TEXAS WATER DEVELOPMENT BOARD

REPORT 49

HURRICANES AFFECTING
THE TEXAS GULF COAST

By

John T. Carr, Jr.

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FOREWORD

Storms producing major floods at interior locations are often related to hurricanes which strike the Texas coast and move inland. Information on hurricanes therefore is important for design and operation of reservoirs and other flood control facilities, as well as protection of coastal areas.

The Water Development Board often receives requests for information on hurricanes, related weather phenomena, areas subject to inundation from hurricane tides, and hurricane protection facilities. This report is intended to provide both general and specific answers to both the professional and nonprofessional. It describes the recurring hurricane problem, hurricane meteorology, five study areas of the Texas Gulf Coast, the status of hurricane protection projects, and standard project hurricanes and standard project storms. A convenient glossary of terms is included in the interest of a better understanding of the presentation.

Although the report provides considerable specific information, it is not its intent to provide detailed data for each specific area or storm. Such data can be obtained readily by those individuals requiring it for design purposes.

Texas Water Development Board

John J. Vandertulip

John J. Vandertulip
Chief Engineer

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GLOSSARY OF TERMS

Definitions in this list are intended to explain terms as used in this report. For the most part, definitions are taken from the "Glossary of Meteorology," published by the American Meteorological Society in 1959 and edited by Ralph E. Huschke.

advection. The horizontal shifting of a mass of air (or water).

anticyclonic. Having a sense of rotation about the local vertical opposite to that of the earth's rotation; that is, clockwise in the northern hemisphere, counter-clockwise in the southern hemisphere.

astronimical tide. The common oceanic tide--a vertical wave-like movement of water.

condensation. The physical process by which a vapor becomes a liquid or solid; the opposite of evaporation.

condensation-coalescence process. The physical change of water vapor to a liquid state and the subsequent merging of two of the newly formed water drops into a single larger drop.

downwelling. The sinking of surface waters to subsurface layers in a body of water.

easterly wave. A migratory wave-like disturbance aloft in the tropical easterlies (easterly trade winds).

extratropical. In meteorology, typical of occurrences poleward of the belt of tropical easterlies.

fault or faulting. A fracture in the earth's crust, with displacement of one side of the fracture with the respect of the other and in a direction parallel to the fracture.

filling. An increase in the central pressure of a pressure system on a constant-height chart, or an analogous increase in height on a constant-pressure chart; the opposite of deepening. The term is commonly applied to a low pressure area rather than to a high pressure area.

isotach or isovel. A line on a given surface connecting points of equal wind speed.

kinetic energy. The energy which a body possesses as a consequence of its motion.

latent heat of condensation. The heat released per unit mass by a system in a reversible isobaric-isothermal change of phase--597.3 calories per gram.

percolation. Downward seepage of water in a permeable sea bottom.

recurvature. With respect to hurricanes, the change in direction from westward and poleward to eastward and poleward.

silver iodide. A salt, having a crystallographic similarity to the ice lattice, used to promote a phase change from liquid to solid when seeding clouds containing supercooled water droplets.

standard project hurricane. The most severe storm that is considered reasonably characteristic of the region in which the basin is located.

subsidence; land subsidence. A sinking or settling of the land above areas where fluids such as oil or water have been withdrawn from the ground.

synoptic. In general, pertaining to or affording an overall view, with the additional connotation of simultaneity.

troposhere. That portion of the atmosphere from the earth's surface to the tropopause; that is, the lowest 10 to 20 kilometers of the atmosphere.

trough. In meteorology, an elongated area of relatively low atomspheric pressure.

upwelling. The rising of water toward the surface from subsurface layers of a body of water.

velocity surge. Velocity is a change of position expressed in terms of speed and direction; a surge is a sudden increase in the velocity or a sudden change in the direction, or any sudden combination of velocity increase and direction change.

westerly trough. In meteorology, an elogated area of relatively low atmospheric pressure moving from the west towards the east.

wind set-up. A tendency, due to wind action, for water levels to drop at the upwind shore of a lake and to increase at the downwind shore.

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ABSTRACT

Along the Texas Gulf Coast, damage from high water caused by hurricanes and their heavy attendant rains has been greater than the damage done by hurricane winds and hurricane-spawned tornadoes combined. Because of wind set-up and the configuration and depth of Texas bays, hurricane-caused high water has been higher at the heads of bays and in estuaries than on the open beaches. Land subsidence in certain coastal areas of heavy ground-water and oil withdrawals has amounted to as much as 5 feet during the period 1905-64.

A total of 32 hurricanes affected Texas during the period 1900-1965. All occurred from June to October. Hurricanes of both Atlantic Ocean and Gulf of Mexico origin cross the Texas coastline at irregular intervals and move inland to become extratropical. Some incipient hurricanes originating in both areas remain undeveloped because of regional meteorological conditions but continue moving and affect the Texas coast as tropical storms or depressions.

The U.S. Army Corps of Engineers is studying the entire Texas coast for hurricane protection measures in five study areas, each of which includes one or more of the major inland bay areas. Construction or modification of hurricane protection works has been federally authorized in three of the five study areas. A Standard Project Hurricane has been designed for small radius, mean radius, and large radius hurricanes moving at various speeds of translation.

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INTRODUCTION

The knowledge that severe hurricanes will cross the Texas coast at unforecastable intervals, causing tidal flooding and high winds, has inhibited industrial growth in low-lying coastal areas for many years. Beaches, recreational areas, bridges, port facilities, and even entire cities have undergone severe hurricane damage at least four times during the twentieth century. Indianola was destroyed twice in the nineteenth century, and plans for the city to be a major Texas seaport were abandoned because of the risk of repeated hurricane damage.

Economic justification for adequate hurricane protection levees has been slow to come in some Texas coastal areas. Along particular segments of the Texas coast, such as the upper coast, the other economic advantages which accrue to industry by locating large plants in that area have prompted industrial expansion despite the recurrent hurricane problem. When enough industry and enough people locate in a coastal area, the cost-benefit ratio for hurricane protection projects becomes more and more favorable. When favorable enough, proposals for construction of hurricane protection levees always have been made. It has seemed that industry first must risk locating plants in an area before hurricane protection works will be proposed or built. At this point in time, it seems economically unfeasible to build hurricane protection works as an inducement for industrial development.

A master plan for protecting the entire Texas coast from hurricane tidal flooding is under study by the Corps of Engineers. When completed, the plan is expected to recommend some sort of levee system for the length of the coastline. In the meantime, local or federally authorized projects should be constructed as segments of the overall master plan. These hurricane protection works will be constructed according to a definite design. Providing complete protection for the Texas coast will be an easier job if these smaller segments are built to be tied together at some future date dependent upon the arrival of enough people and industry.

Purpose and Scope

The purposes of this report are to inform interested parties of the current status of hurricane protection works along the Texas Gulf Coast; to explain in general terms what causes hurricanes and tropical storms; to chronicle the statistics on hurricanes of the past; and to provide information on what is being done to modify hurricanes by seeding them with chemicals. A thorough knowledge of the recurring hurricane problem on the Texas Gulf Coast might provide funding agencies with a partial basis for deciding upon some of the risks involved in making funds available for municipal and irrigation distribution systems and waterworks in low-lying coastal areas. The possible hazards of locating storage reservoirs too close to coastal areas susceptible to periodic hurricane tidal flooding might also be evident.

Personnel

This report was prepared by John T. Carr, Jr., initially under the direct supervision of John P. Dougherty, Head, Flood Control and Hurricane Protection Unit, and later under the general direction of John J. Vandertulip, Chief Engineer, Texas Water Development Board.

The author wishes to thank M. G. Lockwood and H. P. Carothers for their review of the manuscript and especially for their advice regarding the portion of the report dealing with land subsidence along the upper Texas coast.

THE RECURRING HURRICANE PROBLEM

Hurricane Damage

Damage from hurricanes crossing the Texas Gulf Coast consists mainly of damage caused by high winds, high tides, and from flooding due to the heavy attendant rains which often persist for days after the high winds and tides have subsided. Today, due to the extensive warning systems utilized by the U.S. Weather Bureau, the danger of heavy loss of human life during hurricanes is substantially less in comparison with the not-too-distant past. Dunn and Miller (1964) compare the great hurricane which struck Galveston on September 8, 1900, taking about 6,000 human lives, with Hurricane Carla, September 8-13, 1961, another vicious September storm said by many to have been equal to or more severe than the 1900 hurricane. But Carla was responsible for taking no more than 40 human lives in Texas and Louisiana combined. During the life of Hurricane Carla, the timely and accurate hurricane advisories issued by the U.S. Weather Bureau are credited with providing the impetus for perhaps the largest mass exodus in the Nation's history. Improved warning systems using radio, television, and newspapers, together with accurate radar tracking of Carla, were responsible for saving perhaps thousands of lives.

Wind Damage

The dollar value of hurricane wind damage, including hurricane-induced tornado wind damage, is much less than the dollar-value of water damage caused by the high tides and floods accompanying or following a hurricane passage. Tornadoes, whether hurricane-spawned or otherwise, are the most concentrated and viciously destructive forces in nature. But because they cut a narrow swath or skip over the countryside, their damage usually is not substantial until they strike a heavily populated or industrialized area. Studies made by Smith (1965) indicate that the path of the non-hurricane tornado is about twice as long as the hurricane-induced tornado. Table 1 shows the results of 35 verifiable hurricane-tornado reports Smith studied during the period 1955-62.

Table 1.--Non-hurricane tornado paths compared with hurricane-tornado paths

	Hurricane-Tornado	Non-Hurricane Tornado
Average path width	97 yards	250 yards
Average path length	7.6 miles	16 miles

The statistics in Table 2 illustrate the wind damage credited to hurricane-tornadoes during Hurricane Carla 1961 as tabulated in Monthly Weather Review, v. 93, no. 7, July 1965, p. 459. Of the total of 26 Carla-spawned hurricane-tornadoes, 11 occurred while Carla was in Texas.

Table 2.--Carla-spawned hurricane-tornado wind damages
(Hurricane Carla, September 10-13, 1961)

Date	Tornadoes Observed In:		Damages
	Texas	Elsewhere	
Sept. 10	0	6	Houses; one death.
Sept. 11	3	3	Radio tower, buildings, houses; 25 injured.
Sept. 12	7	2	Buildings, houses, school; 49 injuries; 32 deaths.
Sept. 13	1	4	Houses, buildings, 11,000-lb. trailer; 2 injuries.
Totals	11	15	Injuries-76; Deaths-33.

The damage from winds attributable to hurricanes proper is widespread, but because hurricane winds are usually not as strong as hurricane-tornado winds, hurricane wind damage appears light by comparison when only small areas are considered. When damages caused by hurricane winds are totaled for the entire affected area, however, it is apparent that the overall hurricane wind damage amounts to a much greater loss than that due to hurricane-tornado winds alone.

Consider, for instance, the case where a hurricane-tornado rips a typical 100-yard path eight miles long through a city the size of Beaumont. Although every building within the path of the hurricane-tornado may be damaged or completely destroyed by the 400+ mph tornadic winds, the entire city would receive some wind damage by the 150+ mph winds attributable to the hurricane proper.

An important variable to be considered when speculating on wind damage from hurricanes is the angle at which a given hurricane strikes the coastline. If one of the relatively infrequent north or northeastward moving hurricanes closely parallels, or "rakes" the coastline, a greater land area will be exposed to hurricane winds, therefore subject to damage, than will be the case if a hurricane approaches and crosses the coastline at a perpendicular angle.

Table 3, compiled by Dunn and Miller, shows 10 high hurricane wind measurements. In addition to these, engineers have examined stressed and twisted materials and made many calculations of the probable winds required to cause some of the damages noted after passage of severe hurricanes. Some estimated winds:

(1) 200-250 mph in the Florida Keys on Labor Day 1935, and

(2) 150-160 mph at Cameron, Louisiana, during Hurricane Audrey in June 1957.

Water Damage Due to High Tides

In the past, water damage due to high tides and tide surges associated with hurricanes has been far greater than the damage due to hurricane winds and hurricane-tornado winds combined. So great is the dollar-value cost of hurricane-caused rising water damage to land improvements (buildings, homes, crops, etc.) that most insurance companies in Texas will not write policies covering that damage. In hurricane-prone areas, the cost of full-coverage water damage insurance might be prohibitive, if such coverage could be obtained at all. It can be reasonably hoped that in the future some types of hurricane flood damage insurance can be obtained in areas where adequate hurricane protection works have been constructed.

Beach Tides

More studies can be found concerning high water caused by hurricanes on open beaches than can be found concerning high water caused by hurricanes in bays and estuaries. One apparent reason for this is that many recording tide gages are located on jetties and near where Texas bays empty into the Gulf of Mexico. Extreme low as well as extreme high tides can be measured, and the larger boats used by maintenance and technical personnel can have deeper water in which to navigate. Another reason one finds more literature on high beach tides than on high bay tides could be that investigators are reluctant to write convincingly about the heights of hurricane-caused water except in locations where basic scientifically derived tide height data are gathered. In the back bays and in the estuaries, high-water data are all too often based on estimations made from high-water marks on buildings and tanks or on estimations made by local residents with no references to datum or other elevation plane.

A great many cities along the Texas Gulf Coast are located on inland bays and where estuaries empty into bays. Much of the State's industry is also located in such places. As a general rule, losses due to high water caused by hurricanes are greater where cities and industry are concentrated. The need is great for more scientifically obtained high-water measurements where industrial complexes are located.

The height of open beach tides associated with hurricanes is dependent upon many factors. The major ones follow:

(1) The direction from which the hurricane is moving as it approaches the coastline. The maximum contribution to tide height is made by this factor when the hurricane approaches the coastline at a 90-degree angle.

Table 3.--Maximum winds recorded in hurricanes

Date	Place	Remarks
1. Jan. 11, 1878	Mt. Washington, N. H.	186 mph Robinson 140 mph true velocity
2. Sept. 18, 1926	Miami Beach, Fla.	128 mph for 5 min. 123 mph true 138 mph for 2 min. 132 mph true
3. Sept. 13, 1928	San Juan, Puerto Rico	150 mph for 5 min. 160 mph estimated for 1 min. 144 mph true†
*4. Apr. 12, 1934	Mt. Washington, N. H.	188 mph gusts 229, 231 extreme 225 mph true
5. Sept. 21, 1938	Milton, Mass.	121 for 5 min.‡ 186 for shorter period
6. Sept. 21, 1938	Mt. Washington, N. H.	186 mph
7. Oct. 18, 1944	Havana, Cuba	163 mph
8. Sept. 17, 1947	Hillsboro Lighthouse, Fla.	155 extreme 121 max. mph
9. Aug. 26, 1949	Juniper Lighthouse, Fla.	132 mph 153 extreme
10. Sept. 27-28, 1955	Chetumal, Mexico	175 mph

*Mt. Washington velocities were not observed during hurricanes
†Extreme
‡Probably some orographic effects

(2) The height of the "forerunner", i.e., the tide produced by swells preceding the hurricane. Swells caused by hurricanes sometimes affect coastlines hundreds of miles and many days ahead of the hurricane itself.

(3) The barometer effect. The efforts of the water in the vicinity of the hurricane to attain hydrostatic equilibrium. In hurricanes, the atmospheric pressure is relatively lower than the environmental atmospheric pressure.[1] Roughly speaking, the water in the low pressure area of the hurricane, generally the eye, will be about a foot higher for every inch of mercury the barometer has fallen below the environmental atmospheric pressure. This "inverted barometric effect" is discussed in some detail by Harris (1956).

(4) The bottom slope and profile. The depth and variations in depth of water over which the hurricane must pass as it approaches the coastline is a factor which helps determine the height of the forerunner swells and the hurricane tides. A gently sloping bottom profile and shallow water extending outward into the Gulf from the coastline are ideal conditions for maximum hurricane tide heights. If the off-shore water is too shallow, however, the hurricane tide might not be amplified because of bottom friction, percolation, and other factors (Munk and Arthur, 1951).

(5) The stage of the astronomical tide. Some effect of this partial tide will be superimposed on the height of the total tide associated with hurricanes. Both the forerunner tide and the hurricane tide will be higher during periods of high astronomical tides. While important, the phase of the astronomical tide cannot be a dominant feature in determining the variability of high water marks in a small region, or in investigations of the large-scale organization of the surge if the storm surge is defined as the difference between the observed tide and the predicted (astronomical) tide (Harris, 1962).

(6) The shape of the coastline. When the hurricane path parallels the coastline, first high and then low tides can be experienced in bays and estuaries as the hurricane "sweeps" the coastline. Under such low tide conditions, waves sometimes smash small boats against the bottom. High flood tides may also again follow such low tides (Price, 1956). Figure 1 is a composite of the winds about the hurricane of October 3, 1949, which passed between Palacios and Freeport, Texas. Note that the winds ahead of the hurricane were easterly, bringing more water shoreward, while on the left of the hurricane the winds were northerly and westerly, sweeping water out of the bays and away from the coast. This is the typical wind field near almost all hurricanes.

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[1] The atmospheric pressure in the same general area, but out and away from the hurricane circulation proper.

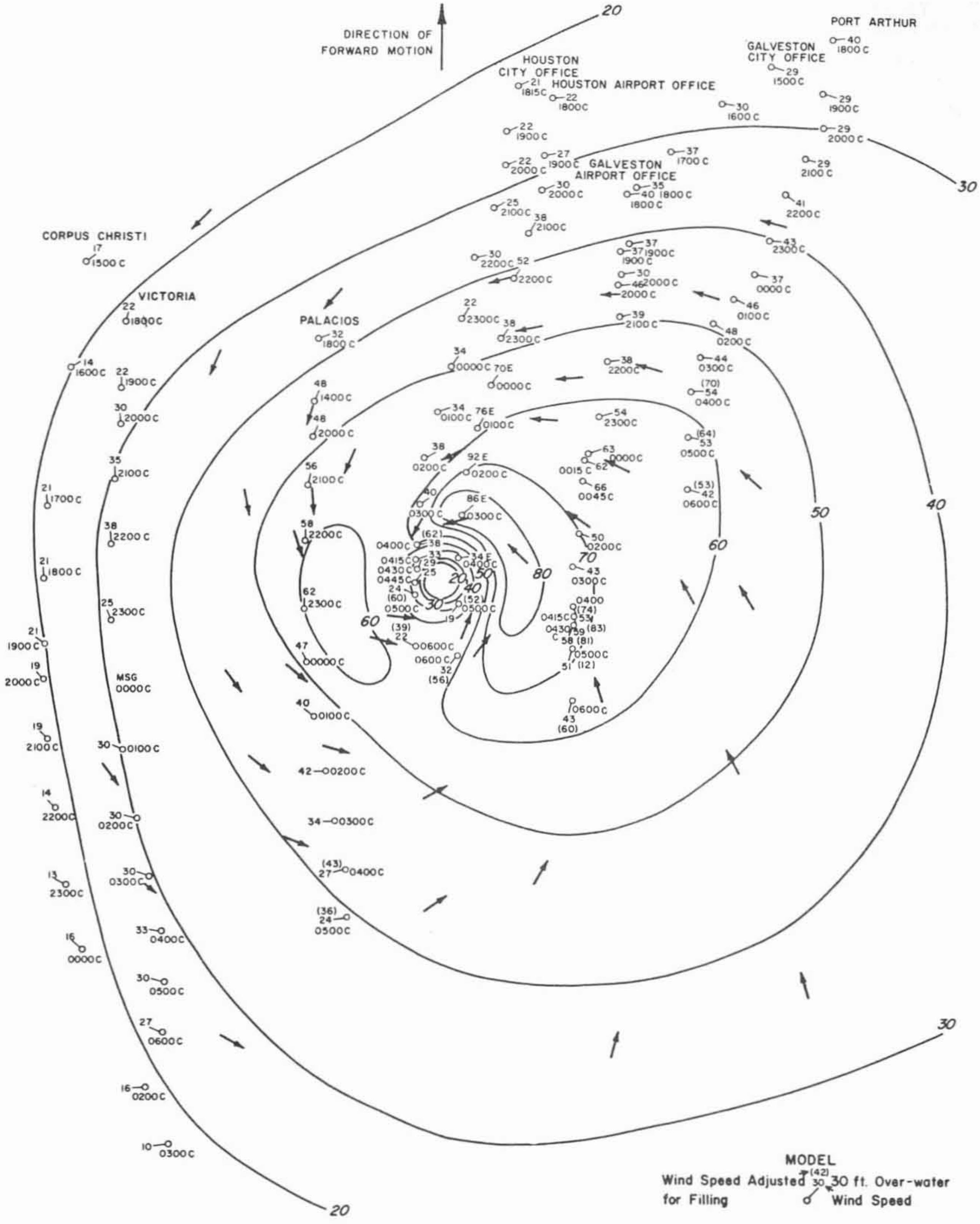

Figure 1.--Composite Wind-Speed and Direction Pattern, October 3, 1949, Near the Texas Coast. All times CST. Speeds in mph adjusted to 30 feet above water. (From NHRP Rept. no. 39.)

