near the time of normal high tide, while the 1944 storm had its greatest effect near the time of normal low tide.

The astronomical tides affect the generation and propagation of storm surges in estuaries and rivers in such a way that it is possible for a given storm to produce a greater abnormality if it coincides with a normal low tide than if it coincides with a normal high tide [1, 2]. However, no reliable method of determining the magnitude of this bias is available at the present time.

In order to obtain a satisfactory separation of the storm surge and the normal tide, it is necessary to have a continuous record of the tide during the storm, as well as the necessary information for computing the normal tide at the same location. Records sufficient for the determination of the normal tide have been collected from many locations. There are also many records of the highest water levels observed at particular places during outstanding storms. However, few continuous records of a storm tide during major storms, which can be matched with accurate tide predictions, are available. The spacing of tide gages, satisfactory for most purposes, leaves many gaps large enough to miss most peak hurricane tides. Even if the storm passes directly over the station the continuous tide record may be lost because the tide house is destroyed or inundated, or because the range of the instrument is too restricted to record the full range of the storm tide. Some efforts made during the past year to improve the observations are described in a later section.

CAUSES OF STORM SURGES

The fundamental causes of storm surges are the frictional drag of the wind on the water, the reduction of atmospheric pressure near the center of the storm, and the accumulation of water near the coast by the breaking of waves and swells. Water movements created in these ways can be greatly modified by the velocity of the storm, the variable depth of the water, and the shape of the shore lines. The principal characteristics of these effects are summarized below:

Effect of Wind Stress

The frictional stress of the wind blowing over the water generates a current which, in general, causes the water to move in a direction somewhat to the right of the direction in which the wind is blowing. For a steady wind over the deep ocean, this current is almost at right angles to the wind. However for a moving storm of limited extent, such as a hurricane, and over shallow water, the currents in the water are almost parallel to the wind, except where this is prevented by the shape of the coast line. These currents cause the water to pile up against any obstruction to the flow, and consequently the sea level tends to rise with onshore winds, and to fall with offshore winds. Exceptionally high tides can be produced in this way if the moving storm-induced ocean current is directed into a harbor or bay. This effect of the wind is approximately proportional to the square of the wind speed. For example, it is four times as great for a wind of 60 miles per hour as for a wind of 30 miles per hour. This effect depends inversely on the depth of the water. It is approximately twice as great in a depth of 30 feet as in a depth of 60 feet.

In the Northern Hemisphere, the winds blow counterclockwise around a storm. Thus, on the right-hand side of a moving storm, the wind has a component in the direction of storm movement, and on the left-hand side of the storm, the wind direction is opposite to that of the movement of the storm center. As one would expect from this circulation pattern, the highest water levels generally occur on the right-hand side of the storm track. Occasionally the level of the sea drops below normal on the left-hand side of a hurricane, but this is the exception rather than the rule. It is evident that in most hurricanes some other mechanism which tends to raise the water level overcomes the tendency for offshore winds to blow the water away from the coast.

Effect of Pressure Differences

There is a tendency for the water level to rise in regions of low atmospheric pressure by approximately one foot for each one-inch reduction in atmospheric pressure. This effect alone can often account for a rise of water level of one to two feet in the center of a hurricane. It is believed that on the open ocean and at small islands having steep shores, such as Bermuda, most of the elevation in the level of the sea associated with the passage of a hurricane is due to this effect [3].

Effect of Breaking Waves

Breaking waves run up on the shore to elevations above the crests of the waves in the open sea. This behavior of the waves causes water to be piled up along the beaches and in coves and bays. In normal weather this effect does not exceed a few inches, but in a hurricane the increase in water level from this cause may reach two feet [4]. This effect can sometimes be observed several hundred miles from the storm and is often referred to as a "forerunner" of the storm.

Effect of Storm Velocity

The wind waves generated by a hurricane or other storm move outward from the generating area at a speed which depends on the period of the individual waves. If the speed of the storm coincides with that of the speed of motion of any group of surface waves, these waves grow higher than would be the case if the storm moved at any other speed, either faster or slower. The mound of water raised by reason of the low atmospheric pressure has a rate of progression which depends on the depth of the water, and this mound grows by resonance if the storm speed is approximately equal to this rate of progression.

