U.S. DEPARTMENT OF COMMERCE / Environmental Science Services Administration

ESSA Technical Report

WEATHER BUREAU WB-6

Climatology of Atlantic Tropical Storms and Hurricanes

SILVER SPRING, MARYLAND
May 1968

ESSA Technical Reports
Weather Bureau Series

ESSA Technical Reports will, in general discuss the results of a single research project or completed phase of research, or may present the results of scientific or engineering analysis in a single field of specialization. The Weather Bureau Series is part of the technical reports literature and can be cited in the literature.

The Weather Bureau series of ESSA Technical Reports WB-1 through WB-3 are available through the Clearinghouse for Federal Scientific and Technical Information, U.S. Department of Commerce, Sills Building, Port Royal Road, Springfield, Virginia 22151. Price $3.00 paper copy, $0.65 microfiche. Issues beginning with WB-4 are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D. C., 20402. Prices vary.

WB-1 Monthly Mean 100-, 50-, 30-, and 10-Millibar Charts January 1964 through December 1965 of the IQSY Period. Staff, Upper Air Branch, National Meteorological Center. February 1967.

WB-2 Weekly Synoptic Analyses, 5-, 2-, and 0.4-mb. Surfaces for 1964 (based on observations of the Meteorological Rocket Network during the IQSY). Staff, Upper Air Branch, National Meteorological Center. April 1967.

WB-3 Weekly Synoptic Analyses, 5-, 2-, and 0.4-mb. Surfaces for 1965 (based on observations of the Meteorological Rocket Network during the IQSY). Staff, Upper Air Branch, National Meteorological Center. August 1967.

WB-4 The March-May 1965 Floods in the Upper Mississippi, Missouri, and Red River of the North Basins. J. L. H. Paulhus and E. R. Nelson, Office of Hydrology. August 1967. Price $0.60.

WB-5 Climatological Probabilities of Precipitation for the Conterminous United States. Donald L. Jorgensen, Techniques Development Laboratory. December 1967. Price $0.40.

U.S. DEPARTMENT OF COMMERCE
C. R. Smith, Secretary
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
Robert M. White, Administrator
WEATHER BUREAU
George P. Cressman, Director

ESSA TECHNICAL REPORT WB-6

Climatology of Atlantic Tropical Storms and Hurricanes

M.A. ALAKA

TECHNIQUES DEVELOPMENT LABORATORY
SILVER SPRING, MARYLAND
May 1968

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 20 cents

Contents

List of Illustrations

List of Tables

Climatology of Atlantic Tropical Storms and Hurricanes[1]

M. A. ALAKA

Techniques Development Laboratory
Weather Bureau, ESSA

1. ABSTRACT

THE climatology of Atlantic tropical storms and hurricanes is derived from data from 1871 to 1963. There are sections on hurricane formation, frequency, motion, and structure. Under these headings, the thermodynamics and mechanics of hurricane formation, the upper and lower level wind flow, seasonal and secular variations in storm frequency, storm movement, storms affecting the United States, and the wind, pressure, and rainfall patterns associated with these storms, are discussed and illustrated.

2. CLASSIFICATION OF DISTURBANCES IN THE TROPICS

Corresponding to the typhoons of the western Pacific Ocean, the most severe tropical storms of the Atlantic Ocean[2] are the hurricanes. These violent storms originate from weaker circulations and pass through several increasingly intense phases before they ultimately attain hurricane status. To make this report meaningful, the following terminology most commonly used in the Atlantic area is used, but unfortunately not universally adopted.

The weakest stage is the *tropical disturbance* in which rotary circulation is slight or absent at the surface, but possibly better developed aloft. There are no closed surface isobars and no strong winds. Disturbances of this type are common in the tropics. Next in intensity is the *tropical depression* which is associated with one or more closed surface isobars and with sustained winds equal to or less than Beaufort force 7 (32-28 m.p.h.). When the winds are of Beaufort force 7-11 (39-72 m.p.h.) are considered a *tropical storm.*[3] Finally, the strongest stage, with winds of Beaufort force 12 ($\geq$73 m.p.h.), is the *hurricane.*

3. SOURCES OF INFORMATION

Although the first recorded account of Atlantic hurricanes dates back to the time of Cobumbus, very little has been written about storm occurrences in the centuries immediately following, to provide a basis for meaningful climatological studies of these storms. According to Tannehill [32][4], who summarized known records of early West Indian hurricanes, only 16 hurricanes were listed by Poëy as having occurred in the 16th Century. Of these, two were probably not authentic tropical cyclones [12]. Judging from present-day frequency, the number of storms was more nearly 800.

Toward the last quarter of the 19th century, records of tropical cyclone occurrences became sufficiently complete so that a systematic climatology of hurricanes began to be established. The records have been summarized, among others, by Mitchell [19], Colón [2], and Dunn [8]. One of the most complete summaries for the period 1886-1958, published as Technical Paper No. 36, was prepared in the Office of Climatology of the U.S. Weather Bureau by Cry, Haggard, and White [6] who scrutinized and combined available records including earlier works by Garriot [11], Fassig [10], Cline [1], Mitchell [19, 20], and Tannehill [33]. Technical Paper No. 36 was recently brought up-to-date by Cry [4].

The above works, in addition to many others to which reference is made in the text, represent the sources on which the material presented in this report is based.

4. HURRICANE FORMATION

Birthplace of Atlantic hurricanes

Gradually, with increased traffic over the tropical Atlantic and, more recently, as a result of systematic air reconnaissance and the advent of meteorological satellites, the number of undetected tropical storms in the Atlantic has become vanishingly small and the positioning of these storms has become more and more accurate. It

---

[1] Manuscript written in June 1965.

[2] For the purpose of this study the Atlantic Ocean is considered to include the Caribbean Sea and the Gulf of Mexico.

[3] Frequently the terms "tropical storms" and "tropical cyclones" have been used interchangeably in the literature. For the purpose of this report the term "tropical cyclones" is used to denote tropical disturbances of all intensities while "tropical storms" comprise only those with winds between 39 and 72 m.p.h.

[4] Numbers in brackets [32] refer to references given at end of this report.

is a fact, nevertheless, that long-period records, on which any climatological studies can be based, perforce suffer from a lack of homogeneity and deteriorating reliability as we go backward in time.

But aside from the uneven quality of the data, the exact locality where a hurricane originated is not always easy to determine. As mentioned earlier, hurricanes develop in preexisting disturbances, waves, or shearlines. Sometimes the intensification is rapid; at other times it is slow. It is not uncommon that an easterly wave travels several thousand miles before it eventually develops into a warm-core vortex of hurricane intensity. Dunn and Miller [9] ask: "Where would it be said that the hurricane formed? When the initial disturbance began to intensify, when the tropical storm reached hurricane intensity, or perhaps at some other point in its life history?"

The literature contains many conflicting statements about the birthplace of even such important and recent storms as hurricane Connie of 1955. Namias and Dunn [25] contend that this storm, though first reported on August 4 at about 16.6°N. and 48.0°W., actually developed earlier off North Africa. Similarly the birthplace of the September 1938 storm has been variously located by different authors at longitudes 68°W., 50°W., 37°W., and 50°W. [13].