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Bay Tides

The factors which contribute to high beach tides during hurricanes also contribute to high bay tides as well. There is one important additional contributor, however, that historically has produced hurricane tides in the upper bays and estuaries higher by several feet than were produced on the open beach when the hurricane passed. This additional factor is termed "wind set-up" and is discussed in detail by Harris (1963) in U.S. Weather Bureau Tech. Paper 48, "Characteristics of the Hurricane Storm Surge."

Shorn of scientific language, the wind set-up is simply the result of the wind driving and channeling the bay water and damming or piling it up in the downwind reaches of the bay and its estuaries. In effect, the water level is depressed (lowered) at the upwind end of the bay and piled up (raised) at the downwind end of the bay. As described by Harris (1963, p. 5), "This effect is inversely proportional to the depth [of the water in the bay] 2/ and is greatest when the wind blows along the axis of the lake." In the upper reaches of bays and in the estuaries, water piles up higher because the area over which the water can spread is small when compared with the area along a smooth, clean, flat coastline.

Other modifications of the hurricane surge which may affect the high-water level in bays and estuaries are discussed also by Harris, q.v. For one, the height of the surge entering from the Gulf of Mexico increases if the estuary narrows down inland from the mouth, but the height of the surge decreases if the estuary is over flat land and widens out inland from the mouth. The surge may increase, then decrease, and perhaps increase again as the surge propagates up a bay, the banks of which first narrow down, then widen, then narrow down again progressively inland from the mouth of the bay. Under certain angles of hurricane approach, a hurricane surge might behave in a similar way or vice versa in either the Galveston Bay, Matagorda-Lavaca Bay, or Aransas-Copano Bay areas.

Flood Damage Due to Heavy Rains

When describing hurricane rains and floods caused by them, Dunn and Miller (1964) and Schoner and Molansky (1956) point out that although some of the world's heaviest rainfalls have occurred during hurricanes, many flood producing rains have come from storms of tropical origin but not of hurricane intensity. Because wind speed is the yardstick by which the intensity of tropical storms is measured (74 mph or greater for hurricanes), and because far more meteorological parameters than wind speed come into play during periods of heavy rainfall, it seems hardly appropriate to limit the discussion of tropical-storm rainfall to only those cases where the wind speed exceeds 73 mph. Indeed, many authors, Price (1956) and Graham and Hudson (1960), either use an elaborate classification system for tropical storms, or simply refer to such storms as being of "hurricane intensity" or "not of hurricane intensity."

One such storm of less than hurricane intensity which affected Texas was the first tropical storm of the 1960 season--an unnamed storm that formed in

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2/ Editor's interpretation

the Bay of Campeche and drifted northward to move inland near Corpus Christi on June 24, 1960. This storm caused more than 29 inches of rainfall at Port Lavaca during the four-day period June 23-26. The storm went on to cause flood damages estimated in excess of 3.5 million dollars, and 15 drownings were charged to the storm.

Hurricane Cindy, September 16-20, 1963, (Figure 2) is an example of flooding due to hurricane rains. The U.S. Weather Bureau "National Summary" for September 1963 reported that the slow movement of Cindy resulted in an extended period of heavy rainfall over southeast Texas and southwest Louisiana. Rainfall totals were 15 to 20 inches in portions of Jefferson, Newton, and Orange Counties, Texas. Deweyville, in southern Newton County, had a three-day total of 23.5 inches, 20.6 inches of which fell in a 24-hour period. Flood damage from high tides was comparatively light, but flooding due to the heavy rains caused water to enter about 4,000 homes. Property damage was estimated at 11.7 million dollars and crop damage was about $500,000 in Texas alone. Two small twin sisters drowned at Port Acres, Texas, on September 22, in the persistent flood waters still covering the area.

Significance of the 15-Foot Topographic Contour

The place where the 15-foot topographic contour occurs inland from the coast is generally considered by the Corps of Engineers, and many other agencies and engineering firms, to be about the average "limit of flooding" due to hurricane-caused high water. This consideration is based mainly on inland high-water marks left by the severest of the hurricanes known to have occurred. Periods of historical record are usually too short to be a firm basis for confident extrapolation into the future of weather occurrences and associated phenomena. This is especially true when considering maximums and minimums. Even though this basis may not be very firm, we must with due caution try intelligently to use the historical record when no firmer basis for projections into the future are obtainable. Such must be the case when deciding how high to build levees for hurricane protection. What height levees are needed to afford protection against what magnitude of tidal surges, and what height levees are economically and technically feasible, are questions which must be considered.

During the period of reliable record, the four severest hurricanes to have gone ashore in the Gulf of Mexico are generally conceded to be:

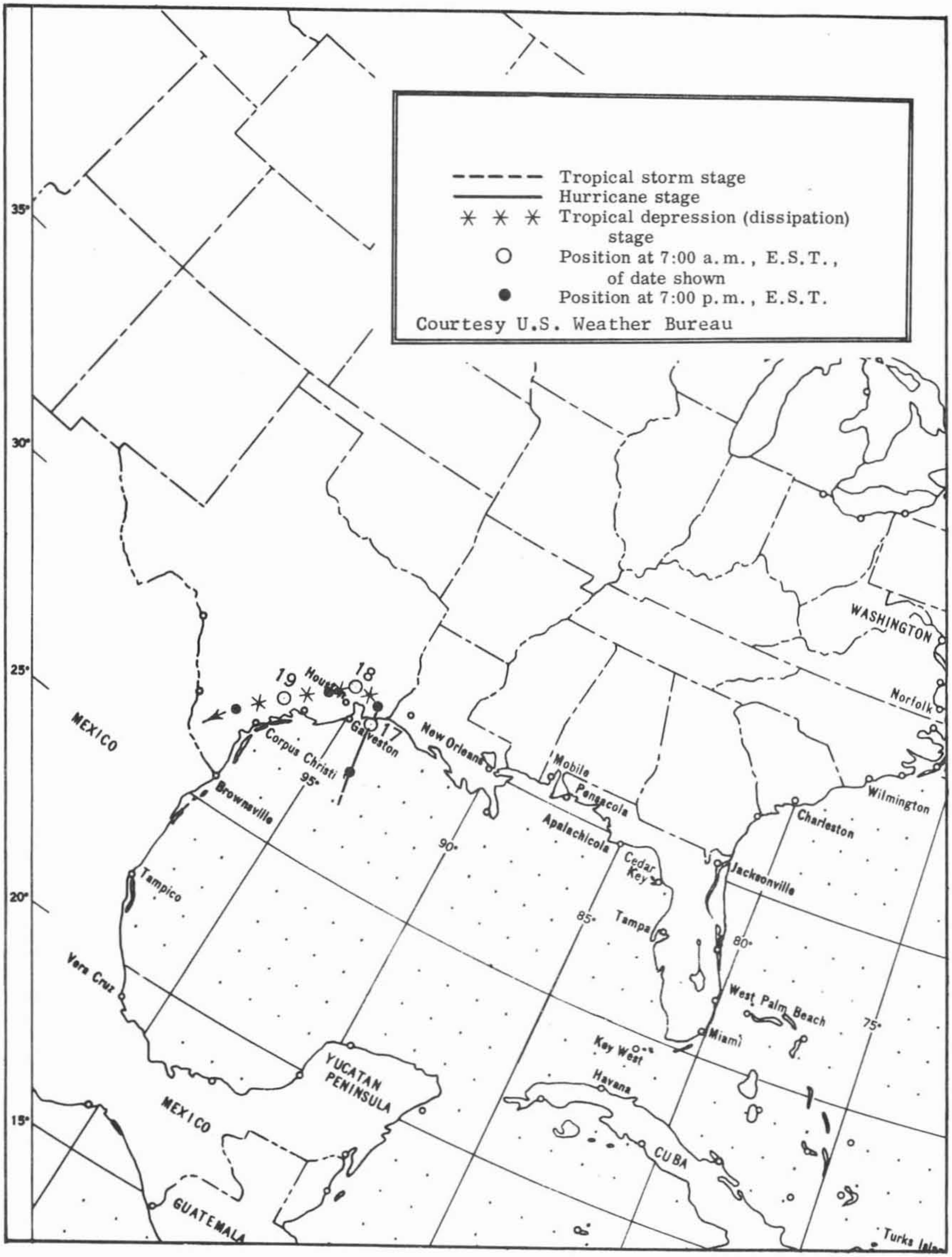
(1) The Great Galveston Storm of September 8, 1900, which caused a 14.5-foot tide;

(2) The hurricane which struck in the vicinity of Sarita on September 14, 1919, and caused a 15-foot tide;

(3) Hurricane Carla, September 9-12, 1961, which caused maximum tides as shown in Figure 3; and,

(4) Hurricane Betsy, September 7-9, 1965, which struck New Orleans, causing 12-foot tides there and 15-foot tides at Pointe-a-la-Hache.

It is a significant fact that the severest hurricanes to have affected Texas during the twentieth century caused gaged tides in the neighborhood of 15 feet. High-water marks in some cases were found above 20 feet near the



Courtesy U.S. Weather Bureau

Figure 2.--Hurricane Cindy, September 16-20, 1963

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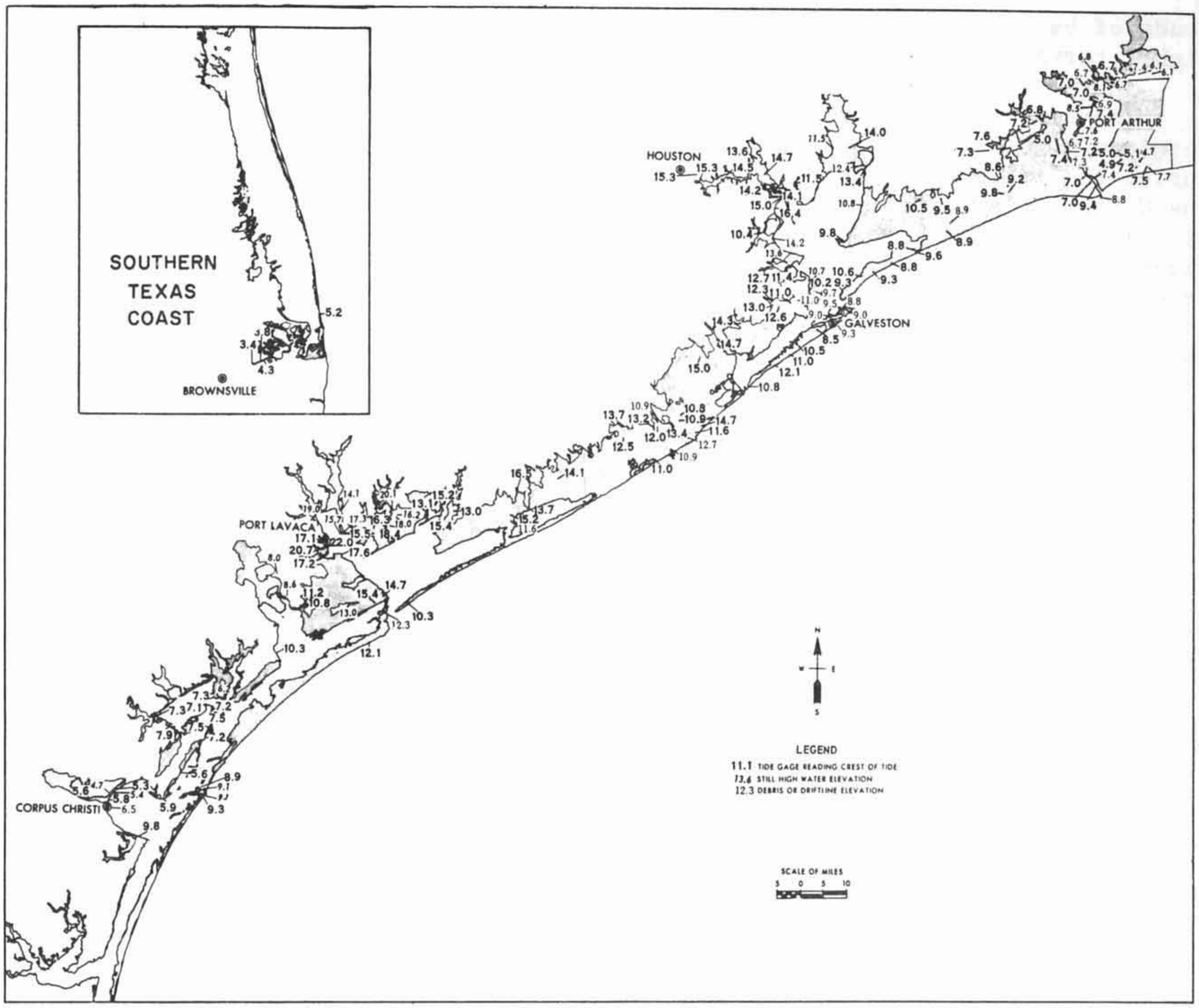

Figure 3.--Hurricane Carla, September 7-12, 1961. High water mark chart for Texas. Shaded area indicates the extent of flooding. (Based on data obtained from the Galveston District of the U.S. Army Corps of Engineers.)

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heads of bays and estuaries where the windblown waters were bottlenecked by higher terrain and could not spread out.

The degree of hurricane protection desired (height of levees) must be determined for specific locations subject to inundation by design hurricane tides during the project's planning stage. To help calculate the needed information, the Corps of Engineers uses "design hurricanes," or "hurricane models," which will later be described in detail. Most of the Corps of Engineers "design hurricane" protection plans reviewed by the author specify 15 to 22-foot high levees in the mean sea level and over-water segments of the levees, grading into the 15-foot natural topographic contour wherever it is encountered inland. The distance inland from the coast to the 15-foot natural topographic contour will be a major consideration when estimating the cost of constructing the levees--the further inland the levees extend before the 15-foot contour is encountered, the higher will be the construction costs.

Subsidence Affecting Hurricane Protection Works

The U.S. Coast and Geodetic Survey leveling program and levels run by industry and engineers disclose progressive land subsidence in the Houston-Galveston area and at Texas City and Freeport (Winslow and Wood, 1959). Subsidence along a general north-south section through Houston is shown in Figure 4 for the period 1905-1964. Land subsidence has occurred in many areas throughout the world--a total of 23 feet has been noted in Los Banos-Kettleman City area in California (Poland and Ireland, 1965).

The literature points to a major correlation between land subsidence and withdrawals of fluids such as water and oil from the ground. A decline of hydraulic pressure heads in the underlying sands is produced by fluid withdrawal. The pressure difference between underground clays and sands forces the water to move from the clays to the sands, thereby allowing permanent compaction of the clays and subsidence at the surface.

Hurricane protection levees built on subsiding land will suffer loss of freeboard directly proportional to the subsidence experienced. If a hurricane protection levee had been built to a height 15 feet above mean sea level in 1905 near the three U.S.C. & G.S. bench marks shown in the inlay on Figure 4, the height above mean sea level of that levee would now be only about 10 feet.

Texas Hurricane Statistics

Many legends but few facts in the form of useful statistics can be found on hurricanes known to have affected Texas prior to 1887, the year the official Texas Gulf Coast hurricane record begins and the same year the Corpus Christi weather station was established. Since that time some very useful statistics have been gathered on Texas hurricanes.

With the advent of aircraft reconnaissance and radar tracking, the accuracy of hurricane statistics has increased to a point of near perfection in all vital areas of consideration except hurricane tide and surge data. More extensive instrumentation of the Texas coastline with adequate tide and surge gages will be necessary before enough can be known of this important parameter which is such a vital consideration when the erection of hurricane protection works is

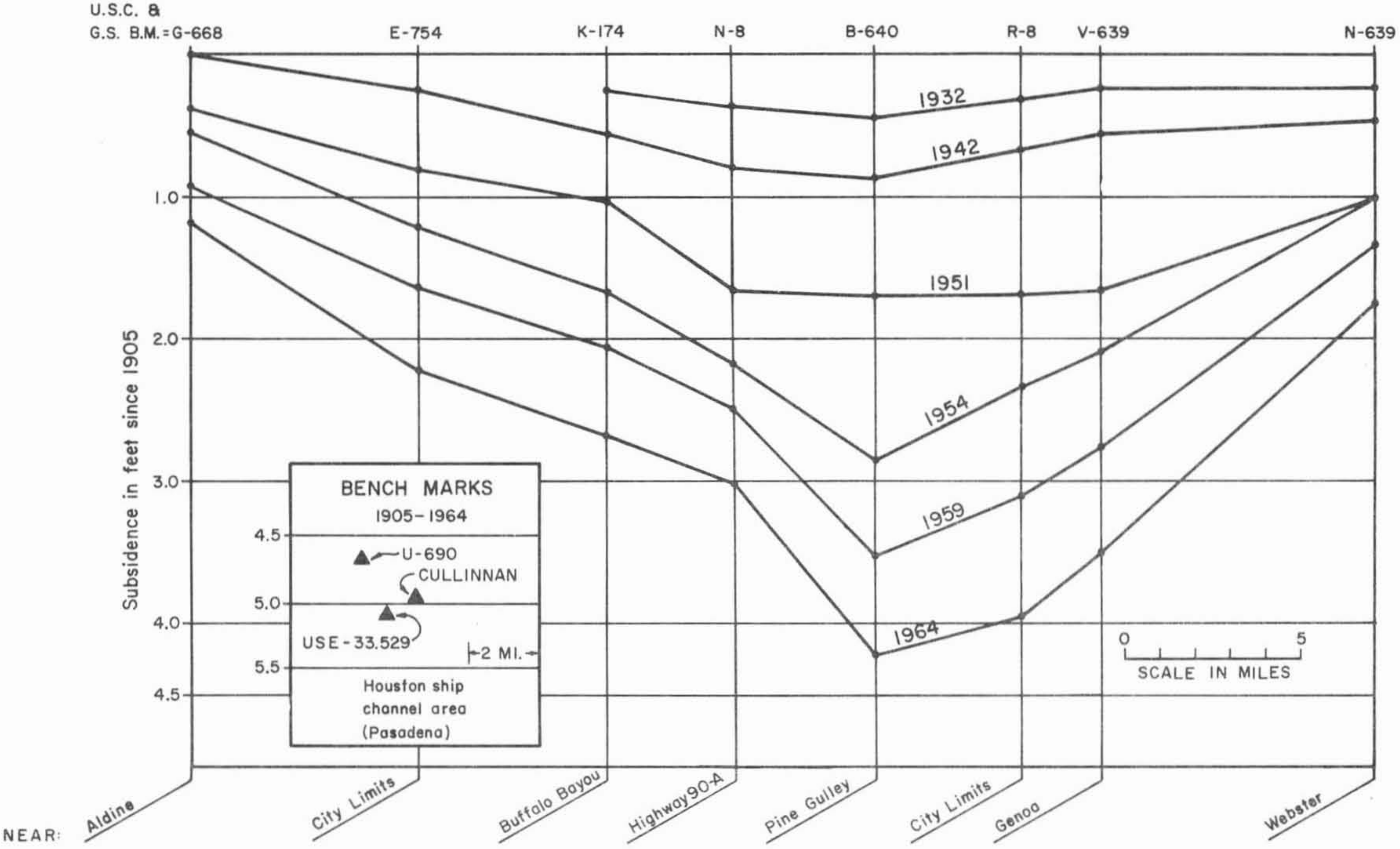


Figure 4.--Land Subsidence in the Houston Area. The section extends generally southward from Aldine to near Buffalo Bayou; then generally southeastward to near Webster, bypassing the area of greatest subsidence near Pasadena (see inlay). Bench mark elevations through 1951 were scaled (Lockwood, 1954). Elevations since 1951 are U.S.C. & G.S. data added onto Lockwood, q.v.

contemplated. Of necessity, the risk when designing hurricane levee heights to afford protection against repetition of historical hurricanes is not wholly defineable because the height of the highest historical hurricane tide is not known--if it were known there could be no guarantee a higher hurricane tide would not occur in the future.