Effect of Variable Depth of Water

Ordinary waves grow in height as they move into shallow water. The same general law applies to the mound of water created by the low pressure in a hurricane. In theory at least, the height of this mound of water could increase by a factor of two or more as the storm moves from the deep ocean to the coast.

Effect of Shape of Shore Lines

If the storm wave generated by any of the mechanisms described above enters a bay which is wider and deeper at the mouth than at the head, such as Narragansett Bay or Delaware Bay, the height of the surge increases as it travels up the bay. Many of the highest storm tides on record have been produced in this way. On the other hand, if the mouth of the bay is narrow compared to the interior, the amplitude of the disturbance in the bay will be less than that on the open coast.

In the case of long, shallow bays, such as Long Island Sound, several hours may be required for the surge to reach the extreme end of the bay, and maximum coastal flooding due to the storm may occur several hours after the low pressure, high winds, and excessive rainfall of the storm have passed.

In some shallow bays having a very restricted connection with the sea, such as Pamlico Sound in North Carolina and Lake Pontchartrain in Louisiana, the effect of wind stress over the bay in piling up water at the leeward end of the bay may far exceed the effect of any water coming in from the ocean. In Lake Okeechobee, Florida, which has no connection with the sea, hurricane winds have piled the water as much as 12 feet above normal in one corner of the lake. In fact, one situation of this kind in Lake Okeechobee in 1928 accounted for as many deaths in the United States as all later hurricanes combined.

Resurgences

The rise in water level which accompanies a hurricane is sometimes followed by a train of disturbances in which the water continues to rise and fall with a period of several hours for a day or two after the storm. If the storm passes at the time of normal low tide and the resurgence has a period of about six hours, as is sometimes the case, the highest storm tide may occur at the following high tide as much as six hours after the passage of the storm.

RECENT IMPROVEMENTS IN OBSERVATIONS

Tide Gages and Water Level Reports

During the past year the Coast and Geodetic Survey has developed a method of using two recording pencils with their tide recording gages. This should extend the range of each gage about 80 percent and decrease the amount of data which are lost because of instruments of restricted range. With some assistance from the Weather Bureau they have also elevated or relocated a number of tide gages so as to reduce the probability of loss of record by flooding of the gage house. This program should be extended until it covers all basic tide stations in the area which is likely to be affected by tidal floods.

With the cooperation of the Coast and Geodetic Survey, remote tide recorders have been established at 12 Weather Bureau offices along the Atlantic and Gulf coasts. For the first time these recorders give a forecaster who must issue storm tide warnings a reliable means of knowing the current stage of the sea level. Their use has shown us that exceptionally high tides may be produced by some types of weather which we did not previously consider important in this respect.

A number of cooperative observers have been furnished tide staffs of the type used on rivers. In many cases the Corps of Engineers has cooperated in the installation of these gages and has carried out the surveying necessary for their evaluation. In times of high tides we are able to obtain tide readings from some of these observers and from other tide gages operated by the Corps of Engineers or private interests. However, these reports are not always available when they are most needed, as the observers may be very busy with their own essential duties at such times. An extension of the network of remote recorders is urgently needed.

The selection of gages for which remote recorders were established in 1956 was based largely on the proximity of the Coast and Geodetic Tide Stations to Weather Bureau offices, with a view toward establishing first, those stations which could be installed or operated most economically. It is planned to extend this network by an additional 12 to 15 gages selected on a basis of filling in the biggest and most important gaps in the network as soon as practicable.

Discussions with representatives of the Netherlands Weather Service indicate that for approximately 300 miles of coast line, they have about ten recording tide stations and an equal number of supplementary staff gages from which reports can be obtained as needed. The Atlantic and Gulf coast lines of the United States exceed 9,000 miles, so that more than 300 recording gages and a similar number of staff gages would be required to give a comparable coverage. The work in this field is not yet sufficiently advanced to determine the optimum spacing of tide gages for the United States.