Colón [2] used the beginning of published tracks as an indication of storm formation. He used all published tracks from 1887 to 1950. Colón pointed out that the beginning of the track was not necessarily the point of formation, since the initial disturbance usually existed for some time prior to intensification. Moreover, in the earlier years of the record, disturbances of hurricane intensity, east of the Lesser Antilles, could well remain undetected for several days. Colón's results are given in figure 1 which shows the total number of tropical storms with tracks starting within each 5° square during the period 1887-1950.

Dunn [8] devised a different procedure to determine the place of formation of Atlantic hurricanes. He plotted the points at which each storm reached hurricane intensity, using only those storms during the period 1901-1955 for which he was reasonably confident that this point could be established accurately. The result of this procedure, extended to include the years 1956-1963, is shown in figure 2 which is discussed in terms of the following climatological factors relevant to hurricane formation.

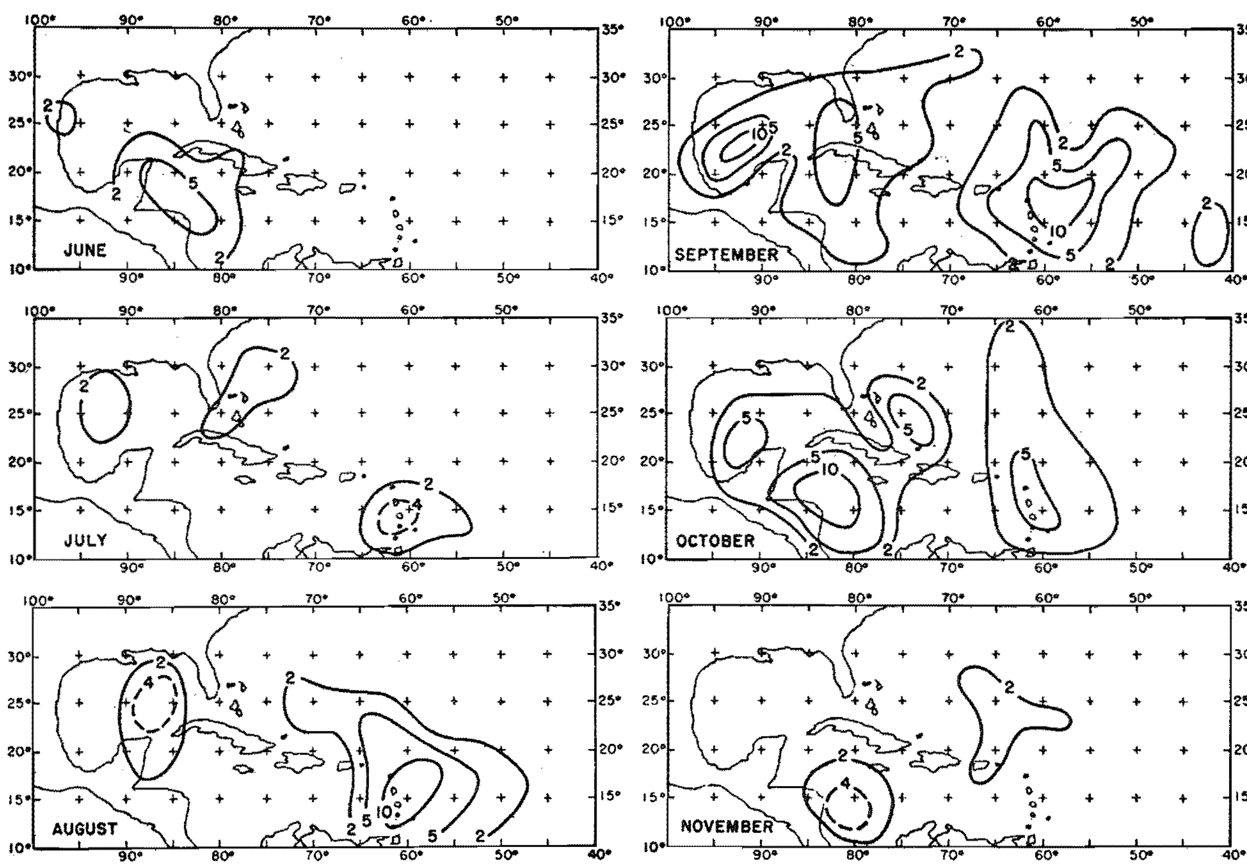

FIGURE 1.—Isopleths of total number of Atlantic tropical storms with tracks starting within each 5° square, during the period 1887-1950. After Colón [2].

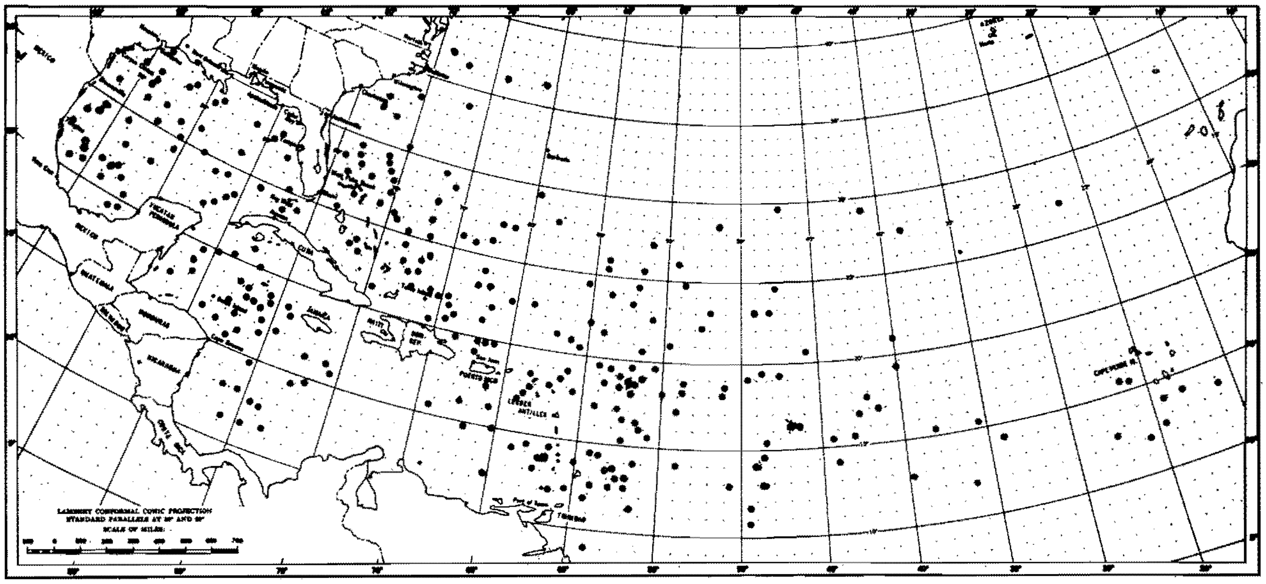

FIGURE 2.—Points at which Atlantic tropical storms reached hurricane intensity during the period 1901-1963.

Availability of latent energy

The formation of hurricanes cannot be explained directly in terms of a simple buoyant convective process. Indeed it has been established that the horizontal scale of circulations produced by thermal buoyancy is different from the observed scale of tropical cyclones [36]. Nevertheless the availability of latent energy plays a fundamental role in hurricane formation since it indubitably constitutes the principal energy source of these storms. Thus, land areas are not only immediately excluded as likely sites for hurricane development, but are indeed known to be effective graveyards for these storms.