History of Occurrences of Gulf of Mexico Hurricanes Which Affected Texas

Hurricanes are postulated to have been occurring in the Gulf of Mexico since long before the time of man. Dunn and Miller (1964) report that a number of the ancient tongues of the Caribbean and Central American Indian tribes used words with pronunciation and meaning similar to "hurricane". Following are some of these:

Origin	Word
Mayan	Hunrakin
Greater Antilles	Huracan
Galibi (Guiana)	Hyoracan
Guatemala	Hurakan
Carib Indian	Aracan, Urican, Huiranvucan

Dunn and Miller note that 94 tropical cyclones affected Texas during the period 1766-1958, although not all were of major intensity. During the period 1959-1963, five more occurred including the devastating Carla during the second week of September 1961. As a matter of significant fact, the five most severe hurricanes of the twentieth century all occurred during the second week of September.

Of the approximate 99 tropical cyclones affecting Texas during the period 1766-1961, 16 have been designated "major." These, with some generally verifiable statistics about each, are listed in Table 4.

History of Occurrences of Atlantic Ocean and Caribbean Sea Hurricanes

Some hurricanes which have affected Texas originated in the Atlantic Ocean--not the Caribbean Sea or the Gulf of Mexico. This report will not dwell on the history of Atlantic Ocean hurricanes because more Gulf and Caribbean hurricanes affect Texas than do Atlantic. In general, the recorded history of Atlantic and Caribbean hurricanes antedates Gulf hurricanes. Christopher Columbus is thought to have first encountered a hurricane in October 1495 near what is now known as the island of Hispaniola (Tannehill, 1938), as revealed in logs of his voyages.

Listed in Table 5 are the earliest recorded dates of occurrence, the section of the United States affected, and the approximate number of hurricanes which occurred during the period between the earliest date shown and 1958.

Table 4.--The 16 most costly hurricanes to affect Texas during the 195- year period, 1766-1961

Date	Location	Remarks
Oct. 1818	Galveston Island	Four of Jean Lafittes' ships damaged
Aug. 1844	Rio Grande Mouth	Seventy lives lost
Sept. 1875	Indianola	City destroyed; 176 lives lost
Oct. 1880	Brownsville	City nearly destroyed
Aug. 1886	Indianola	City destroyed second time
Sept. 1900	Galveston	6,800 lives lost; $30 to 40 million damage
July 1909	Velasco	City half destroyed; 41 lives lost
Aug. 1915	Galveston	275 lives lost; $50 million damage
Aug. 1916	Corpus Christi	20 lives lost; $1.8 million damage
Sept. 1919	South of Corpus Christi	284 lives lost; $20.3 million damage
Sept. 1933	North of Brownsville	40 lives lost; $12 million damage
Aug. 1942	Matagorda Bay	8 lives lost; $26.5 million damage
July 1943	East of Galveston	19 lives lost; $16.6 million damage
Aug. 1945	Port O'Connor	3 lives lost; $20.1 million damage
Oct. 1949	Freeport	2 lives lost; $6.7 million damage
Sept. 1961	Port O'Connor	34 lives lost in Texas; 465 persons injured; over $300 million damage

Data supplied by Texas State Climatologist, U.S. Weather Bureau, Austin Municipal Airport.

Table 5.--Sections of the United States affected by hurricanes
(After Dunn and Miller, 1964)

Period (Earliest dates to 1958)	Section of U.S. affected	Number of occurrences
1766-1958	Texas	94
1635-1958	New England States	46
1743-1958	Middle Atlantic States	37
1700-1958	Carolinas and Georgia	105
1559-1958	Florida	166
1559-1958	Louisiana, Mississippi, and Alabama	98

Intensity Criteria and Hurricane Classification

While it is difficult to isolate in any given instance the parameter responsible for the most hurricane damage, i.e., wind damage, flood damage due to high tides, or flood damage due to excess rainfall, the problem of classifying tropical disturbances according to relative strength is nevertheless real and we must arrive at some criterion by which this factor can be evaluated. Two interrelated parameters, low barometric pressure and high wind speed, are common to all tropical disturbances. The numerical values of these parameters usually fluctuate less than the parameters of inches of rainfall and feet of high water. Of the two, barometric pressure and wind speed, wind speed is the parameter most easily measured with or without instruments; therefore, wind speed has most often been designated the criterion by which the relative strength of tropical disturbances will be assessed when a single criterion is used.

After tropical disturbances reach recognized hurricane strength, there is the matter of classifying them according to relative severity. Different agencies have different methods of classification, but the method used by each agency seems to be based on the damage-parameter illustrative of the interests of the agency concerned. For example, if the agency's area of interest is flooding, the severity index might be based entirely on the height of the rising water; if the agency's area if interest is human life, the number of lives lost might be the basis for its severity classification system, and, if the interest is in dollar-value loss, the severity classification system may be based on total damages from all causes.

In attempting to weigh all factors and provide a universal hurricane intensity classification system, Dunn and Miller, in their book, "Atlantic Hurricanes," classify hurricanes as listed in Table 6 on the following page.

Table 6.--Dunn and Miller hurricane classification system

Classification	Maximum winds (mph)	Minimum central pressure (inches Hg.)
Minor	Less than 74	More than 29.40
Minimal	74 to 100	29.03 to 20.04
Major	101 to 135	28.01 to 29.00
Extreme	136 and higher	28.00 or less

Price, q.v., chose to classify these storms as follows:

H for hurricanes

C for lesser tropical storms

T for storms about which it is known only that they produced abnormally high tides on the Texas Coast

F for storms known only for their river floods

W for storms known for wind damage

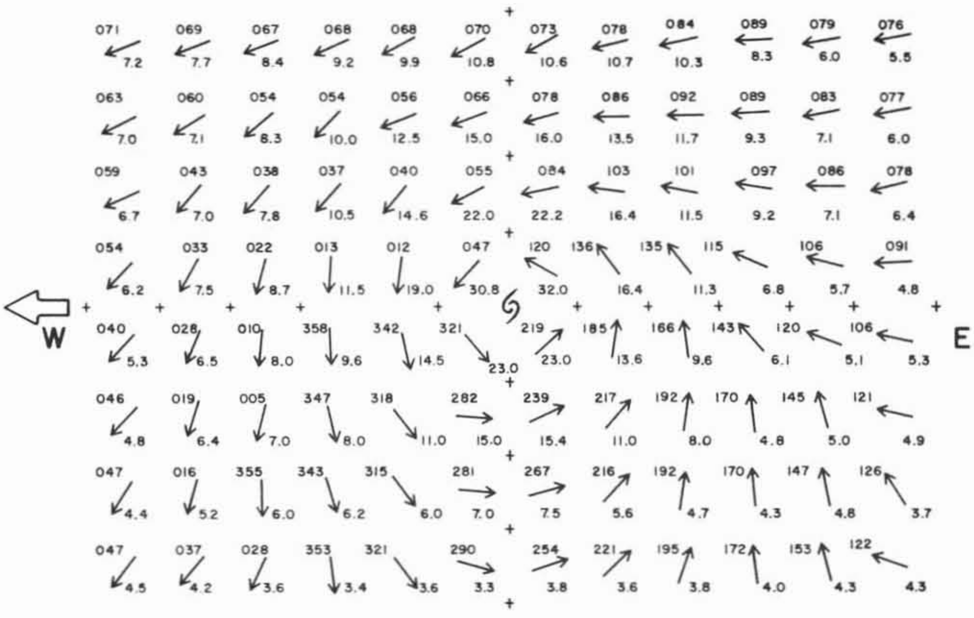
Hurricane Wind Field

As explained by Miller (1958), the total wind field on a given plane within the hurricane circulation is the sum of the radial and tangential components plus the motion of the storm. Only the relative wind field remains when the motion of the storm is removed. The relative wind field, then, represents essentially the circulation about a stationary hurricane. The mean wind field and the mean wind field with motion of storm removed (o-1 km layer) are shown in Figures 5a and 5b, respectively. The data Miller used to construct these illustrations were based mainly on observations made in conjunction with Hurricanes Hazel 1954; Connie, Diane, Ione, and Janet 1955; and Betsy 1956.

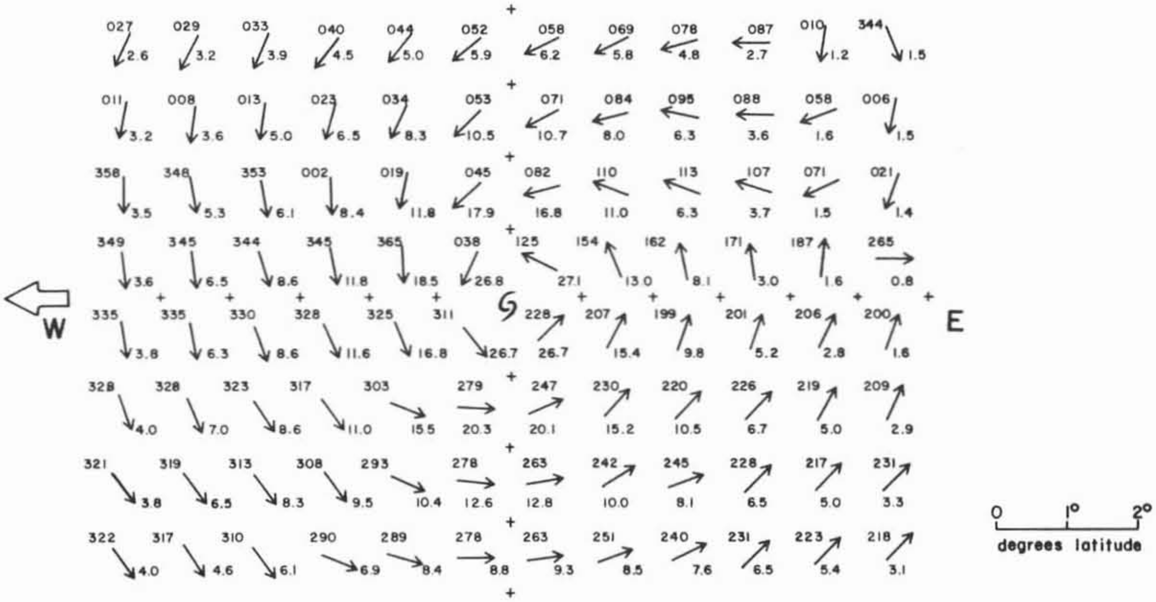
The composite wind field at 30 feet above the surface around the hurricane of October 3, 1949, Freeport, Texas, as reconstructed by Graham and Hudson (1960) and as previously shown in Figure 1, quite clearly points up the accepted hypothesis that the strongest winds in the circulation around a moving hurricane are to the right of the direction of forward motion of the storm.

Hurricane Pressure Parameters

As pointed out by Miller (1957), the minimum pressure that can occur within a hurricane is related to the temperature of the sea surface over which the hurricane moves. After studying the water circulation beneath and in the proximity of hurricanes, Gutman (1965) concluded that as long as a hurricane moves faster than the water current it has generated, cold upwelled water will remain to the rear of the storm but the downwelling ahead of the storm will induce the warm



a. Mean wind field in the 0-1 km layer above a typical westward-moving hurricane. Speed in meters per second. (From NHRP Rept. no. 15, January 1958.)



b. Mean wind field with motion of storm removed in the 0-1 km layer above a typical westward-moving hurricane. Speed in meters per second. (From NHRP Rept. no. 15, January 1958.)

Figure 5.--Mean Wind Field Above a Typical Westward-Moving Hurricane

surface water in the storm's vicinity to move out ahead of the storm. Thus, a warm water area develops ahead of the storm. This area ahead of the storm can be no warmer than the water in the area from which it was advected. The advection, however, may be accelerated somewhat by the additional downward movement of the water (downwelling) which speeds up the advection process.

The possibility should not be overlooked that a hurricane may influence the ocean in such a manner that it keeps its own pool of warm water ahead of it as long as it moves fast enough. If the foregoing reasoning is correct, a popular theory that hurricanes sometimes follow warm water may be eventually discarded in favor of a theory that hurricanes "push" warm water out ahead as they go along, thus appearing to see out and "follow" warm water.

Miller suggests that the maximum intensity a hurricane may be expected to reach is partially dependent on the temperature of the water over which the storm moves, but that the water temperature is only one of several factors which contribute to intensification and that these other factors are of at least equal importance. These factors include:

(1) Features of the field of air-motion in the lower and middle troposhere in the vicinity of the storm;

(2) Temperatures within the upper troposphere;

(3) The relative humidity within the lower air layers;

(4) The presence or absence of an efficient high-level out flow mechanism, which is necessary to remove the air that has been lifted from the surface. Otherwise, the rising warm air will cool rapidly within the upper portions of the storm area and the storm may not deepen.

While (4) above is classical, there are notable exceptions as reported by Alaka and Rubsam (1965). Such was the case with Hurricane Ella 1962. In contrast with other hurricanes described in the literature, Ella did not develop under an upper troposphere anticyclone. Rather, anticyclonic circulation first appeared in the middle troposphere and gradually extended upward while the storm was intensifying into a hurricane. Correspondingly, the warm core structure characteristic in hurricanes first appeared in the low levels of the atmosphere and then spread to the upper troposphere. Alaka and Rubsam postulated that Ella 1962 may be typical of a class of late-season Atlantic hurricanes which develop in the higher latitudes of the tropics, although there have been similar cases reported in the Australian region.

Historical Surges and High Tides

Until recent years, no one seemed to realize how important it is to collect and preserve for future research every possible scrap of synoptic information on tides and surges associated with hurricanes affecting the Texas Gulf Coast. Formerly, it was deemed sufficient to chronicle only the extremes of weather and flood conditions resulting from hurricanes. For instance, the one figure denoting the single occurrence of the highest tide at one location might be the only statistic to be found on a given hurricane known to have occurred. This one figure cannot be called entirely useless--it happens to be the only piece of information available. If present values had been placed on data useful for research, however, a more complete record of synoptic tides along the Gulf Coast might be available and some important correlations of hurricane tide parameters might be found.

In sharp contrast with the one single high-tide figure often found as the only statistic preserved after the passage of some of the earlier hurricanes is Figure 3. It shows the numerous tabulated high-tide measurements recorded during the passage of Hurricane Carla in 1961, and illustrates the trend of present thinking on the value of hurricane tide statistics.

Of the approximately 102 officially recognized hurricanes and tropical cyclones known to have affected the Texas coast since 1818, useful tide information was found on only a fraction of them. Table 7 shows, by months of occurrence, the number of hurricanes and tropical cyclones which occurred and on which hurricane tide data are available.

Table 7.--Number of hurricanes and tropical cyclones affecting the Texas coast since 1818, shown by month of occurrence with availability of hurricane tide information

Month of occurrence	Number of hurricanes		
	Tide data available	Tide data unavailable	Total
June	3	13	16
July	5	5	10
August	11	14	25
September	11	18	29
October	4	9	13
November	0	1	1
Month unknown	0	8	8
Total	34	68	102

Probable Cycles of Hurricane Occurrence

The results of considerable research on hurricanes were published by the U.S. Weather Bureau in 1965 (Cry). Data on hurricanes affecting the Texas Gulf Coast were for the most part lumped together with other North Atlantic Ocean hurricanes but the data were easily separated and supplemented to enable construction of Table 8, Tables 9a and 9b, and Figure 6.

The three tables and one figure are self-explanatory for the most part; however, note that Figure 6 illustrates the frequency of occurrence of all types of tropical cyclones which affected Texas, not just the hurricanes. Some of these crossed the Texas Gulf Coast and some did not. Hurricanes, tropical storms, and tropical depressions all affect Texas to varying degrees. High winds, heavy rainfall, or high tides and surges can and do occur with all types of tropical cyclones. The official U.S. Weather Bureau classification system for tropical cyclones (used in this report) is based solely on the following sustained wind speeds accompanying the cyclone.

Table 8.--Monthly and annual frequencies of hurricanes affecting Texas, 1900-65

Year	June	July	Aug.	Sept.	Ann.
1900				1	1
1901					0
1902	1				1
1903					0
1904					0
1905					0
1906					0
1907					0
1908					0
1909		1	1		2
Subtotal	1	1	1	1	4
1910				1	1
1911					0
1912*					1
1913	1				1
1914					0
1915			1		1
1916			1		1
1917					0
1918			1		1
1919				1	1
Subtotal	1	0	3	2	7*
1920					0
1921	1			1	2
1922					0
1923					0
1924					0
1925					0
1926					0
1927					0
1928					0
1929	1				1
Subtotal	2	0	0	1	3
1930					0
1931					0
1932			1		1
1933			1	1	2
1934					0
1935					0
1936	1				1
1937					0
1938					0
1939					0
Subtotal	1	0	2	1	4
1940			1		1
1941				1	1
1942			2		2
1943		1			1
1944					0
1945				1	1
1946					0
1947			1		1
1948					0
1949				1	1
Subtotal	0	1	4	3	8
1950					0
1951					0
1952					0
1953					0
1954	1				1
1955					0
1956					0
1957	1				1
1958					0
1959		1			1
Subtotal	2	1	0	0	3
1960					0
1961				1	1
1962					0
1963				1	1
1964			1		1
1965					0
Subtotal	0	0	1	2	3
Grand Total	7	3	11	10	32*

*Includes the one October (1912) in which a hurricane affected Texas. Otherwise, hurricanes affected Texas only in the months shown (June-September).

(Tabulated from data contained in U.S. Weather Bur. Tech. Paper 55.)

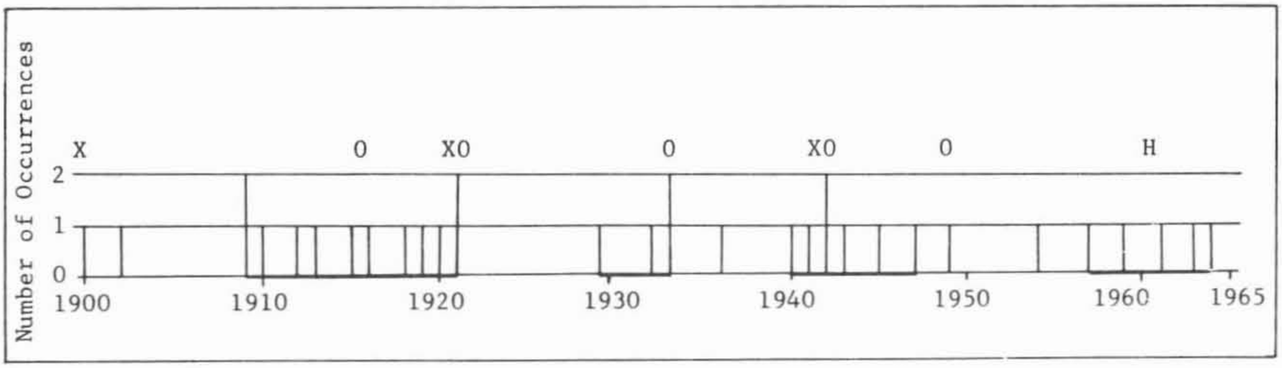
Table 9a.--Observed frequency of hurricanes affecting Texas during the period 1900-1965

Number of storms	June	July	Aug.	Sept.	Oct.	All other months	Annual
0	59	63	55	56	65	0	38
1	7	3	10	10	1	0	28
2	0	0	1	0	0	0	4

Table 9b.--Observed probability of occurrence of hurricanes affecting Texas during the period 1900-1965

Number of storms	June	July	Aug.	Sept.	Oct.	All other months	Annual
None	0.89	0.95	0.83	0.85	0.98	1	0.58
At least 1	.11	.05	.15	.15	.02	0	.42
2 or more	0	0	.02	0	0	0	.07

Table 9c.--Hurricane frequency by years. Hurricane-rich periods are underlined; symbol "O" denotes 10-ft. high water occurred; "X" denotes 15-ft. high water occurred; "H" denotes 22-ft. high water occurred. Source: Dunn and Miller (1964) and Cry (1963).