Tide Gage Index

Water level gages are operated along the coasts and in the tidal waterways of the United States by the Coast and Geodetic Survey, the Corps of Engineers, the Geological Survey, Navy Department, the Weather Bureau, and many private interests. Some of the gages are operated exclusively by one agency, others by cooperative agreements involving two or more agencies. At the beginning of the Weather Bureau project for the forecasting of storm surges no consolidated list showing the location and character of all of these gages existed, and it was found necessary to compile such an index. This index, which will soon be published, shows the location, period of operation, and other pertinent information for all water level gages likely to be affected by storm tides along the Atlantic and Gulf coasts of the United States which have been in operation for three months or longer since 1900.

Post-Hurricane Inspections

In the two days following the landfall of hurricane Flossy, the Weather Bureau and Coast and Geodetic Survey, in cooperation with the State Highway Department of Florida, made an inspection of the Florida coast from St. Marks to Pensacola to establish as many high water marks as possible from the debris left on the beaches. Since limited funds and time were available for the inspection, high water marks were sought only in the vicinity of established bench marks. The difficulty of separating the effects of wave action and rainfall runoff further reduced the number of high tide marks which could be established. Nevertheless, a number of reliable high tide marks were established, and most of these could not have been identified a few weeks later. The highest water level established, 7.4 feet mean sea level at Laguna Beach, Fla., about 20 miles to the right of the landfall of the storm, was about two feet higher than any nearby recording gage. The storm tide crest at Philip Powel Lake, about five miles west of Laguna Beach, was 4.5 feet mean sea level, and at Destin, Fla., about 40 miles to the west, the crest was 5.4 feet mean sea level. At Panama City, about 10 miles to the east, a crest of 4.3 feet mean sea level was established from the Coast and Geodetic Survey tide gage. Differences in storm tide height of this magnitude have been observed in other hurricanes. They can be explained primarily by irregularities in the shore line, but are probably due to some extent to the wind structure of the hurricane near the center of the storm.

Later information showed that even higher storm tides occurred on the eastern shore of the Mississippi Delta, and significantly high tides were reported as far south as St. Petersburg, Fla.

The great variability of the height of the storm tide over short distances indicates that a great deal of consideration will have to be given to local configuration of the shore lines before it will be practical to make storm surge forecasts with a completely satisfactory degree of accuracy.

Many inspections and surveys of the type described above are needed for the development of a satisfactory storm tide warning system. They are likely to be even more essential for the administration of the federal flood insurance program.

SUMMARY

Hurricanes are often accompanied by local and short-duration increases in sea level. Although this is not an important characteristic of every hurricane, it is too common to be considered unusual. More than three-fourths of the loss of life due to hurricanes has been due to these floods, which are caused in part by the high winds and in part by the low pressure associated with the storms. The waves generated by the storm while it is still at sea also make a contribution to the high tides. The local topography of any region has an important effect on the time and intensity of any storm tide which may occur. The astronomical tide has a minor effect on the generation of the storm surge, but it may be of primary importance in determining the seriousness of the resulting storm tide.

With the cooperation of the Coast and Geodetic Survey, remote-indicating tide recorders were established in twelve Weather Bureau offices in 1956, so that the weather forecaster would know the current stage of the tide when making

his forecasts of storm tide development. Improvements have also been made in the installation of a number of tide gages so as to preserve the records in times of exceptionally high tides. Several additional tide staffs have been installed and a cooperative network for obtaining additional tide reports on a current basis has been established.

A prompt inspection of the coast was conducted to study the high tides generated by the only hurricane which crossed the coast line in 1956. Similar inspections are planned for future hurricanes.

More recording tide gages are needed, and it is hoped that an additional 12 to 15 gages can be installed in 1957. More recording gages will be needed as the program is developed but it is not possible to say at this time what the ultimate total number of such gages should be. Most gages must be installed in connection with some other project which can provide mounting space for the gage. However, wharfs and other structures which can be used for this purpose usually do not exist at the most ideal locations from the standpoint of an optimum gage network. Thus, it is usually necessary to use gages that are not ideally located, and it may be necessary to obtain several months of data from some locations before the warning value of the gage can be determined.

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