Nor do the tropical oceans always endow the atmosphere above them with large quantities of latent energy available for release. When air is lifted beyond its condensation level, latent heat is released so that the potential temperature is increased while the equivalent potential temperature remains constant. If the resulting temperature of the rising air particle is higher than that of the surrounding air, it is accelerated upward by its buoyancy. If we neglect friction, we may write the expression for this acceleration as:

$$\frac{dw}{dt} = g\,\frac{T' - T}{T} \qquad (1)$$

where w denotes the upward motion, T' the temperature of the rising air and T the temperature of the ambient atmosphere. Equation (1), integrated over the path of the rising air particle from sea- level to the top of the atmosphere, gives the total latent energy (E_l) which may be converted into the kinetic energy of the rising particle. Thus

$$E_l = \tfrac{1}{2}w^2 = g\int_0^z \frac{T' - T}{T}\,dz = -R\int_{p_0}^{p} (T' - T)\frac{dp}{p} \qquad (2)$$

Palmén [24] has found a remarkable variation, both seasonal and areal, in the availability of latent energy over the Atlantic. Figure 3 shows the remarkable variation at Swan Island (17°N., 84°W.) in the difference in temperature between a parcel of ascending air and the ambient air at various isobaric levels. Assuming that the surface air has the same temperature as the ocean and a relative humidity of 85 percent, Palmén considered as a latent instability index the difference between the mean 300 mb. temperature and the temperature of an air parcel lifted adiabatically to its condensation level and then pseudoadiabatically to 300 mb. Palmén's results are shown in figure 4.

Figure 4a, for February, shows only a very weak instability over the West Indies and surrounding seas. Figure 4b, for September, shows a large area where the rising air particle at 300 mb. has a temperature in excess of the surrounding atmosphere. The figures may explain why Atlantic hurricanes are exceedingly rare during the cold season. Figure 4b which shows the latent instability decreasing eastward may also explain the lower tendency for hurricanes to form in the eastern Atlantic.

The above consideration led Palmén to suggest that hurricanes can form only in regions where the

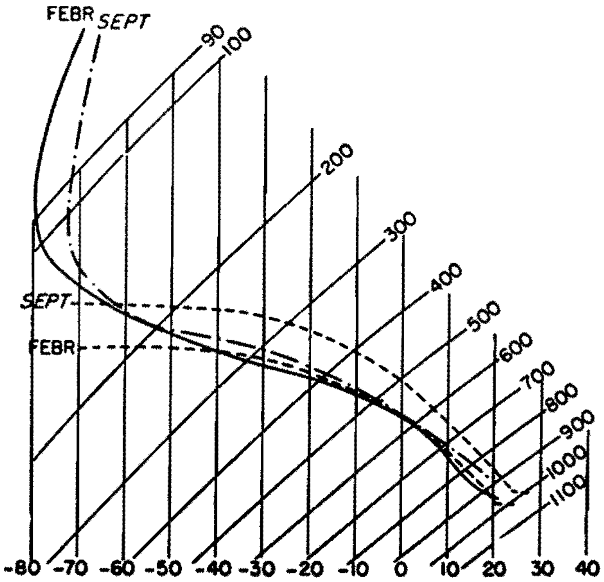

FIGURE 3.—Mean tephigram for September and February at Swan Island (17°N., 80°W.) showing the difference between an ascending air mass and the ambient air at different isobaric levels.

mean surface water temperature is above 26°-27°C. Figure 5 delineates the area in February and September where the water temperature in the North Atlantic exceeds 27°C. Comparison of the size of this area during these two months again explains why winter hurricanes are unlikely in the Atlantic. In February, 27°C water is confined to an area within 10°N. of the equator. In September, the northern edge of the 27°C. water ranges from about 15°N. in the eastern Atlantic to about 34°N. in the western Atlantic. This boundary runs almost north-south in mid-Atlantic, and separates the western North Atlantic, which is more susceptible to hurricane development, from the eastern North Atlantic—as is clearly depicted by figures 1 and 2.

Figure 6, adapted from an earlier figure published by Palmén [24] shows that water temperatures in the warmest season are appreciably lower south than north of the equator. This may explain why no storms of hurricane intensity have been known to occur in the South Atlantic.

Vorticity due to earth's rotation

The change of relative vorticity (ζ) along an air trajectory is given with sufficient approximation by the following simplified form of the vorticity equation:

$$\frac{d\zeta}{dt} = -(\zeta + 2\,\omega \sin\varphi)\, div_H \mathbb{V} \qquad (3)$$

where ω is the earth's rotation, φ the latitude and $div_H \mathbb{V}$ the horizontal wind divergence. Palmén [24] has argued that since a hurricane represents an area of large cyclonic vorticity produced by

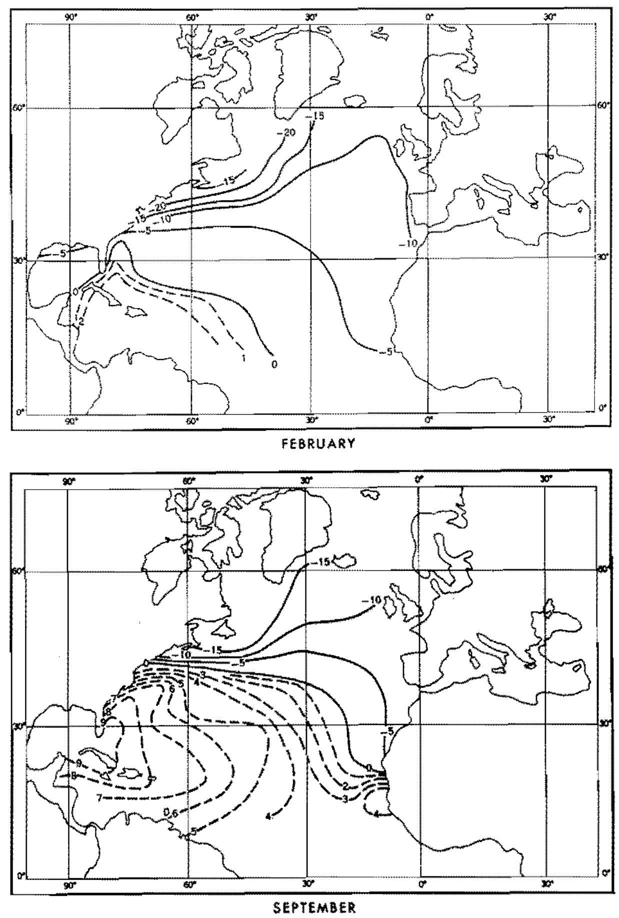

FIGURE 4.—Difference in temperature (°C) between air lifted adiabatically from the sea surface to the 300 mb. level and the air at the same level over the North Atlantic Ocean: a) in February; b) in September. After Palmén [24].

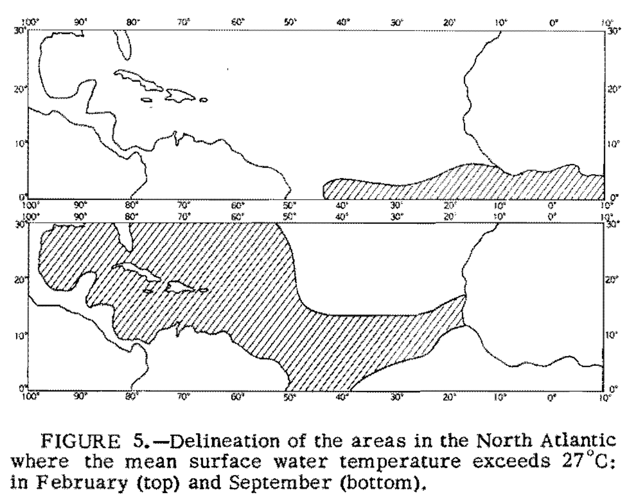

FIGURE 5.—Delineation of the areas in the North Atlantic where the mean surface water temperature exceeds 27°C: in February (top) and September (bottom).