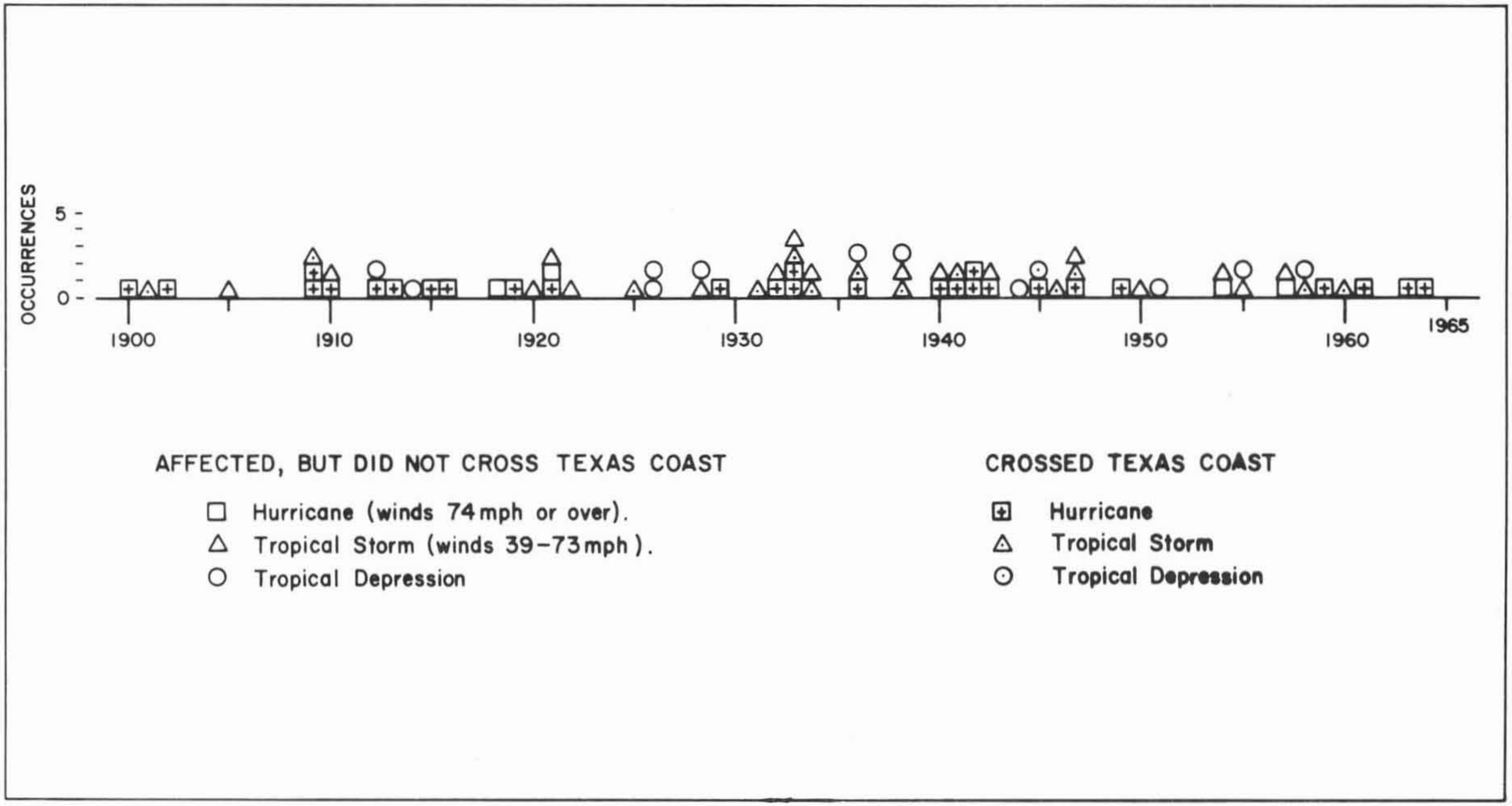


Figure 6.--Annual Frequency of Tropical Cyclones Moving Inland Over Texas or Passing Close Enough Offshore to Affect Significantly the Texas Coast with Storm or Hurricane Winds, Heavy Rainfall, or High Storm Tides, 1900-1965. (Computed from data contained in U.S. Weather Bureau TP no. 55 and from U.S. Weather Bureau Annual Summaries.)

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(1) Hurricane - winds 74 mph or over;

(2) Tropical Storm - winds 39 to 73 mph; and

(3) Tropical Depression - winds less than 39 mph.

HURRICANE METEOROLOGY

Detailed information on hurricane meteorology is ably presented in several texts and numerous technical papers. An attempt even to summarize the work of many scientists having studied the hurricane phenomenon is beyond the purpose of this report. A very generalized explanation of some of the hurricane parameters is provided, however.

Hurricane Genesis and Growth

A condition found to be quite favorable for hurricane genesis is a situation occurring in tropical seas. When a stable tropical disturbance exists over warm water, an outside influence subsequently arriving on the scene can make the disturbance unstable and trigger it into cyclonic action (Riehl, 1954). The Intertropical Zone of Convergence (ITC), is a narrow zone of converging winds positioned between the northeast trade winds of the northern hemisphere and the southeast trade winds of the southern hemisphere. The ITC nearly always is present over large water surfaces, as opposed to large land surfaces, and is itself strong enough to qualify as a tropical disturbance capable of spawning hurricanes when triggered by an outside influence. The ITC migrates seasonally from the southern hemisphere to the northern hemisphere. Two other disturbances capable of hurricane genesis when intensified by outside influences are easterly waves and troughs in the westerlies, but these two disturbances may also provide the trigger when they come into contact with the ITC.

The outside influence triggering the disturbance into cyclonic action could also be a wind shear or a velocity surge in the trade winds (due to reinforcement of the Atlantic Ocean High Pressure Cell). Or, the pre-existing disturbance could be triggered into cyclonic action if it merged with another disturbance. Such could be the case if a stable trough in the westerlies met and merged with a stable trough in the easterlies.

Once triggered into cyclonic action and made unstable, a tropical disturbance may not necessarily intensify to hurricane force unless other conditions are met. For one thing, the incipient hurricane is sure to be short-lived if the ascending air within the cyclone does not rise at a rate sufficient to carry great quantities of water vapor (moist air) to very high altitudes.

While converging air currents such as those produced in the ITC are necessary at low levels, diverging currents are of prime importance at high levels. This encourages the warm air to rise rapidly and enhances the intensification process in the incipient hurricane. Something somewhat analogous to a pumping action is thus set up and a constant supply of moisture is made available for conversion to heat, the life-blood of any hurricane.

As the ascending air cools, invisible water vapor is condensed into cloud droplets, and the latent heat of condensation thus is converted into sensible heat. The kinetic energy of radial motion is also converted to tangential kinetic energy, and heat may be added to the system by descending air currents. The main energy input, however, is the latent heat produced from condensation of water vapor (Dunn and Miller, 1964).

When the input of latent or sensible heat is reduced by any means, a hurricane will soon weaken or an incipient one may not intensify. When heat or energy is added, or when great quantities of air are removed from the hurricane at high levels, the hurricane will maintain itself or will intensify. A comprehensive discussion of all hurricane processes is beyond the scope of this report; however, some of the hurricane genesis and growth-enhancing parameters previously discussed are illustrated in Figure 7.

A Hurricane Model

Hurricanes are characteristic non-conformers to model. The hurricane model in Figure 8 is one adopted by "Project Stormfury" personnel, a group of scientists engaged in hurricane-seeding experiments. "Project Stormfury" is a joint U.S. Weather Bureau-U.S. Navy program of scientific experiments designed to discover and test methods of modifying hurricanes by artificial means. An initial three-year inter-departmental agreement launching the program began on July 30, 1962. An actual hurricane that was seeded with silver iodide (Hurricane Esther 1961) is shown in Figure 9 (Simpson, Ahrens, and Decker, 1963). Note the non-typical features of Esther when compared with the model: spiral rain-bands are better developed south of the eye of Esther and the coverage of middle and high clouds is extensive south of Esther.

Hurricane Tracks

The U.S. Weather Bureau's Technical Paper 55 (Cry, 1965) contains the most comprehensive set of maps of North Atlantic hurricane tracks to be reviewed by the author. That publication is highly recommended for those seeking a more detailed analysis of the subject. For convenience to the reader, certain of the maps contained in that publication have been reproduced in part (Figures 10-14) to show the tracks of hurricanes affecting Texas, the main area of concern in this report.

For perspective, the whole map, "Weather Bureau North Atlantic Hurricane Tracking Chart," used in U.S. Weather Bureau Technical Paper 55, is shown in Figure 10, which in this case depicts the tracks of North Atlantic tropical storms during the period November-May 1871-1900. No tropical storms are known to have affected Texas in the months of November, December, January, February, March, April, or May during the period of record used, 1871-1963.

To illustrate what happened during the other months (June-October), the tracks of hurricanes known to have affected Texas (1871-1963) were taken from the Weather Bureau North Atlantic Hurricane Tracking Chart and arranged to more convenient form as shown in Figures 11, 12, 13, and 14.

Examination of Figure 11 discloses that before 1901: tropical storms occurring in June and July showed a marked tendency to cross the Texas coast in the bend between Galveston and Corpus Christi; during the months of August and September, tropical storms showed no preferred segment of the Texas Coast to

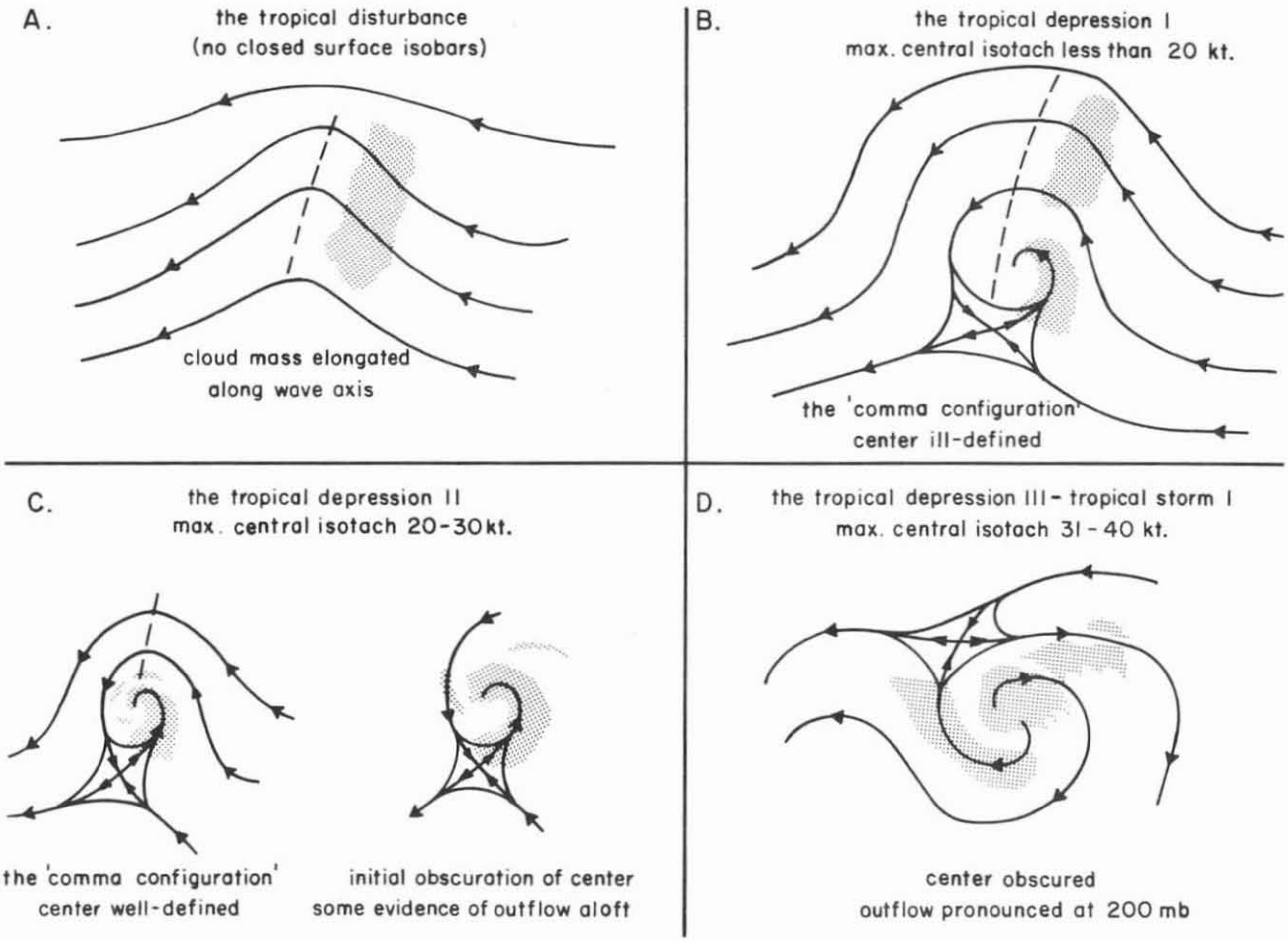

Figure 7.--A Model Describing the Cloudiness Distribution Associated with the Formative Stages of Tropical Cyclone Development. The model applies to formative tropical cyclones of the Northern Hemisphere embedded in easterly flow. In stages A, B, and C, the typical gradient wind streamline pattern is superimposed over the shaded TIROS-observed cloudy areas. In stage D, the typical 200-mb. streamline pattern is shown. (From Monthly Weather Review, V. 94, no. 1.)

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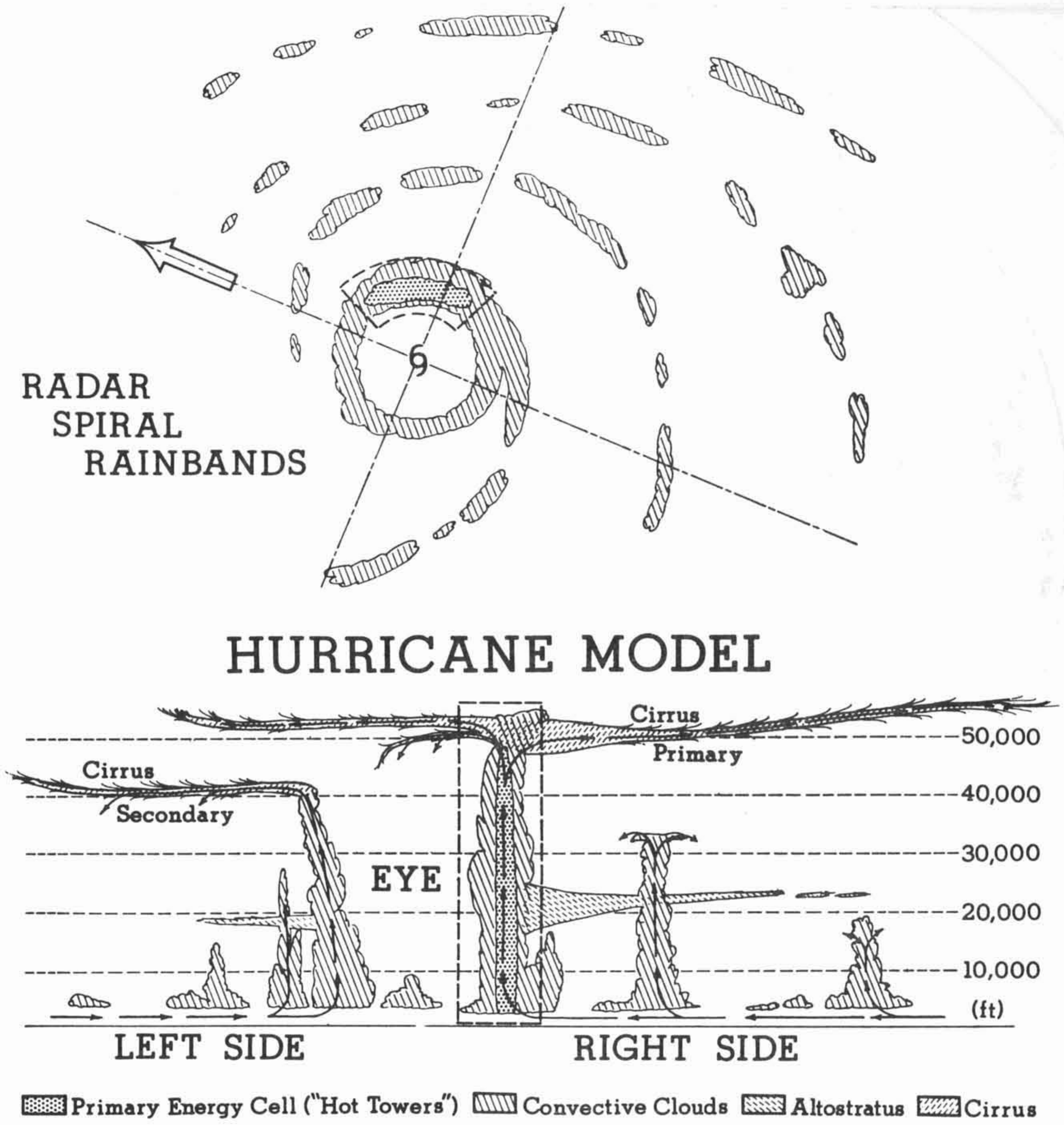

Figure 8.-- The Hurricane Model. The primary energy cell (convective chimney) is located in the area enclosed by the broken line. (From NHRP Rept. no. 60, Hurricane Esther 1961.)

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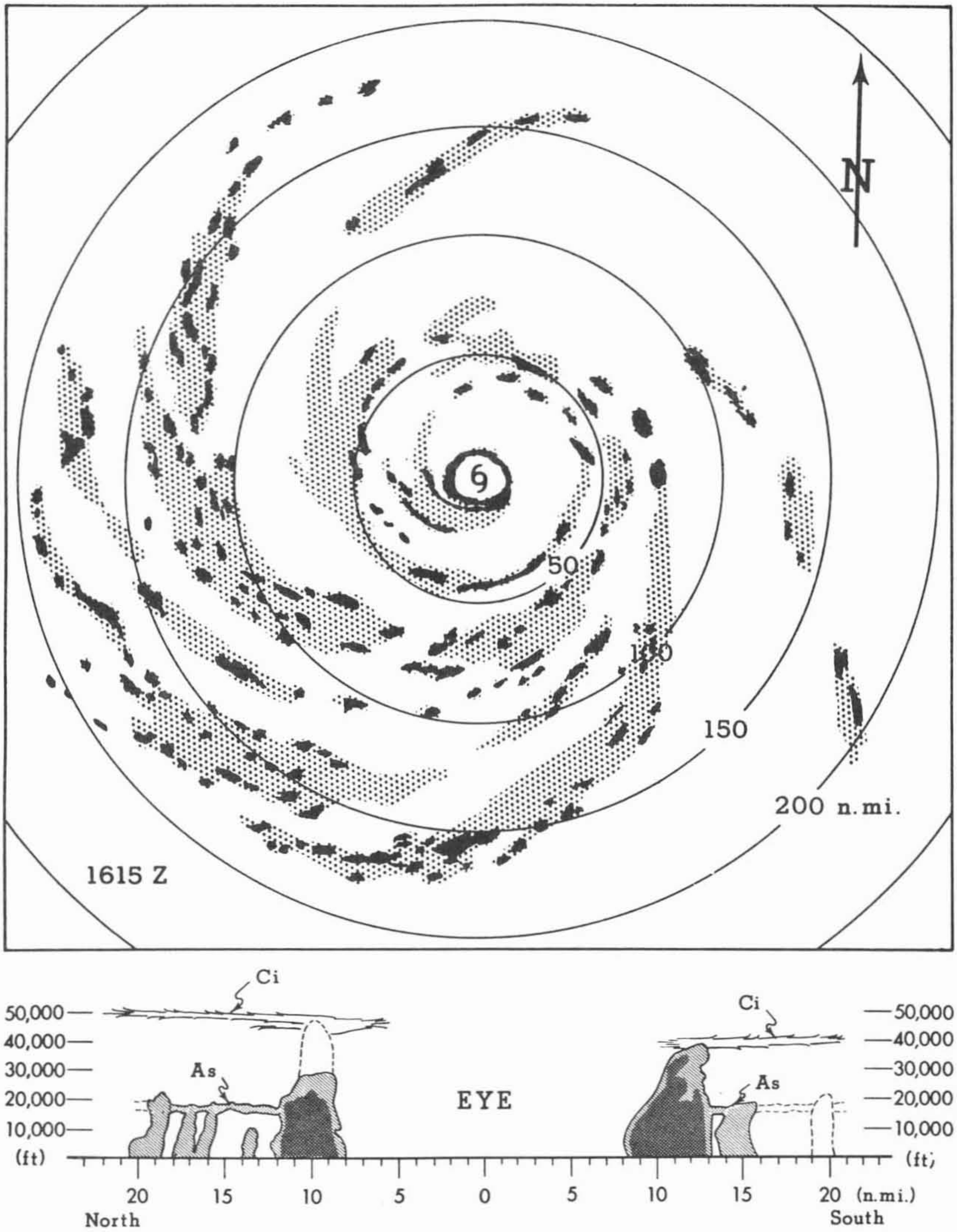

Figure 9.--Radar Composite of Hurricane Esther, September 16, 1961. (3-cm. and 10-cm. radar) (From NHRP Rept. no. 60, Hurricane Esther 1961).

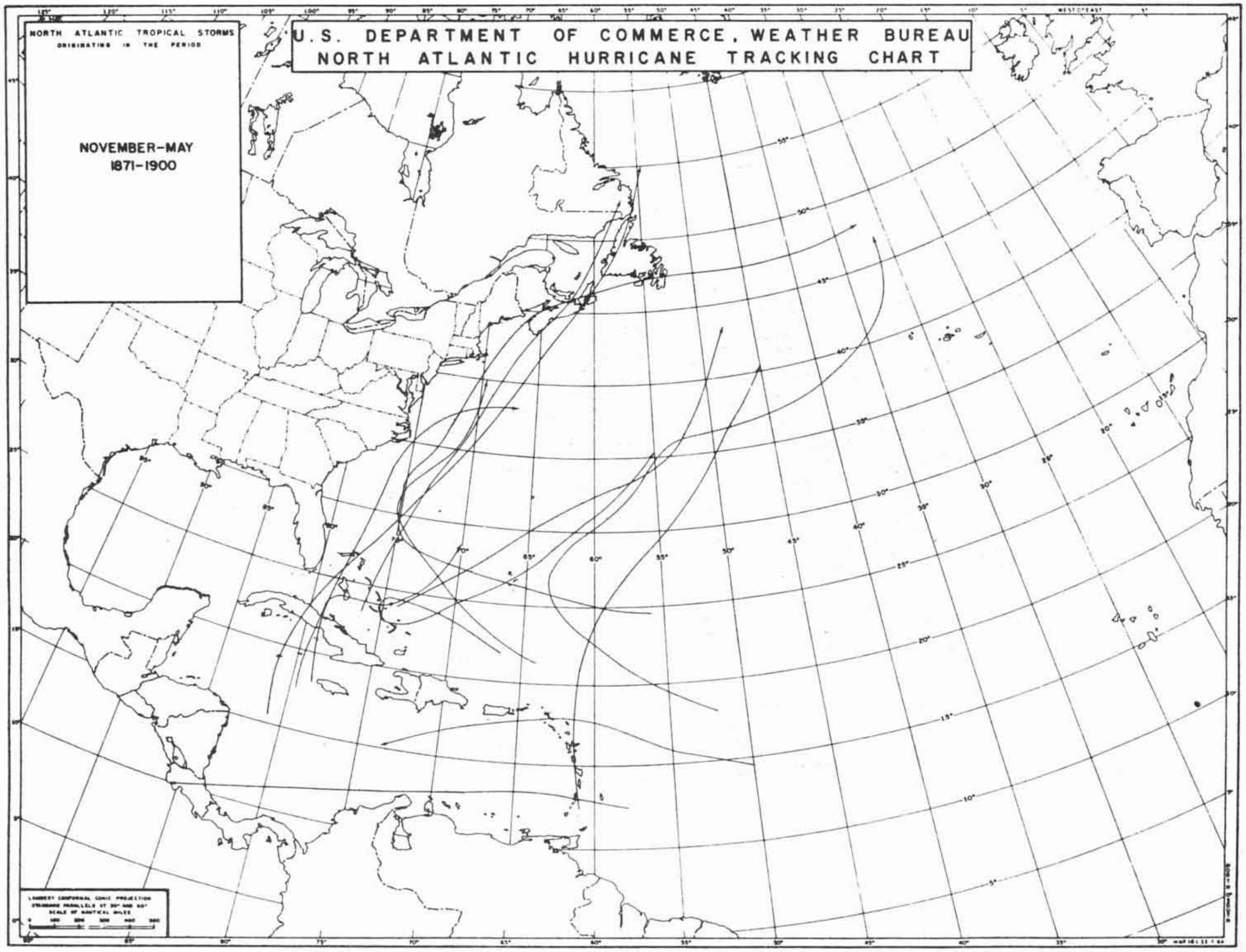

Figure 10.-- Tracks of North Atlantic Tropical Storms, November-May 1871-1900. None affected Texas. (From U.S. Weather Bureau TP no. 55, 1965.)

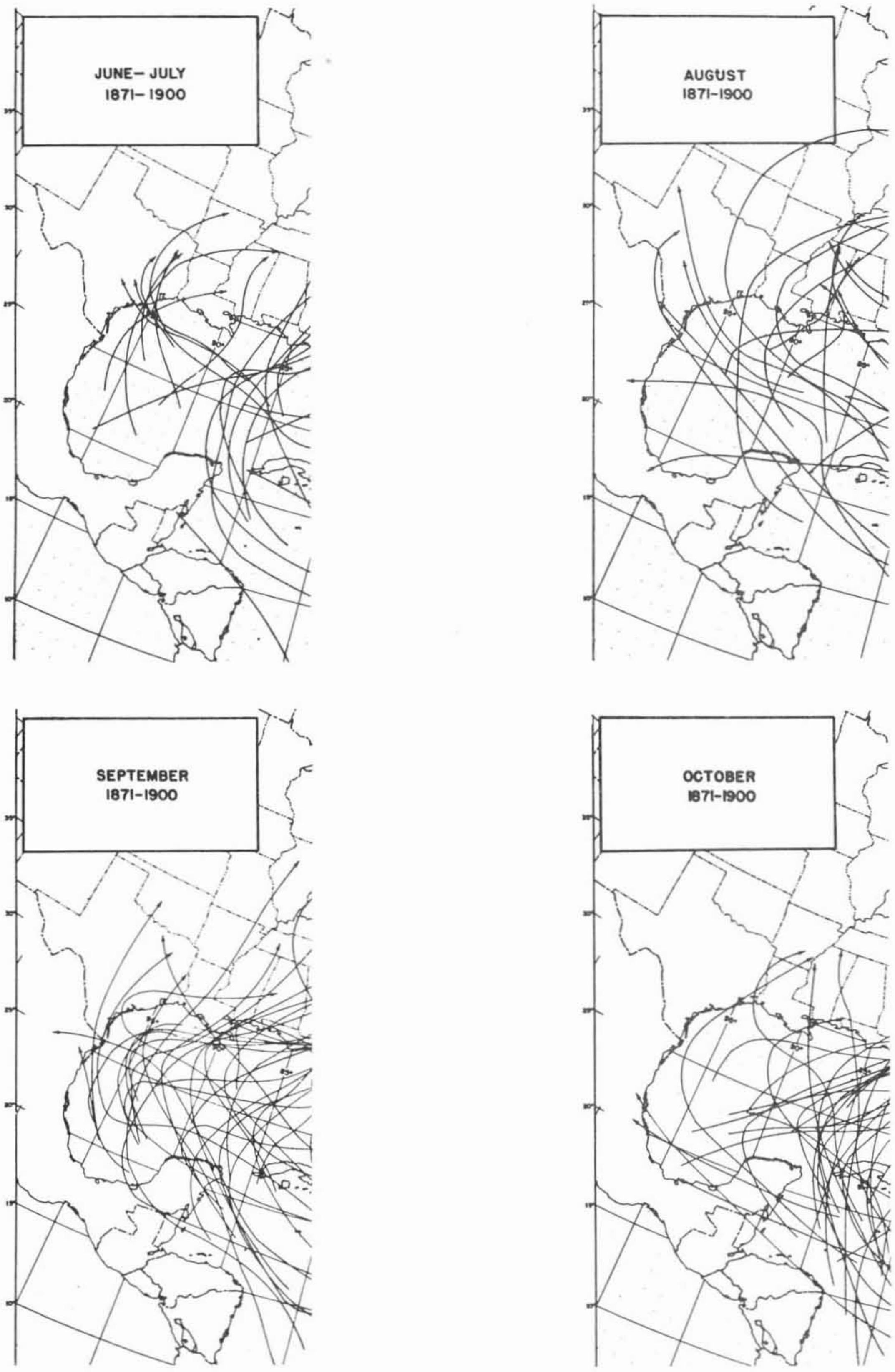

Figure 11.--Tracks of Tropical Storms Affecting Texas 1871-1900.
(From U.S. Weather Bureau TP no. 55)

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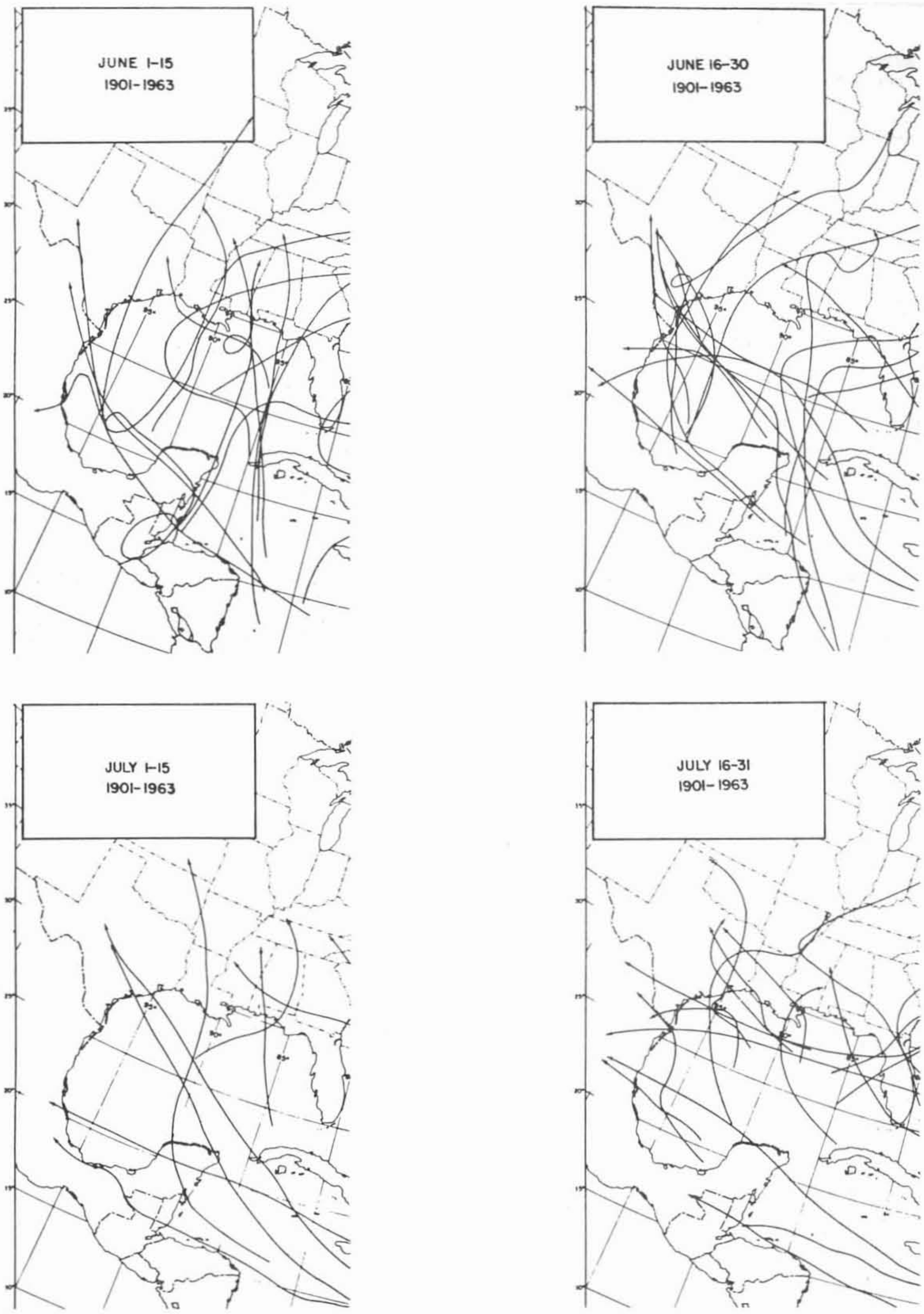

Figure 12. Tracks of Tropical Storms Affecting Texas, June and July 1901-1963.
(From U.S. Weather Bureau TP no. 55)
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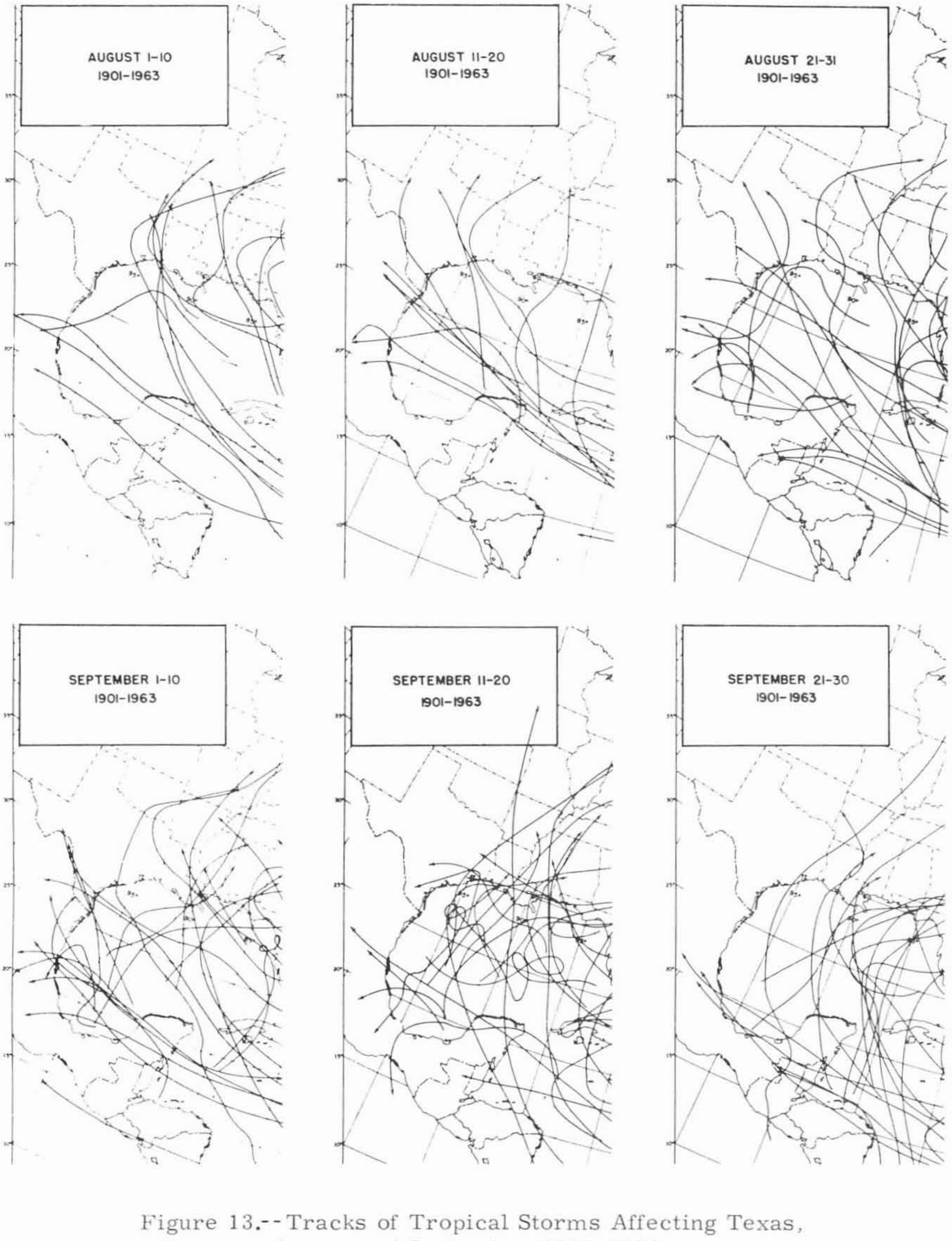

Figure 13.--Tracks of Tropical Storms Affecting Texas,
August and September 1901-1963.
(From U.S. Weather Bureau TP no. 55)
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Figure 14.--Tracks of Tropical Storms Affecting Texas, October-May 1901-1963.
(From U.S. Weather Bureau TP no. 55)
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make landfall; and, during October, the two tropical storms to make landfall in Texas did so along the upper coast.

Figure 12 shows that in the 64-year period, 1900-63, tropical storms entering Texas during the month of June were steered by atmospheric forces to the lower Texas coast, while those in July were not steered toward any particular segment of the coast.

From Figure 13 it can be seen that the 1900-63 tropical storms during the first 10 days of August went ashore on the upper Texas coast; the upper and the lower coast were favored during the middle 10 days of August; and no particular segment of the Texas coast was favored during the last 10 days of August. The lower coast was crossed by tropical storms more often during the first 10 days of September, but the upper coast was crossed most often during the last 20 days of September.

Figure 14 shows that October tropical storms favored no segment of the Texas coast when making landfall and that no tropical storms at all crossed the Texas coast from November to May.

Extratropical Stage

When a hurricane becomes so modified (weakened) as to lose its tropical characteristics, it is said to have become extratropical. The extratropical stage can and does occur while a hurricane is still over water, but it usually occurs after it has moved northward and out of the tropical latitudes. Most hurricanes which affect North America, however, do not become extratropical until they make landfall. A major reason for this is that once a hurricane loses its moisture source it has lost its "fuel," the water which is ultimately converted to energy to run the hurricane machine.

Many hurricanes recurve, i.e., fall under the influence of westerly winds, before becoming extratropical. The point of recurvature is the farthest western point reached by a hurricane. Recurvature can occur over water as well as over land. Hurricanes form and move before recurvature while still "embedded" in the tropical belt of prevailing easterly trade winds. Temperate zone winds are prevailing from the west.