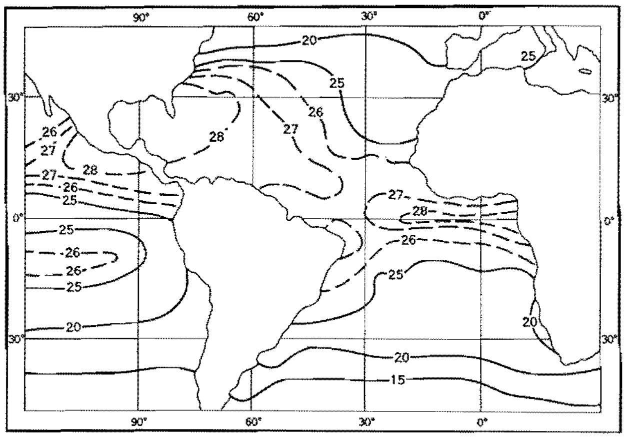

FIGURE 6.—Surface water temperature during the warmest season in the North and South Tropical Atlantic Ocean. Adapted from Palmén [24].

the convergence of air and since, according to equation (3), the effectiveness of the convergence in increasing the vorticity varies directly with the initial total vorticity ($\zeta + 2\omega \sin \varphi$), and since moreover the initial relative vorticity in the tropics is not usually very great, effective cyclogenesis must depend on a comparatively large value of the Coriolis term.

According to this reasoning, hurricanes cannot occur very close to the equator—a conclusion which is amply confirmed by figure 2 where no hurricanes are reported to have occurred equatorward of 9°N. This observation should not be confused with the fact that hurricanes are known to form in disturbances which originate in the equatorial zone. Indeed out of the 242 hurricanes considered by Dunn [8] approximately 40 percent developed in perturbations moving away from the Intertropical Convergence Zone (ITC); but almost all cases of development occurred when the perturbation was a considerable distance from this zone, well in the trade-wind current. A majority of the hurricanes developed in easterly waves.

The upper air flow

Riehl [26] was among the first to emphasize the importance, for hurricane development, of mass divergence in the upper troposphere associated with migratory upper anticyclonic vortices. This places the poleward limit of the tropical belt which is propitious for hurricane development well equatorward of the subtropical jet stream. Figure 2 indeed shows that very few tropical disturbances developed north of 30° of latitude and these are confined to the western Atlantic.

The low level flow

Wind constancy (q) is defined as (V_r / V_s) x 100, where V_r is the magnitude of the resultant mean wind vector and V_s is the scalar mean wind speed. If the wind always blew from one direction the value of (q) would be 100 percent. Most trade winds are characterized by a high value of (q) while winds of the doldrums have minimum values. Cry [4] has plotted cases of tropical storm occurrence on maps with isolines of wind constancy. Almost all cases of development occurred where the wind constancy is higher than 80 percent.

Figure 2 shows a concentration of cases of development just to the east of Swan Island and another just east of the Leeward and Windward Islands. A relative void is indicated between Hispaniola and Venezuela, in agreement with the observation by Mitchell [19] that "in every instance, the first evidence of storm development, although rather obscure in some cases, was found either over the western third of the Caribbean Sea (west of long. 78°W.) or the east of the eastern limits of the Caribbean Sea." Dunn and Miller [9] ascribe the comparatively infrequent development of hurricanes in this area to the significant divergence in the low-level flow as the easterly trade winds are diverted into the semipermanent low over the Amazon Valley. These authors note, however, that two recent severe hurricanes, Hazel of 1954 and Janet of 1955, both attained great intensity in this area.

The total number of tropical storms originating in different areas of the Atlantic during the period 1901-1963 are given in the upper portion of table 1. Comparable figures for locations where tropical cyclones first attained hurricane intensity are given in the lower section of the table.

5. FREQUENCY OF ATLANTIC HURRICANES

Seasonal variation

Atlantic hurricanes occur mostly during the months June through November which are usually considered to constitute the hurricane season. According to table 2 which shows the percentage frequency of all hurricanes and tropical storms occurring in the North Atlantic during each month of the year in the period 1886-1961, only 2.7 percent occurred out of season.

Within the hurricane season, storm activity is far from uniform, as can readily be seen from figure 7 [4] which shows the total number of tropical storms and hurricanes in existence on each calendar day in the months June through November during the period 1901-1963. Starting with a few storms in June and July, there is a sharp increase in storms early in August. This culminates in a peak in mid-September, followed by a decline in early October, a small increase to a secondary peak in mid-October, and finally a sharp decrease to the low level of activity in late October and November. About 79 percent of all hurricanes from 1886 through 1961 occurred during the three months August through October.

Table 1.—North Atlantic Tropical Cyclone and Hurricane Origins by Areas, 1901-1963

(After Cry [4])

	East of 50°W.	50°-60°W.	60°-70°W.	70°-80°W.	80°-90°W.	90°-100°W.	Total
			TROPICAL CYCLONES				
			Origins South of 20°N.				
Total.............	66	88	28	48	59	14	303
Percent..........	21.8	29.0	9.2	15.9	19.5	4.6	
			Origins North of 20°N.				
Total.............	14	26	33	51	41	32	197
Percent..........	7.1	13.2	16.8	25.9	20.8	16.2	
			HURRICANES				
			Development South of 20°N.				
Total.............	27	36	26	16	24	1	130
Percent..........	20.8	27.7	20.0	12.3	18.5	0.7	
			Development North of 20°N.				
Total.............	10	20	29	47	24	30	160
Percent..........	6.2	12.5	18.1	29.4	15.0	18.8	

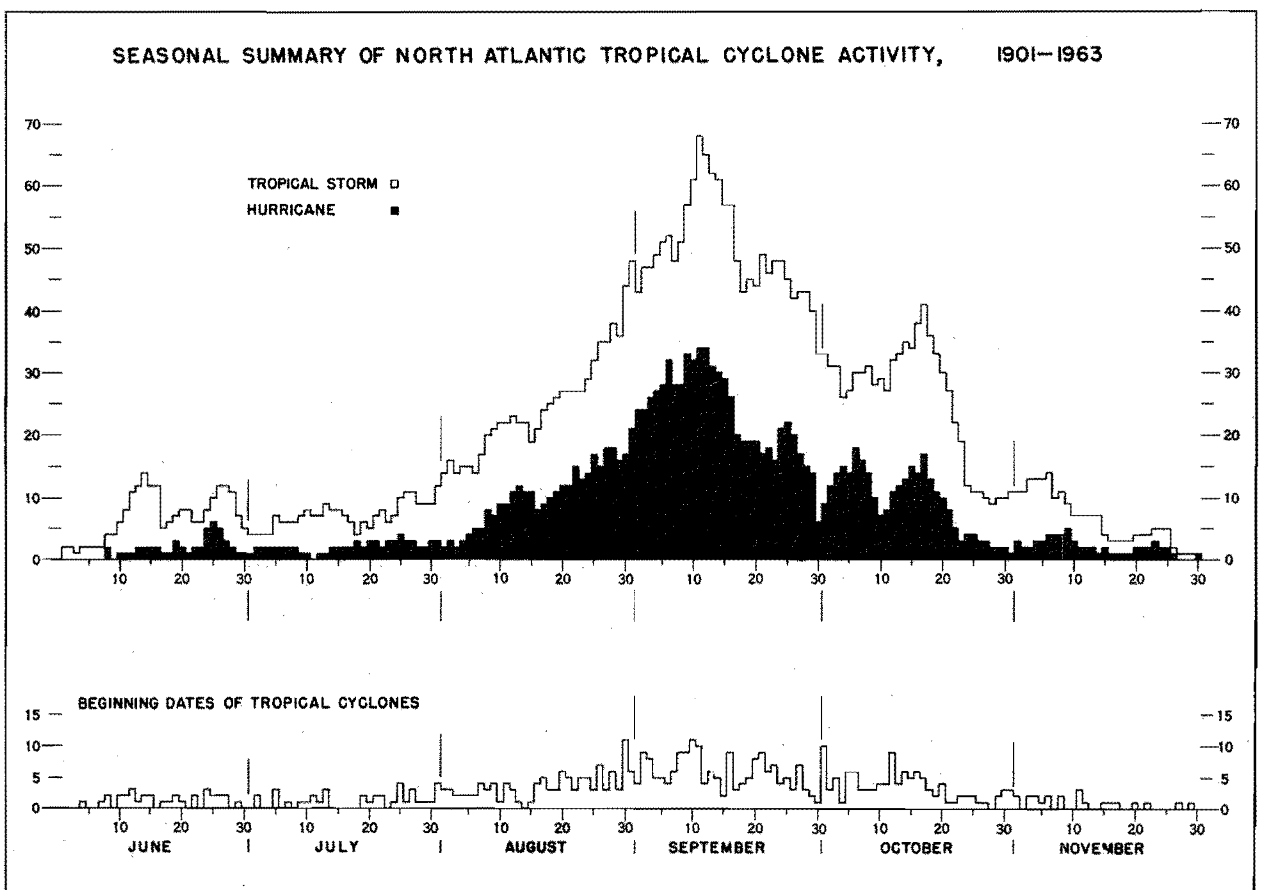

FIGURE 7.—Total daily frequency of occurrence of North Atlantic Tropical Cyclones and dates of beginning of tropical cyclone, 1901-1963. Shading refers to frequency of hurricanes.

The tropical storms that reach hurricane intensity also follow a seasonal trend. According to table 2 nearly 57 percent of all tropical storms intensified into hurricanes in July, 74 percent in August, 65 percent in September, and 46 percent in October. The observed frequency with which a given number of hurricanes occurred in different months is given in table 3. The probability of occurrences of tropical storms and hurricanes, based on observations during the period 1901-1963, is given in table 4.

Table 2.—Percentage Monthly Frequency of Atlantic Tropical Storms and Hurricanes from 1881-1961

(After Gentry [12])

	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Hurricane...	0	1	0	2	17	25	101	132	67	12	2
Percent......	0	0.3	0	0.6	4.7	7.0	27.9	36.8	18.7	3.3	0.6
Storm	1	0	0	8	23	19	35	71	76	16	2
Percent......	0.4	0	0	3.2	9.2	7.6	14.0	28.3	30.0	6.4	0.8
Total	1	1	0	10	40	44	136	203	143	28	4
Percent......	0.2	0.2	0	1.6	6.6	7.2	22.3	33.3	23.5	4.6	0.7

Table 3.—Observed Frequencies of North Atlantic Tropical Cyclone Occurrences, 1901-1963

(After Cry [4])

Number of storms	June	July	Aug.	Sept.	Oct.	Nov.	Dec.-May
			ALL TROPICAL CYCLONES				
0	37	36	14	1	10	42	51
1	20	19	13	17	17	20	12
2	5	6	19	10	22	1	0
3	1	2	11	15	10	0	0
4	0	0	4	13	2	0	0
5	0	0	0	4	1	0	0
6	0	0	1	2	1	0	0
7	0	0	1	1	0	0	0
			HURRICANES				
0	50	46	21	8	21	53	60
1	13	14	16	26	32	10	3
2	0	3	16	10	9	0	0
3	0	0	9	13	0	0	0
4	0	0	1	4	1	0	0
5	0	0	0	2	0	0	0

Table 4.—Observed Probabilities of North Atlantic Tropical Cyclone Occurrences, 1901-1963

(After Cry [4])

	June	July	Aug.	Sept.	Oct.	Nov.	Other months
			ALL TROPICAL CYCLONES				
At least 1............	0.41	0.43	0.78	0.98	0.84	0.33	0.19
2 or more............	0.09	0.13	0.57	0.71	0.57	0.02	0
3 or more............	0.02	0.03	0.27	0.56	0.22	0	0
4 or more............	0	0	0.10	0.32	0.06	0	0
			HURRICANES				
At least 1	0.21	0.27	0.67	0.87	0.67	0.16	0.05
2 or more............	0	0.05	0.41	0.46	0.16	0	0
3 or more............	0	0	0.16	0.30	0.02	0	0
4 or more............	0	0	0.02	0.10	0.02	0	0