The belt of temperate zone westerly winds migrates seasonally northward and southward. A hurricane path, as it nears the "boundary" between easterly and westerly winds, becomes very erratic. It drifts first in one direction and then the other until it finally crosses the boundary of the two prevailing opposite air currents and is firmly in the grip of one or the other. Then the hurricane continues to move while embedded within the air current in which it is finally gripped. More times than not the new path is a complete reversal of the original path, but at a higher latitude. If the recurvature occurred just as the hurricane made landfall, it become extratropical at about the same place and time as the recurvature occurred. These two happenings often signal the end of the "hurricane watch" and usually no more U.S. Weather Bureau warnings are released on that particular hurricane.

Although extremely high wind is normally absent from the remains of a hurricane while it is in the extratropical stage, the potential for heavy rainfall often remains with the storm for many miles and many days inland. Almost without exception, the recorded heavy late summer and early autumn rainfalls which have occurred in Texas are traceable to tropical storms or hurricanes, or to their remains.

These large-scale tropical cyclones bring inland with them vast quantities of water vapor which require only a trigger to start condensing into liquid form and falling to the ground as precipitation. Many times the topography of Texas supplies the necessary trigger. To start a rapid condensation-coalescence process (resulting in heavy precipitation), the vapor might require just a few degrees of cooling. The necessary cooling often is supplied when such topopraphy as the Balcones Escarpment trusts the impinging saturated air in the remnants of the tropical cyclone upward a few hundred feet, cooling it by expansion due to the decrease of atmospheric pressure with altitude. Rain will continue as long as the moist air keeps coming in for the terrain to thrust upward.

The great central Texas storm of September 9-10, 1952, is attributed by Orton (1965) to an easterly wave, a type of tropical disturbance on which hurricanes frequently form. In Blanco and Kendall Counties, totals of 20 to 26 inches of rain fell in 48 hours as a result of this tropical system. It could have been triggered by the topography of the Balcones Escarpment.

The remains of some hurricanes move very slowly or become virtually stationary after they cross the Texas coast. In most of these cases dynamic atmospheric forces combine to produce excessive rainfall and consequent flooding. Such was the case with Hurricane Cindy 1963. Cindy (Figure 2) remained almost stationary for about 18 hours shortly after moving inland.

On June 25, 1954, Hurricane Alice entered Mexico about 85 miles south of Brownsville. This hurricane was classified as being of minor intensity. Alice, while in extratropical stage, subsequently traveled up the Rio Grande Valley to the Lower Pecos and Devils River watersheds where her rains caused flooding that killed 17 people. These heavy rains are attributable to the "lift" (hence cooling) given the moist air by the rising topography as the moist air moved up the Rio Grande Valley.

On October 10, 1966, Hurricane Inez struck the coast of Mexico north of Tampico, but, unlike Alice 1954, Inez moved directly westward and broke up over the mountains in the interior of Mexico. These two hurricanes, Alice 1954 and Inez 1966, made landfall within about 100 miles of each other. One moved northwestward and caused flooding along the upper Rio Grande while the other moved directly westward, once again illustrating the capriciousness of these violent maidens of nature.

STANDARD PROJECT HURRICANES AND STANDARD PROJECT STORMS

The following paragraphs and illustrations concerning design and project hurricanes are analyses of and in some cases outright quotations or repreductions of material taken from National Hurricane Research Project Report (NHRP) 33, November 1959, by Graham and Nunn (1959). Report 33 is a joint U.S. Weather Bureau-Corps of Engineers effort. Study of that report is recommended for a complete understanding of Corps of Engineers design and project hurricanes.

Definitions

"Standard Project Hurricane" (SPH) is analogous to the "Standard Project Storm," and is defined by the Corps of Engineers for a particular drainage basin and season of year as "...the most severe storm that is considered reasonably characteristic of the region in which the basin is located." Like the Standard Project Storm precipitation, the SPH index is based on enveloping the records of past meteorological events, with the elimination of a few extreme events. The SPH index parameters discussed in this section are consistent within the limits imposed by regional variation of climatological features.

The standard project hurricane wind field and parameters represent a standard against which the degree of protection finally selected for a hurricane protection project may be judged and compared with protection provided at projects in other localities. The SPH indices are intended as a geographically consistent set of criteria against which the individual requirements of a project can be judged. The SPH indices and parameters provide a procedure for determining the SPH estimate which reflects a generalized analysis of hurricane potentialities in a region. The SPH indices were derived for use in selecting the standard project hurricane criteria for specified projects. The SPH index is the wind speed and direction pattern with specified dimension spans and ranges of forward speed and direction of movement for a specific location.

The isovel or isotach pattern around a hurricane depicts the wind field in a hurricane about 30 feet above the water.

The central pressure index (CPI) is the estimated minimum pressure for individual hurricanes in each zone and is the principal intensity criterion for defining the SPH index. A record was made of all tropical storms (1900-56) that passed through each zone and had at any time been of hurricane intensity. A notation was made for the period from 1900 to 1956 of the CPI whenever it was estimated to be less than 29.00 inches in any zone. For any hurricane, the CPI was determined from: (a) observations of minimum pressure at a given location, (b) computations based on observational data, or (c) by estimate in event that the hurricane passed through a zone where there were insufficient pressure observations to complete a computation but with enough evidence to warrant an estimate. In the latter case, the CPI has been determined by (a) or (b) in an adjoining zone.

In order to facilitate an analysis of hurricane data, the Atlantic and Gulf coastal areas of the United States were divided into zones of approximately equal area. The Atlantic coastal area was divided into four zones and will not be further discussed in this report. The Gulf coastal area was divided into three zones as shown in Figure 15. Each of these includes an area of approximately 80,000 square nautical miles. Each zone is about 400 nautical miles long and extends 50 nautical miles inland from a generalized coastline to 150 nautical miles offshore from that line.

Gulf Coast Hurricane Occurrences 1900-56

Hurricane occurrences along the entire Gulf of Mexico coast are shown in Figure 16. Zone C, the western Gulf Coast, mostly the Texas Gulf Coast, had a total of 37 hurricanes during the 57-year period 1900-65. The total number of transits through each smaller sub-zone of approximately 10,000 square miles by

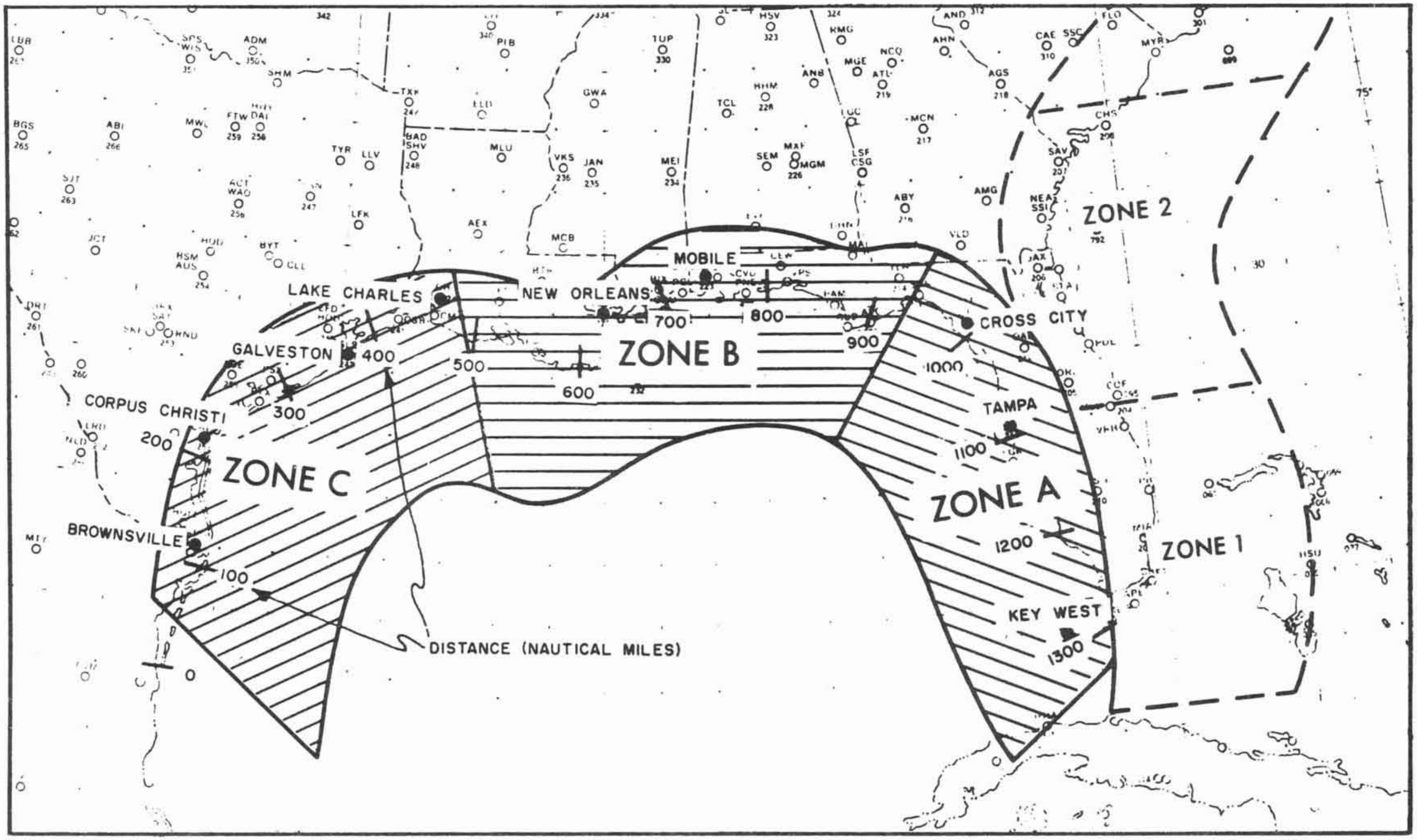


Figure 15.-- Gulf Coast Zones for Hurricane Frequency
50 Miles Inland and 150 Miles Offshore
(From NHRP Rept. no. 33)
Texas Water Development Board

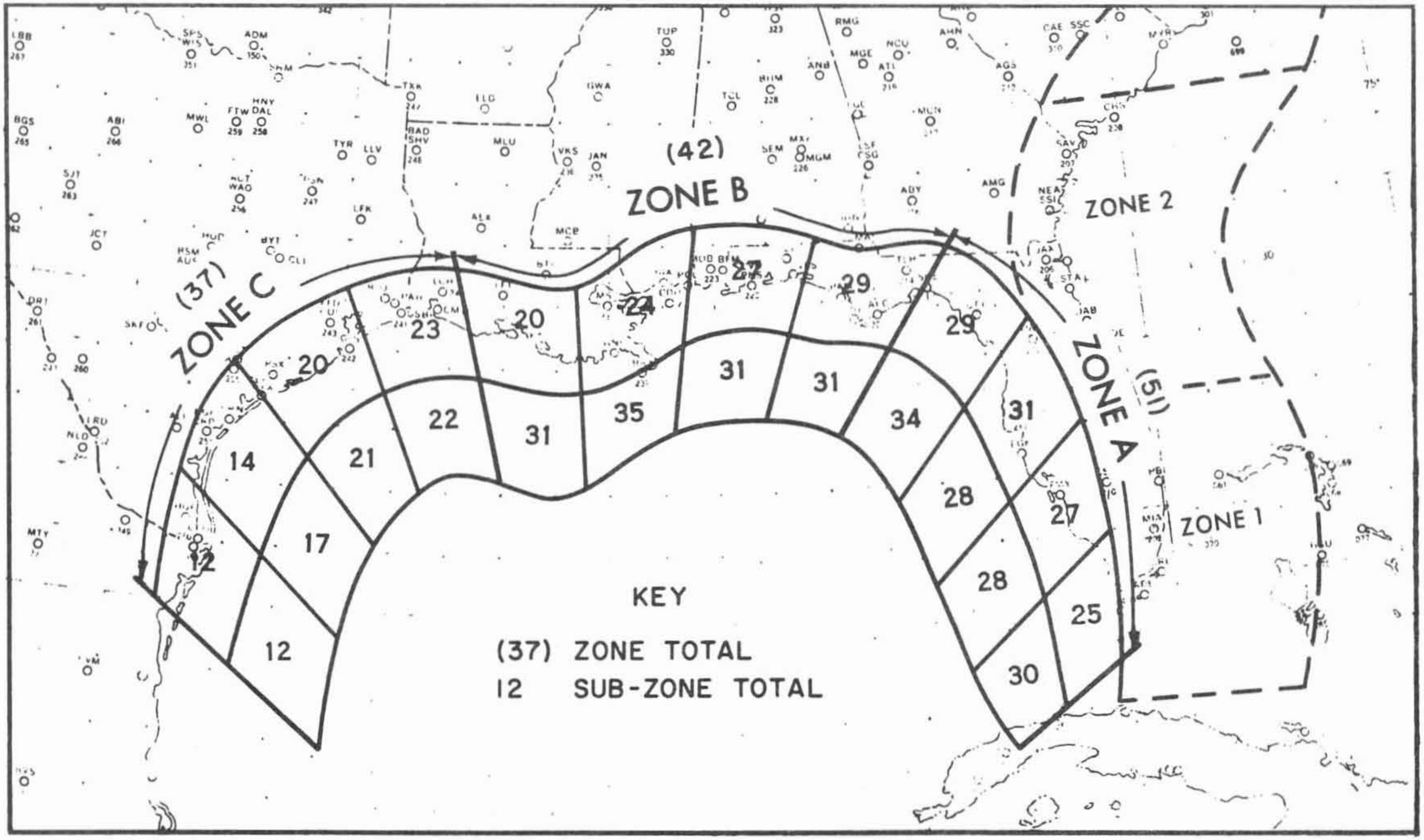


Figure 16.-- Gulf Coast Zone Subdivisions Showing Total Hurricane Occurrences 1900-1956
(From NHRP Rept. no. 33)
Texas Water Development Board

tropical storms which had reached hurricane intensity, either in the zone or previously, is shown also in Figure 16. These data are presented in order to give some indication of the hurricane distribution within zones. A hurricane passing through a zone or sub-zone need not necessarily severely affect the entire coast within the zone. The frequency of damaging effects at a specific coastal location depends on many factors including the CPI frequency, the variations of storm tracks (direction of approach), and the occurrence of maximum winds for various radii and forward speeds that are possible for a given CPI.

Direction of Approach

The azimuth distribution of paths followed by hurricanes of record is shown in Figure 17. No evidence of a systematic relationship between hurricane intensity and direction of movement could be found. All tropical storm path directions may therefore by used to judge azimuth characteristics of paths of severe storms in the zones. Most hurricanes pass through Zone C from the east and southeast.

Maximum Wind Speed 30 Feet Above Water (Isovel Patterns)

The maximum wind speed 30 feet above water for all small-radius (RS) hurricanes, which may affect Texas can be determined from Figure 18. The maximum wind speed 30 feet above water for other hurricanes which may affect Texas can be determined from Figures 19-23 as follows:

		Figures 19 through 23	
Forward Speed	Slow	Moderate	High
Mean Radius (RM)		F 19	F 20
Large Radius (RL)	F 21	F 22	F 23

The Standard Project Hurricane index wind fields (isovel patterns) were developed for the approximate center of each zone from SPH index parameters. Figures 19-23 are synthetically derived isovel charts for RM and RL hurricanes showing wind speed patterns for the Texas Gulf Coast. These charts were prepared for the CPI at the approximate middle of the zones, for forward speeds representative of zonal ranges of the moderate and high speeds of center translation, and for the RM and RL hurricanes. The SPH index isovel patterns were modeled after maximum hurricanes of record, such as the hurricanes of September 29, 1915; September 21, 1938; September 14, 1944; August 26, 1949; and June 27 1957. The isovel charts were constructed in the following steps: (a) computing, for the selected CPI and R, a profile of gradient wind speed for a stationary or slow-moving hurricane using the formula:

$$V_g = \left(\frac{1}{P} (p_n - p_o) \frac{R}{r} e^{\frac{-R}{r}} \right)^{1/2} - K$$

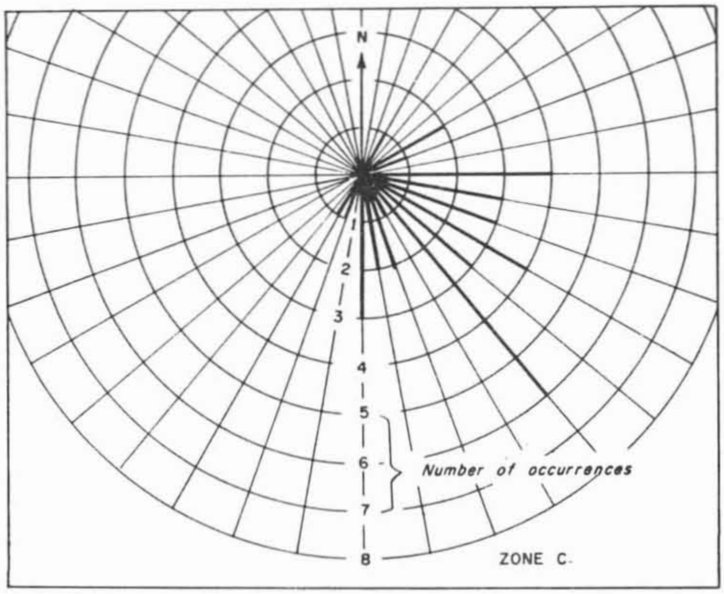


Figure 17.--Azimuth Distribution of Hurricane Paths in Zone C,
Texas Gulf Coast 1900-1956
(From NHRP Rept. no. 33)
Texas Water Development Board

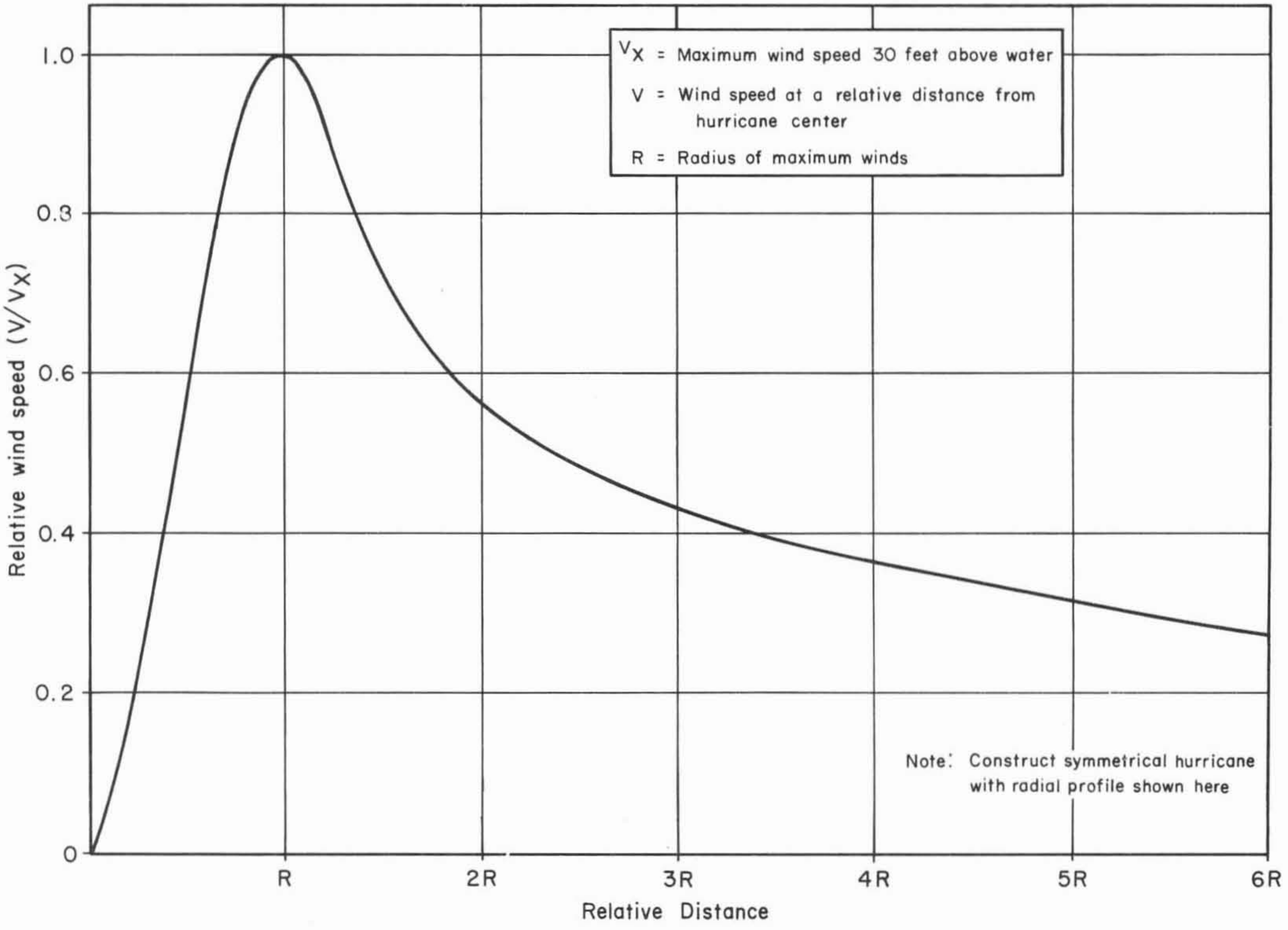


Figure 18.--Standard Project Hurricane Wind-Speed Profile 30 Feet Above Water, Small Radius (RS) Hurricanes, All Zones
(From NHRP Rept. no. 33)
Texas Water Development Board