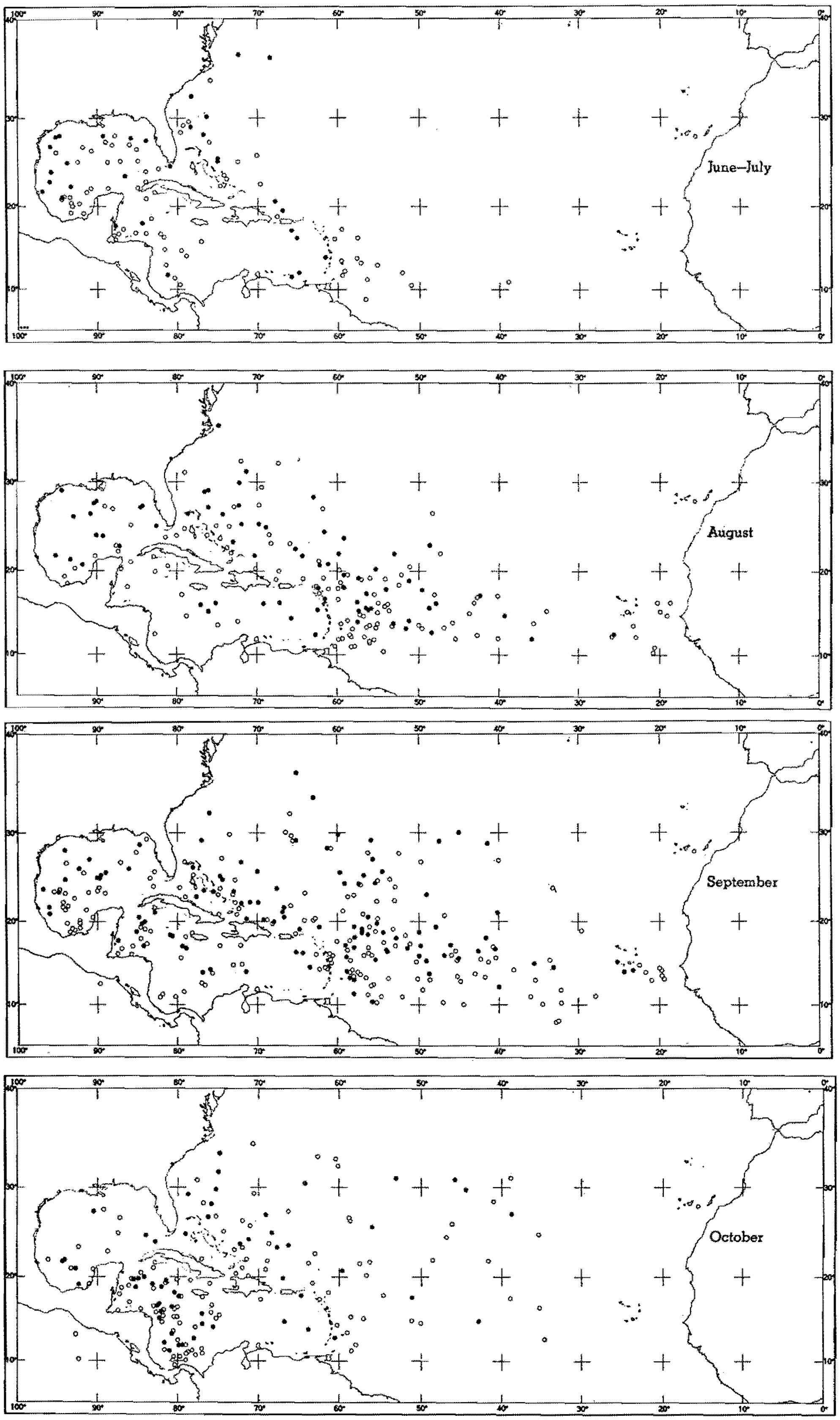

FIGURE 8.—Points of origin of tropical storms (open circles) and hurricanes (black dots) during the period 1901-1963 in: a) June -July; b) August; c) September; d) October. Courtesy of G. Cry.

The seasonal trend applies to the North Atlantic taken as a whole, but it does not obtain to an equal degree in all areas because there is a marked seasonal shift in the main cyclogenetic areas from the western Caribbean and Yucatan in June, eastward to the Bahamas and even to Cape Verde in midseason, and then gradually back to the western Caribbean in November. This seasonal shift is depicted by figure 8 which shows the points of origin of North Atlantic tropical storms and hurricanes during different months of the hurricane season. Cry and Haggard [5] divided the North Atlantic into six cyclogenetic zones delineated in figure 9. The daily distribution of tropical storms and hurricanes originating in each zone is shown in figure 10. The daily contribution of each hurricane or tropical storm is credited to the zone where the tropical cyclone was first tracked. The early season activity is seen to consist almost entirely of tropical storms forming in the western Caribbean and the Gulf of Mexico. Only three tropical cyclones have been noted in June outside this area. In July, the most genetic areas are the

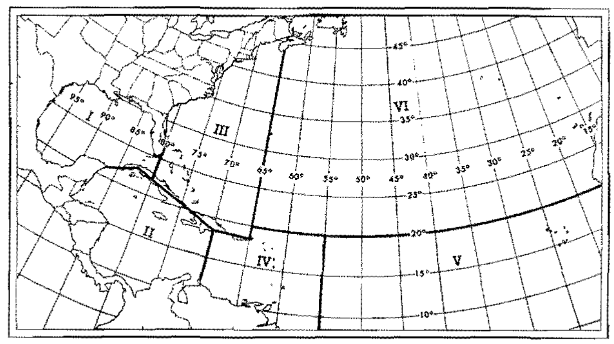

FIGURE 9.—North Atlantic regions referred to in figure 10. After Cry and Haggard [5].

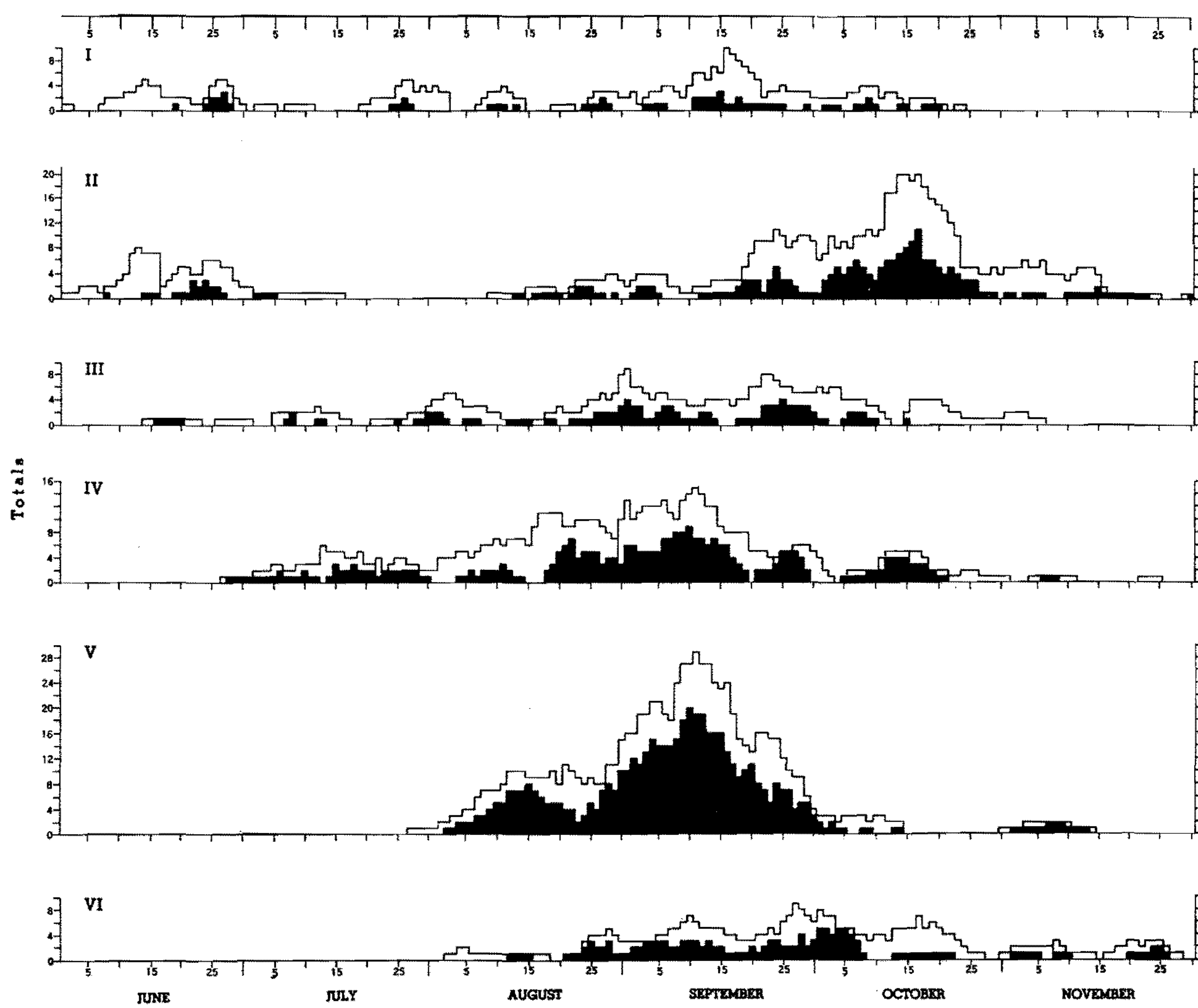

FIGURE 10.—Distributions of tropical storm and hurricane days (1901-1960) associated with tropical cyclones originating in regions delineated in figure 9. After Cry and Haggard [5].

Lesser Antilles and the southwestern Atlantic. During August and the first half of September the Lesser Antilles and the southwestern Atlantic spawn the greatest number of hurricanes while in October the western Caribbean again becomes the primary genetic zone.

Secular variations and trends

The frequency of occurrence of tropical cyclones varies considerably from year to year. During the period 1871-1964, there have been as many as 21 tropical storms and as few as one storm in any one year. The corresponding seasonal maximum and minimum for hurricanes are respectively eleven and one. The high annual variability which is demonstrated in figure 11, completely masks any secular trends. It is to be noted, however, that while the median number of storms for the whole period is 8, it is only 4 in the period 1910-1930 and 10 from 1931-1957. Clearly, this latter period was characterized by a distinctly higher level of tropical storm activity than the former. This is revealed by figure 12 in which running averages have been computed from figure 11. Figure 13 shows the cumulative departure *from the annual* average of storm occurrences. Beginning in 1894, a steady downward progression of activity occurred, becoming more pronounced in 1910 and continuing until 1930. In 1931-1936 a sharp increase in the level of activity occurred and a generally high level has been maintained since. The upward trend is however small when compared to the year-to-year variability. During the years 1901-1963, it amounts to 16 per cent of the total variability for tropical cyclones and 22 percent of the variability for hurricanes [4].

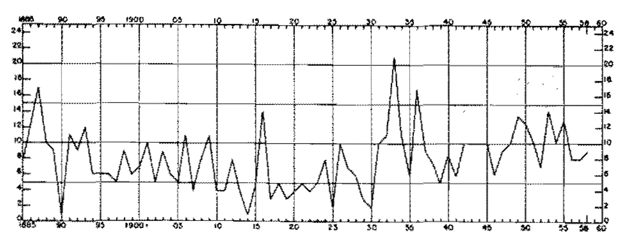

FIGURE 11.—Annual variation in the number of tropical cyclones, 1885-1958. After Dunn and Miller [9].

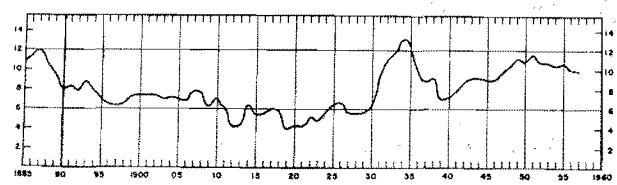

FIGURE 12.—Five-year running average of tropical cyclone frequencies. After Dunn and Miller [9].

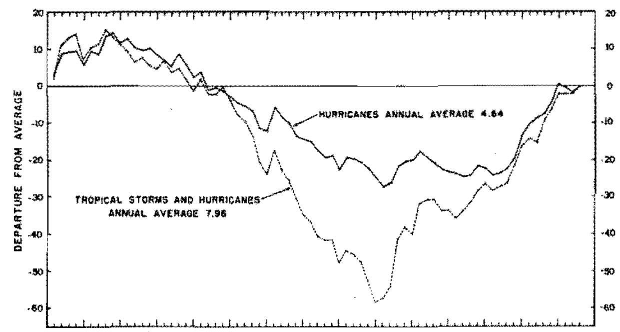

FIGURE 13.—Cumulative departure from annual North Atlantic tropical cyclones, 1886-1958. After Cry, Haggard and White [6].

The causes underlying the variability of hurricane frequencies from season to season are not sufficiently known. The abnormal poleward displacement of the planetary westerlies, which Namias and Dunn [23] associated with the formation of hurricanes Connie and Diane of 1955, has been observed to be generally favorable for hurricane development. Willett [34] and Dunn and Miller [9] have suggested a possible relation between the upward trend in the level of hurricane activity and long-term changes in temperature which might influence the patterns of the general circulation and hence the potential for tropical cyclogenesis.

6. HURRICANE MOTION

Types of storm movements

When paths of individual tropical storms, occurring over many years, are plotted on a chart, as was done by Tannehill [32] and others, there results a hopelessly tangled skein with no noticeable pattern. If however only the paths for a given season of a given year or for a particular month are plotted, a more closely knit family of tracks appears, with the individual storms following similar though never identical courses [21].

For many years it has been known that the movement of tropical cyclones is strongly influenced by the great centers of actions. The recurvature of the storms follows a path which evokes the shape of the isobars around the western periphery of the subtropical high. There is clear evidence that hurricanes are steered by a current in which the vortex is embedded. These currents are in turn influenced both by the small-scale circulation of the vortex and the broad-scale circulation over a large area. The planetary extent of the broad-scale effect was demonstrated by Klein and Winston [16] who traced the failure of the September 1947 hurricane to recurve, as predicted, to dynamic anticyclogenesis over the Eastern United States which was brought about by a chain of events originating in the Pacific Ocean a few days earlier.

Three general types of storm movements may be distinguished: westward, recurving, and eastward. Most tropical storms develop in a deep easterly current and move initially in a westerly direction. Many of these continue their westward motion at low latitudes until they pass inland and dissipate over the United States or Mexico. The majority of storms drift northward as they are carried by the easterly currents of lower latitudes and eventually become dominated by the westerly current of higher latitudes. These are the recurving storms. Finally, a number of tropical storms which develop over the Gulf of Mexico, the Caribbean or occasionally over the Atlantic are steered, throughout their life span, by the westerly wind current in which they form. The annual frequency of tropical storms and hurricanes of the above three categories are given in figure 14. Other statistical characteristics of storm movement during different periods are given in table 5.[5] Tracks for each individual storm since 1871 have been published in U.S. Weather Bureau Technical Paper No. 36 [6].

[5] Occasionally, storms move in an erratic fashion—they remain stagnant, describe loops or change course abruptly. Such storms have not been considered in compiling table 5.