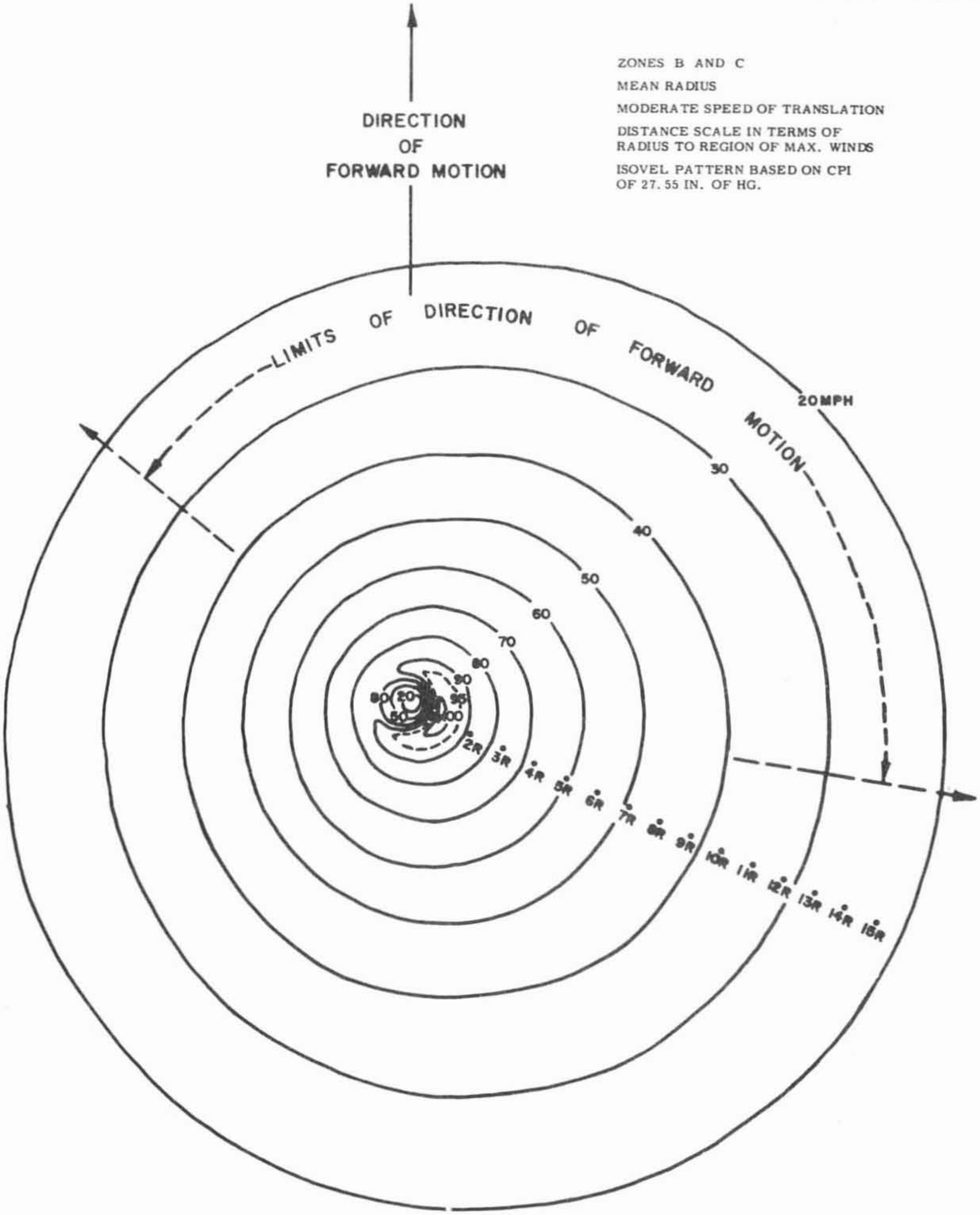
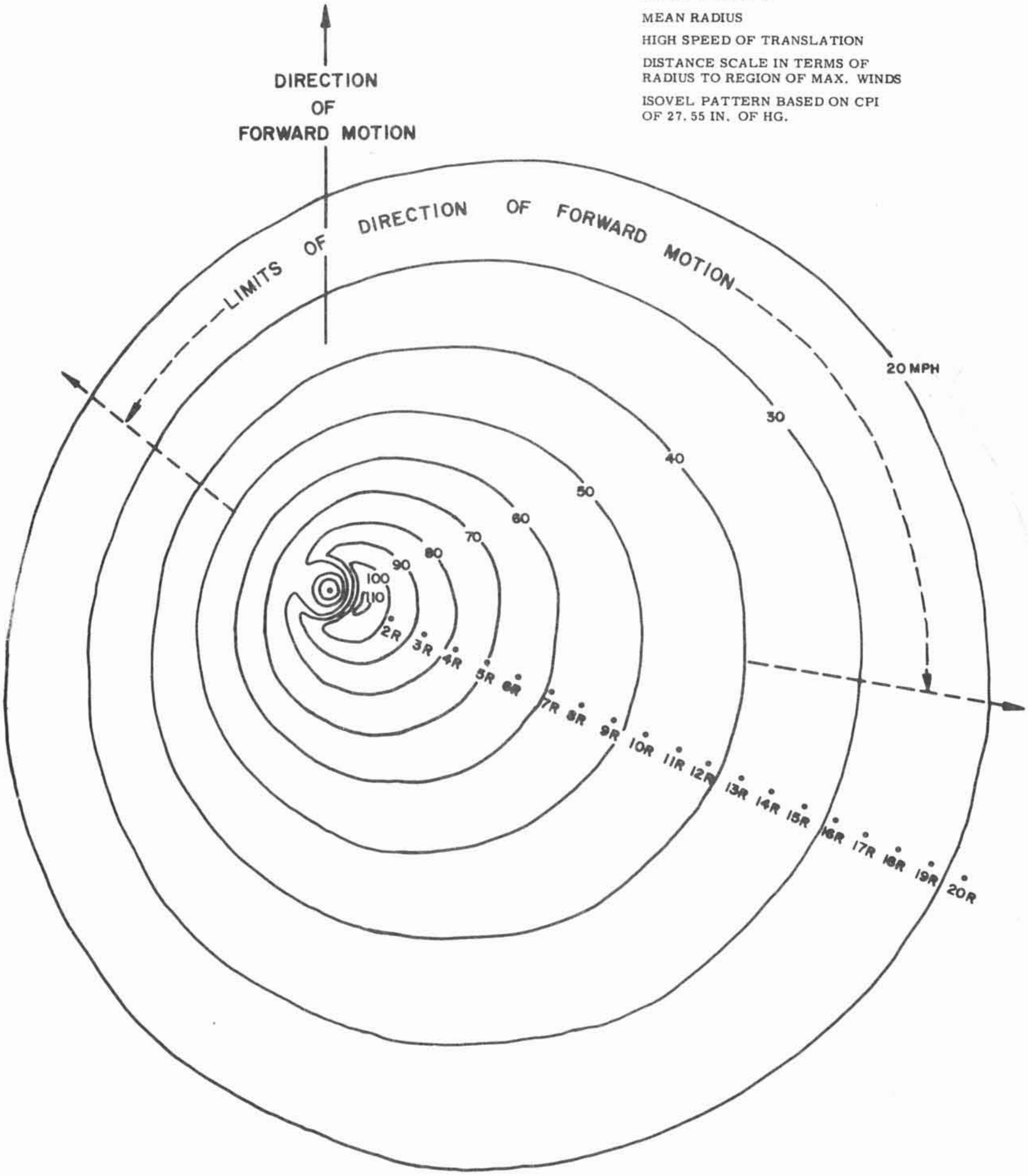


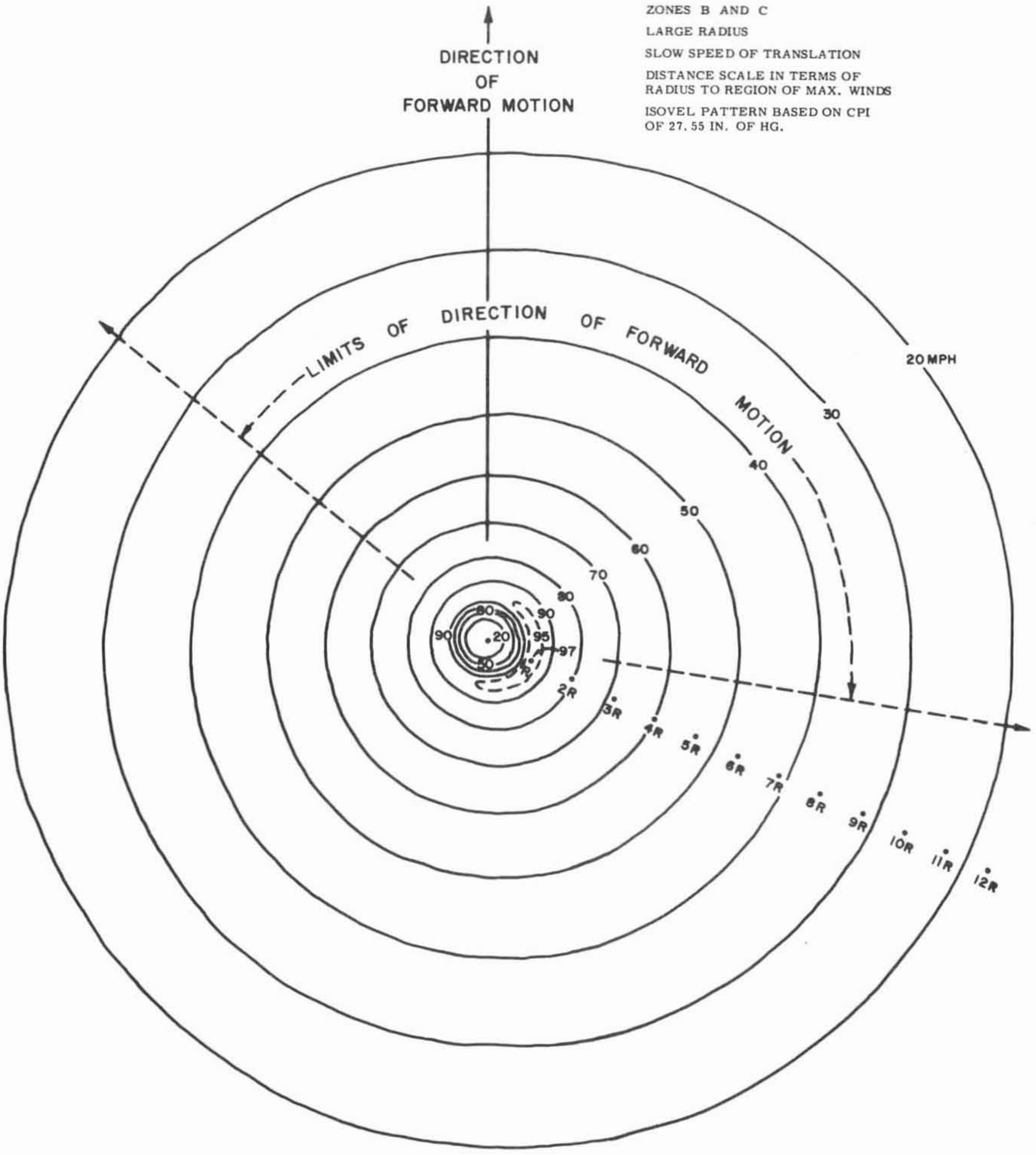
Figure 19.--Standard Project Hurricane Isovel Pattern 30 Feet Above Water
(From NHRP Rept. no. 33)
Texas Water Development Board



ZONES B AND C
MEAN RADIUS
HIGH SPEED OF TRANSLATION
DISTANCE SCALE IN TERMS OF RADIUS TO REGION OF MAX. WINDS
ISOVEL PATTERN BASED ON CPI OF 27.55 IN. OF HG.

Figure 20.--Standard Project Hurricane Isovel Pattern 30 Feet Above Water (From NHRP Rept. no. 33)

Texas Water Development Board



ZONES B AND C

LARGE RADIUS

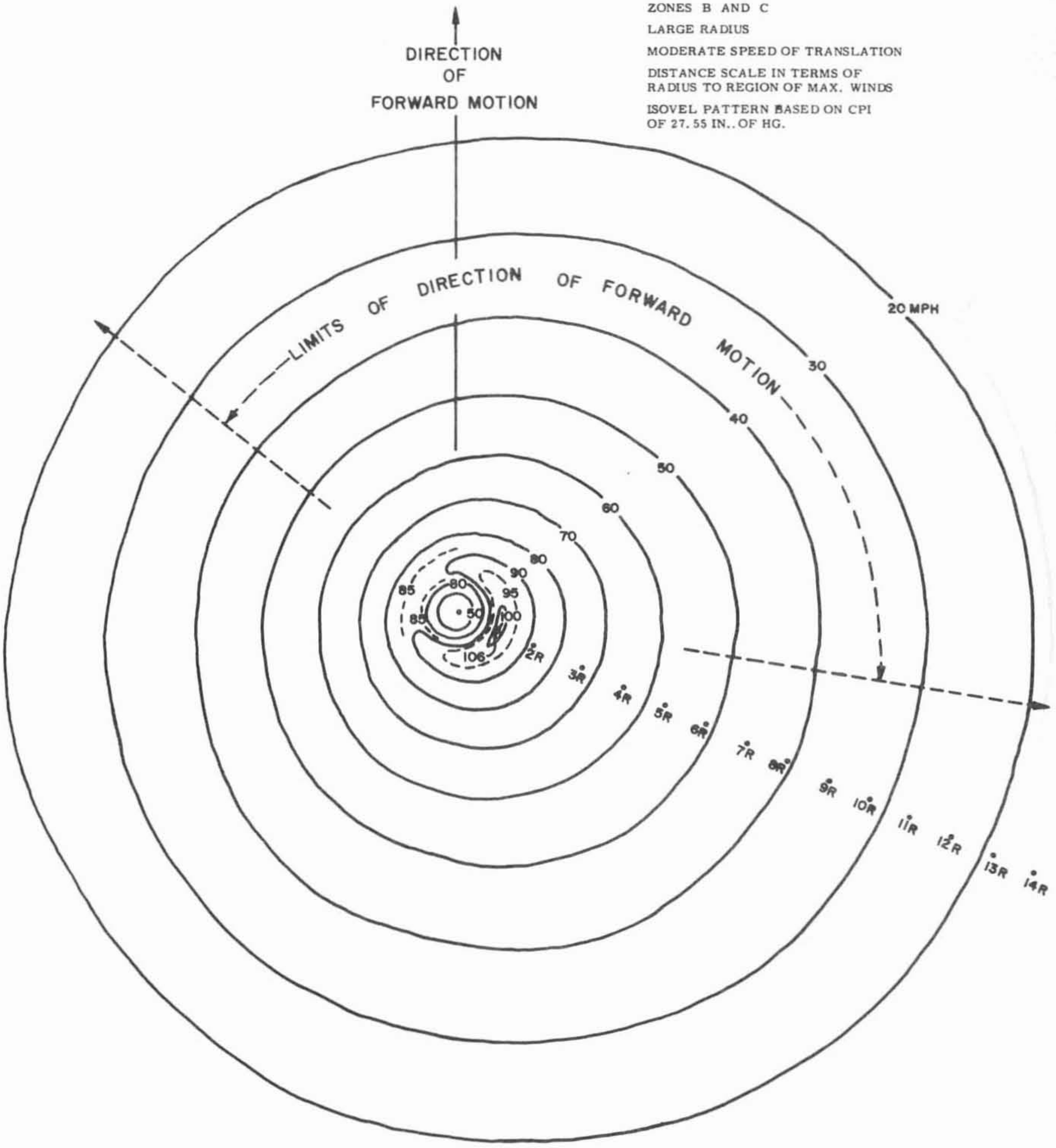
SLOW SPEED OF TRANSLATION

DISTANCE SCALE IN TERMS OF RADIUS TO REGION OF MAX. WINDS

ISOVEL PATTERN BASED ON CPI OF 27.55 IN. OF HG.

Figure 21.--Standard Project Hurricane Isovel Pattern 30 Feet Above Water (From NHRP Rept. no. 33)

Texas Water Development Board



ZONES B AND C
LARGE RADIUS
MODERATE SPEED OF TRANSLATION
DISTANCE SCALE IN TERMS OF
RADIUS TO REGION OF MAX. WINDS
ISOVEL PATTERN BASED ON CPI
OF 27.55 IN.. OF HG.

Figure 22.--Standard Project Hurricane Isovel Pattern 30 Feet Above Water
(From NHRP Rept. no. 33)
Texas Water Development Board

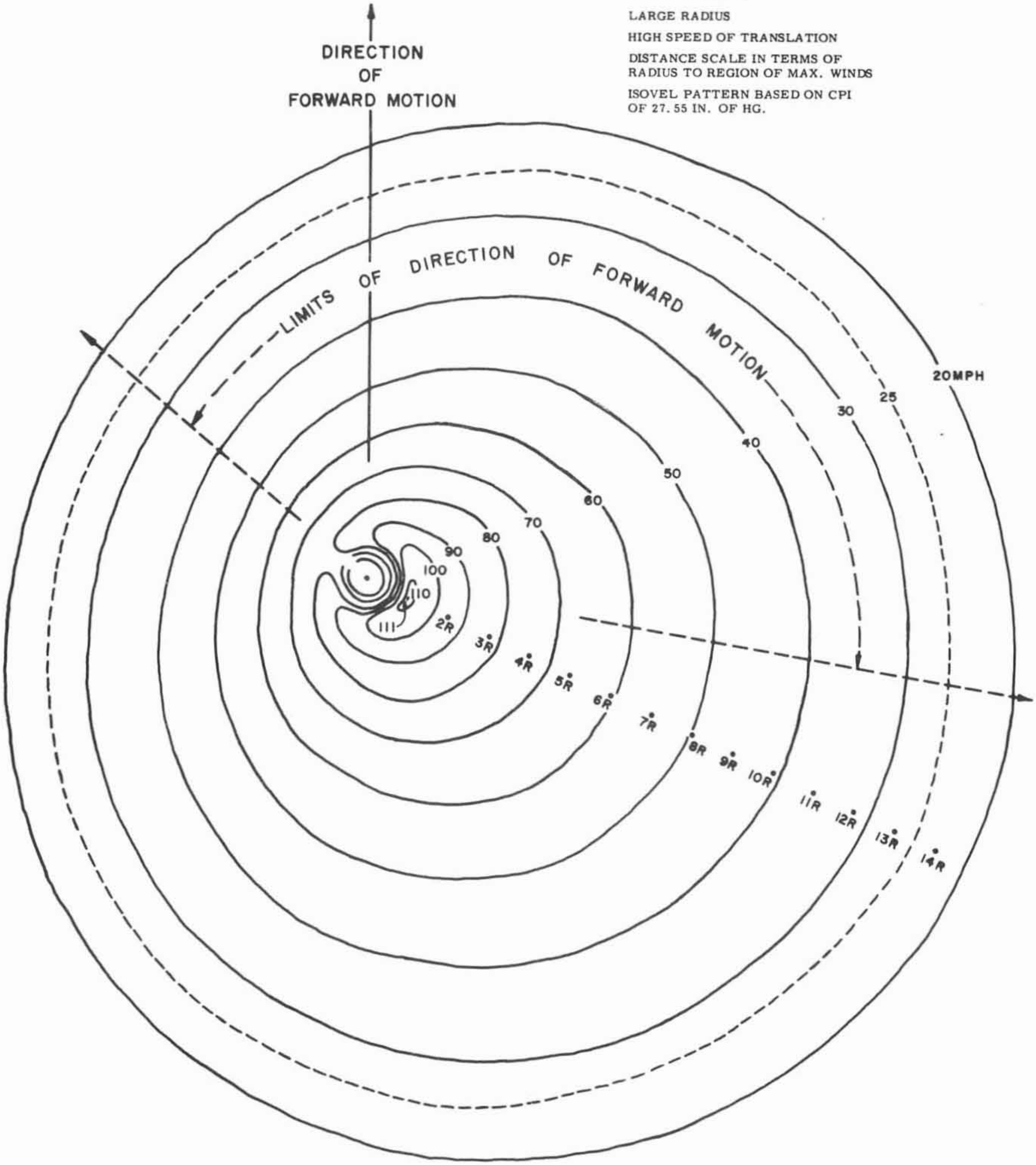


Figure 23.--Standard Project Hurricane Isovel Pattern 30 Feet Above Water (From NHRP Rept. no. 33)

Texas Water Development Board

where V_g is the gradient wind, P is the air density, p_n is the average asymptotic pressure (29.92), p_o is the CPI, R is the radius of maximum winds, r is any assigned radius, and K is a constant depending on latitude and r; (b) proportionately reducing the gradient wind-speed profile to a 30 feet above water wind speed profile by empirical factors; and (c) applying an adjustment to the 30 feet above water wind speed profile so as to show a pattern with a moderate degree of asymmetry which is in direct proportion to the rate of forward speed of the center. The asymmetry factor applied to the 30 feet above water wind speed profile was added to the wind speeds in the right sector of the hurricane and subtracted from the speeds in the left sector according to the formula

$$V = V_a + 0.5T \cos \alpha$$

where V is the 30 feet above water wind speed at any selected point, V_a the average 30 feet above water wind speed at a given radial distance from the center, T the forward speed of hurricane translation in miles per hour, and α the angle between the vectors showing the direction of forward motion of the storm and wind direction. The resulting isovel patterns for the center of each zone (Figures 19 through 23) were obtained by using values of CPI index and the forward speeds.

Summary of Considerations When Selecting the Standard Project Hurricane (SPH)

The need cannot be overstressed to become familiar with NHRP Report 33 before attempting to designate the Standard Project Hurricane for any specific locality.

The hypothetical Standard Project Hurricane for any location is to be selected largely on the basis of the Standard Project Hurricane (SPH) indices developed in NHRP Report 33, which include many parameters beyond the scope of this paper. To determine the SPH for a specific project area or location, the severest conditions should be adopted that are within the limits of the parameters of the SPH indices for that location. In order to determine meteorological conditions which will produce the severest surge, consideration should be given to such local characteristics as coastal configuration and ocean bottom contours as well as the SPH indices.

The following conditions should be considered in determining the Standard Project Hurricane criteria from the SPH indices:

(1) Direction of movement - The most critical path of direction of forward motion for the particular index isovel patterns can be determined on the basis of coastal configuration or inlet, within the span of directions shown to be common on the azimuth charts of past hurricane paths in the zone concerned (Figure 15). It may be necessary to evaluate several paths to determine the most critical path considering the variations in the isovel patterns, radius of maximum winds, areal size, and forward speed.

(2) Geographic reference points - In order to determine a series of isovel patterns, the wind field centers should first be located along the selected critical path at appropriate intervals (one-hour intervals will possibly prove satisfactory). The latitude or location of the isovel pattern center should be used to select the appropriate CPI and other parameters. The hurricane center

location is also important in obtaining the ratio required for adjusting the over-water isovel patterns, which are given for the middle of each zone in Figures 19-23, to the pattern appropriate for the desired location.

(3) Isovel pattern orientation - The orientation of the isovel pattern, with respect to the direction of forward motion, should be determined so that the fetch is directed most effectively for the area under consideration. The critical orientation, which will depend somewhat on local topography, will be within the limits of rotation as shown on SPH index isovel patterns (Figures 19-23).

(4) Forward speed - The most critical forward speed for the project site is to be selected within the span of forward speeds for that latitude or location.

(5) Radius of maximum winds - The radius of maximum winds can be selected depending upon the most critical radius of maximum winds for that particular location. The radius of maximum winds will largely determine the length of fetch of high winds, depending on the hurricane track and coastal configuration.

(6) Adjustment for land effects - As the hurricane approaches land, the isovel pattern near the shore should be adjusted for the greater surface friction, and, if the center moves over land, the entire storm should be adjusted for filling.

EXISTING AND AUTHORIZED HURRICANE TIDAL PROTECTION PROJECTS

This section deals primarily with the major projects existing and authorized. Each project will be described in general terms in subsequent paragraphs. All of these projects are located along the upper Texas coast and southward as far as Freeport, none are between Freeport and Brownsville. This is not because severe hurricanes strike only from Freeport northward. Such is not the case as the record quickly discloses. Economic feasibility, including the desire of local interest to participate in project costs, cost-benefit ratios are more likely to be behind the reason for development of hurricane tidal protection projects along the more highly industrialized upper Texas coast. As the Coastal Bend and lower Texas coast becomes more and more industrialized or thickly populated, economic constraints will lessen and more favorable cost-benefit ratios will emerge.

Port Arthur and Vicinity Project

The Port Arthur and Vicinity Hurricane Flood Protection Project was authorized by the Flood Control Act of October 23, 1962. The authorized plan for improvement provides for enlarging, strengthening, and extending existing levees and floodwalls and for constructing additional earth levees connecting the north and south ends to high ground. The plan includes: about 29 miles of new and enlarged earth levees 12 to 16 feet high; about 5 miles of concrete sea wall and 2 miles of concrete and steel sheetpile floodwalls having a top elevation of 16 feet above mean sea level; drainage structures; pumping plants; and closure structures at openings left in the levees.

Regarding the status of the Port Arthur and Vicinity Project on September 1, 1966, one contract was in progress providing for revetted embankment work on the Sabine-Neches Canal. Another contract had been completed which provided for enlargement of a canal preparatory to blocking off Taylors Bayou to reduce the contribution of floodwaters from that source. Some difficulty has been experienced in obtaining rights-of-way clearance. The remainder of the project was in the design stage. Sufficient funds are available to proceed with the project planning and construction programmed for Federal fiscal year 1967.

Texas City and Vicinity

The Texas City Hurricane Flood Protection Project was authorized by the Flood Control Act of July 3, 1958. A survey to determine the advisability of extending the authorized hurricane flood protection system for Texas City to provide protection to the western portion of La Marque and Hitchcock was authorized under Public Laws 86-645 and 87-874. The project and proposed extension lie along the western shore of the southern extremity of Galveston Bay. The authorized plan for improvement includes construction of:

(1) a little more than a mile of concrete wall;

(2) about 16 miles of earthen levees from 15 to 23 feet high;

(3) related drainage and closure structures;

(4) railroad and highway ramps;

(5) tide control and navigation structures; and,

(6) pumping plants.

The authorized project was scheduled for completion in 1966. The survey for extension of the Texas City project to include La Marque and Hitchcock was scheduled for completion in 1965.

On September 1, 1966, construction was in progress and the authorized project was about 47 percent complete. About 75 percent of the funds needed for the project have been made available. Regarding the survey for extension of the authorized project to include La Marque and Hitchcock, on September 1, 1966, the survey was complete and was en route to Washington, through the Texas Governor's office. In January 1967, it was in Washington and it is expected to be brought up for consideration during the 1967 session of Congress.

Galveston Harbor and Channel Improvement Project

This project provides for construction of 13 groins to protect the Galveston Sea Wall and for a three-mile extension of the existing sea wall. The entire project (which includes considerable dredging, channel improvement, etc., apart entirely from hurricane protection) was officially reported to be about 79 percent complete on June 30, 1965. By September 1, 1966, the three-mile extension to the sea wall had been completed and a proposal for methods of rehabilitating the 13 deteriorated groins protecting the sea wall was nearly complete. The proposal is expected to be completed by mid-February 1967 and construction funds are expected to be available by October 1967.

The Galveston Sea Wall

The Galveston Sea Wall became what it is today, a highly sophisticated hurricane protection network, in the following chronological sequence of events:

(1) Within four years following the disastrous hurricane of September 8, 1900, the citizens of Galveston erected a barrier to the sea that saved the city from futher destruction by another hurricane which occurred 15 years later. About one year after the 1900 storm, the City and County of Galveston appointed a Board of Engineers to investigate the means for protecting the city. The board was requested to report on the most efficient way to protect the city by elevating, filling, and grading to provide sufficient elevation for drainage and sewage, and by erecting a breakwater or sea wall to prevent hurricane tidal overflow and damage to the city.

(2) In 1913, a report prepared at the request of Congress recommended extension of the sea wall from Sixth Street to Fort San Jacinto--a total length of 10,300 feet. Local interests were to construct 3,300 feet of this extension and 7,000 feet were to be constructed by the United States Government.

(3) In 1916, Congress authorized construction of the recommended extension eastward from Sixth Street to Fort San Jacinto. Work began in 1918, but was delayed by wartime labor shortages and lack of materials. Only about half the work was completed when the hurricane of September 13-14, 1919, occurred. The extension of the wall east to Fort San Jacinto was not completed until 1921.

(4) Congress authorized a further extension to the sea wall in 1922. This 2,860-feet-long extension was constructed between May 1923 and January 1926.

(5) In 1926, Galveston County constructed a west extension of the sea wall from Fifty-third Street to Sixty-first Street. This section, 2,800 feet long, was completed in June 1927.

(6) Completion of the 1927 extension brought the Galveston Sea Wall to its condition in the year 1961. Total length of the sea wall constructed was 38,490 feet, or 7.29 miles, of which 23,755 feet were constructed by Galveston County and 14,735 feet were constructed by the U.S. Army Corps of Engineers. Effective length of the sea wall along the Gulf front was 6.64 miles. The cost of the sea wall totals $6,130,000. The cost per foot varies from $90 a foot for the first construction in 1902 to $200 per foot for the last construction in 1927.

(7) The Beach Erosion Board of the Army Corps of Engineers made a survey in 1934 and concluded that additional protection for the sea wall was needed from Twelfth Street to Sixty-first Street. After authorization by Congress in 1936, a system of 13 groins, each 500 feet long and 1,500 feet apart, was constructed from 1936 to 1939.

(8) In 1950, Congress authorized construction of a 3 mile extension of the Galveston Sea Wall similar in design to the existing wall. This extension, which had been nearing completion when Hurricane Carla struck Galveston in 1961, finally was finished in 1962.

Freeport and Vicinity

The Freeport and Vicinity project was authorized by the Flood Control Act of October 1962. It provides for rehabilitating, enlarging, and extending the existing earth levees, and for constructing an additional earth levee connecting the north end of the protective system to high ground. The plan includes:

(1) about 40 miles of earthen levees improved or rehabilitated to provide protection against the design surge and excessive design wave overtopping;

(2) a little less than five miles of new levee; and

(3) drainage structures, pumping plants, and ramps over the levees for roads and railroads.

On September 1, 1966, personnel at the Galveston office of the U.S. Army Corps of Engineers reported that the current phase of construction on the project was about 90 percent complete. This phase involves one contract which provides for tying about two miles of new levees to existing levees and to higher ground inland. Funds are available for initiation of construction planned for this fiscal year.

Vicinity of Corpus Christi

There are no current federally authorized hurricane flood protection projects in the Corpus Christi Bay area at this time. The U.S. Army Corps of Engineers conducted a hearing on hurricane flood protection for the area on November 7, 1961, at Corpus Christi, under authority of Public Law 71, 84th Congress. Recommendations included rehabilitation and extension of dunes on the barrier islands, construction of additional sea walls, a breakwater, and groins to afford protection for Corpus Christi Beach and low-lying areas.

The Corpus Christi Bay area recommended project was dormant on September 1, 1966. This project will be considered in the five study areas to be subsequently described.

Corpus Christi to Brownsville

There are no federally authorized or recommended hurricane protection projects for the area between Corpus Christi and Brownsville, but this area will be considered in the following descriptions of five study areas.

FIVE STUDY AREAS ALONG THE TEXAS COAST

Public Laws 86-645 and 87-874 authorized the U.S. Army Corps of Engineers to conduct studies of the hurricane protection needs of the entire Texas Gulf Coast from the Texas-Louisiana border to Mexico. The studies will include planning a system of levees along the barrier islands and secondary flood protection systems to protect developed areas along inshore bays behind the coastal systems. The authorized studies were in progress on September 1, 1966. These studies are in the "Preliminary Investigation" stage. The Corps of Engineers is now preparing figures for determination of the feasibility of these Texas coast hurricane protection studies. The studies are expected to be completed in fiscal year 1973.

The objective of these studies is to determine the necessity for and the feasibility of providing protection from hurricane flooding to low-lying areas along the Texas Gulf Coast. The long-range problems of the entire coastal region subject to tidal flooding will be investigated. The Texas coast will be studied in five major units centered generally around the five principal inland bay areas. In reaches where the coastal protection systems are not feasible or justified, local protection projects are to be considered. Descriptions of the five study areas follow.

(1) The Sabine Lake Study Area extends from near Cameron, Louisiana, to High Island, Texas.

(2) The Galveston Bay Study Area extends from High Island to Freeport.

(3) The Matagorda Bay Study Area extends from Freeport to the vicinity of San Antonio Bay.

(4) The Corpus Christi Bay Study Area includes Corpus Christi and extends from the vicinity of San Antonio Bay to the vicinity of Baffin Bay.

(5) The Laguna Madre Study Area extends from the vicinity of Baffin Bay to the Rio Grande.

Public hearings were held by the Corps of Engineers to determine local desires on plans for hurricane protection for the Texas coast at the following locations on the dates shown:

Freeport	May 29, 1956
Port Arthur	March 21, 1958
Port Lavaca	December 13, 1960
Corpus Christi	November 7, 1961
Palacios	August 1, 1962
Baytown	March 6, 1962
Kemah	March 13, 1962
Galveston	August 15, 1962

The Galveston Bay Study Area

The Galveston Bay Study Area is the only one of the five study areas now being concentrated on. This area extending from High Island to Freeport is in the "Preliminary Investigation" stage. Funds are available for study during Federal fiscal year 1967, and the study will progress as rapidly as annual appropriations from Congress will permit.

CONCLUSIONS

There is no meterological reason why any of the four major hurricanes which affected Texas during the period 1900-1961 could not have struck the Texas coast at any point between the Sabine River and the Rio Grande. Oceanographic reasons such as configuration of the coastline or bays, or Gulf bottom profile and the location of the continental shelf, may be reasons enough for high water caused by these hurricanes to have been lower, or higher, at some points along the Texas coast if any had actually struck the coast at different points.

Wind and high water or flood damage occurs in the immediate coastal areas when hurricanes strike the coast, but flood damage due to heavy rains caused by the residue of hurricanes sometimes is felt hundreds of miles inland. Remains of hurricanes can transport great quantities of water vapor inland to areas where orographic rises force the water vapor upward to cool, condense, and fall to the ground as hydrometeors. Some of the heaviest rainfalls in Texas history are attributable to this process.

Land subsidence has been occurring at an accelerated rate in some areas along the Texas coast in recent years, due to withdrawals of fluids such as ground water and oil. As much as four to five feet of land subsidence was measured at the end of the period 1905-1964 at some points along the Houston Ship Channel. Loss of freeboard along any hurricane protection levees constructed in subsiding areas will be proportionate to the subsidence experienced after levee construction is completed. Faulting may also take place in areas of greatest land subsidence.

The U.S. Army Corps of Engineers has undertaken the task of studying the entire Texas Gulf Coast for hurricane protection measures to include secondary protection where needed along inland bays and estuaries. The Texas Gulf Coast is being studied in five adjacent areas, each of which includes one of the five major bays. Standard Project Hurricanes are being synthesized for each project by enveloping like parameters of hurricanes known to have occurred in each area and by routing Carla 1961 across points along the Texas Gulf Coast where construction of hurricane protection works is planned. Hurricane protection levees constructed on this basis will provide protection only against repetition of history--not against a maximum possible hurricane, the intensity of which could not be found described in the literature.

RECOMMENDATIONS

1. Before the meterologic, oceanographic, and physiographic hurricane parameters can be correlated quantitatively with the height of water caused by hurricanes, it appears necessary to know not only the height of the water where hurricanes make landfall but also the height of the water all along the Texas coast, simultaneously, as hurricanes approach. This will require that the network of mean-sea-level-datum tide gages along the Texas coast be increased and extended to include at least one gage every 50 miles along the coast and one gage at every estuarial entrance and gulfward exit to each of the major inland bays.

2. The severest hurricane of the twentieth century to strike the Texas Gulf Coast was probably Carla 1961. It is recommended that Carla in her most violent stage be routed through all major inland bays in Texas and at approximate mid-points between these bays to determine the height of levees which would

have been required in the bays and at selected points if protection against Carla had been provided. The necessary degree of protection determined in this manner could provide a basis from which a logical hurricane protection plan for the Texas Gulf Coast could be formulated. Preliminary computations show that Carla 1961, in her severest context could have caused high water over 22 feet above mean sea level at the head of Galveston Bay. Water 22 feet high actually was caused by Carla at the head of Matagorda Bay. Gulf-bottom profile, narrowness of Laguna Madre, and other geophysical parameters probably would prevent a Carla from causing water to stand much higher than about 15 feet above mean sea level in the Port Isable-Brownsville area.

3. Hurricane protection levees along the entire Texas Gulf Coast cannot be economically justified by present developments. It is recommended, however, that a preliminary master plan for hurricane protection be prepared, giving full consideration to the findings of recommendation 2. Segments of the plan which are or may become economically justified can be designed generally in accordance with the preliminary master plan.

4. Land subsidence is a proved fact in Texas coastal areas where there have been heavy withdrawals of fluids from underground. Any hurricane levee construction proposed or undertaken should take into account future land subsidence resulting from underground fluid withdrawals. Even if withdrawals of underground fluids should be completely halted, continued land subsidence would occur until the hydraulic gradient was reduced to zero between the underground sands and clays. For this reason, any levees constructed in areas of known or suspected land subsidence should be built to facilitate compensatory heightening as necessitated by any land subsidence experienced. Periodic, perhaps yearly, elevation checks at points along the levees need to be make to ascertain changes in elevation and further subsidence. Such a requirement could be written into the operation and maintenance agreement negotiated with the local interests on the project.

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