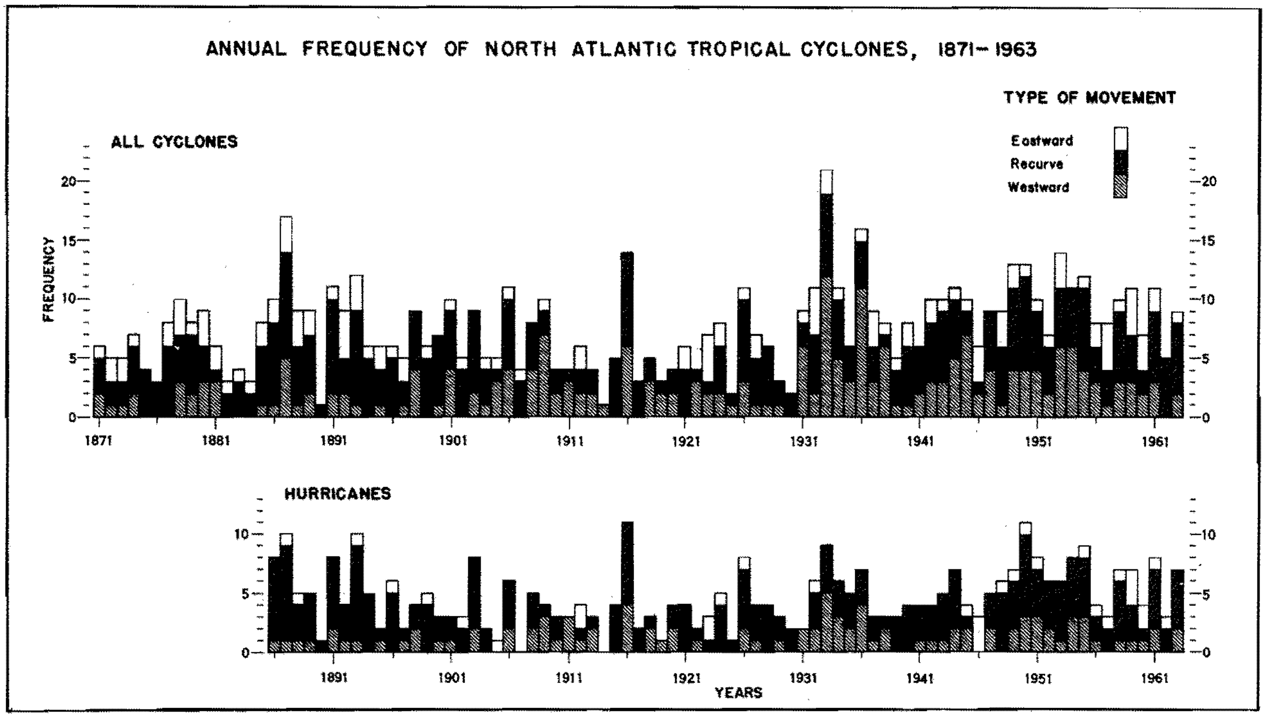

FIGURE 14.—Annual frequency of North Atlantic tropical cyclones, 1871-1963, and hurricanes, 1886-1963. General movement is indicated by shading. After Cry [4].

Table 5.—North Atlantic Tropical Cyclones, Generalized Movement Characteristics

(After Cry [4])

	WESTWARD (Always in Easterlies)			RECURVED			EASTWARD (Always in Westerlies)			TOTAL	
	Number	*Percent*	*Annual mean*	*Number*	*Percent*	*Annual mean*	*Number*	*Percent*	*Annual mean*	*Number*	*Annual mean*
	ALL TROPICAL CYCLONES										
1871-1885	18	20.2	1.2	49	55.1	3.3	22	24.7	1.5	89	6.0
1886-1900	21	17.1	1.4	77	62.6	5.1	25	20.3	1.7	123	8.2
1901-1963	186	37.2	3.0	241	48.2	3.8	73	14.6	1.2	500	8.0
	TROPICAL CYCLONES OF HURRICANE INTENSITY										
1886-1900	13	16.7	0.9	60	76.9	4.0	5	6.4	0.3	78	5.2
1901-1963	86	29.7	1.4	176	60.7	2.8	28	9.6	0.4	290	4.6

Persistence and recurvature

Colón [2] has computed, for each 5° longitude-latitude square, the percentage frequency with which storms have moved along each of the sixteen principal directions. He also calculated the probability of a displacement along the modal direction with the mean speed of motion and the probability that the track in the next 24 hr. would not deviate by more than 10° from that of the previous 24 hr. He found that linear extrapolation verified at least 80 percent of the times over most of the region south of 20°, especially in midseason. Extrapolation was least accurate early and late in the season and near the mean portion of the subtropical ridge, where the storm motion vacillates between the influence of the easterlies and westerlies. This would be the region of maximum frequency of recurvature. Figure 15, which shows the locus of points of highest recurvature frequency, reflects the seasonal shift of the subtropical ridge [27].

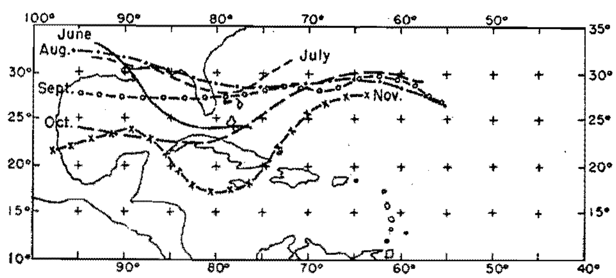

FIGURE 15.—Locus of points of highest recurvature frequency for different months of the hurricane season. After Colón [2].

Tropical cyclones affecting the United States

The incidence of tropical cyclones or their effects on various sectors of the eastern and southern United States is shown in figure 16 [4]. The lower graph represents the number of tropical depressions (unshaded), tropical storms (hatched), and hurricanes (shaded) which passed inland over the continental United States during the period 1901-1963. In the upper six graphs, storms which did not move inland but nevertheless affected the mainland by bringing high wind, rain or high tides are also included.

The regions most vulnerable to tropical cyclone activity are Florida, Texas, the middle Gulf coast and the Carolinas. Florida which experienced a high level of storm activity in the 1940's had a respite during the 1950's and early 1960's. A resurgence occurred in 1964 when no less than 5 storms crossed the peninsula. The Carolinas, on the other hand, were highly vulnerable to tropical cyclone effects during the 1950's. Finally, the Gulf coast region, after being highly vulnerable in the early years of this century, has experienced fewer severe tropical cyclones during the last 20 yrs.

The Middle Atlantic States mostly suffer from storms moving parallel to the coast. Only three hurricanes, one in 1903, one in 1923 and another in 1933, made a landfall on this section of the United States. In contrast, five severe hurricanes have crossed inland over the northeastern United States since 1938.

The observation that years of maximum threat to New England from tropical storms tend to occur in clusters has been ascribed by Namias [22] to the year-to-year persistence of general circulation anomalies. The planetary interdependence of these anomalies may have been responsible for the fact that in the fall of 1954 there was an unusual westward displacement of tropical cyclone tracks, north of 35° N., both along the east coast of North America and over east Asia.

7. STRUCTURAL ASPECTS AND RELATED PHENOMENA

The wind field

The highest winds in Atlantic hurricanes have not yet been directly measured. At sea, such direct measurements are virtually unobtainable because ships are warned to avoid the paths of severe hurricanes. Since 1944, when routine hurricane reconnaissance flights began and these estimates of hurricane winds became available, speeds exceeding 70 m./sec. (150 m.p.h.) or more have frequently been reported.

Over land, direct measurements of the strongest winds associated with hurricanes are no less hard to come by since even the sturdiest wind instruments have been known to collapse by their onslaught. Even so, anemometers have registered some notably high winds associated with hurricanes. Thus the instrument at the airport terminal building at Chetumal, Mexico, registered 78 m./sec. (175 m.p.h.) during the passage of hurricane Janet of 1955 before it collapsed. The wind, however, continued to increase and was estimated to have exceeded 90 m./sec. (200 m.p.h.). Other examples of extremely strong winds measured in hurricanes are described by Dunn and Miller [9]. Table 6 gives a short summary of these records which refer to winds sustained over a period of one or more minutes. Extreme gusts are known to exceed these sustained winds by 30 to 50 percent. Additional details and references on tropical cyclone winds are given in Forecasting Guide No. 3 [35] and National Hurricane Research Project (NHRP) Report No. 5 [17].

The pressure field

Clearly, the devastatingly strong hurricane winds must be associated with a rapid decrease of pressure toward the center of the storm. Cline [1] found an average pressure gradient of 0.42 mb./km. (0.02 in./mile) in the storms he studied.

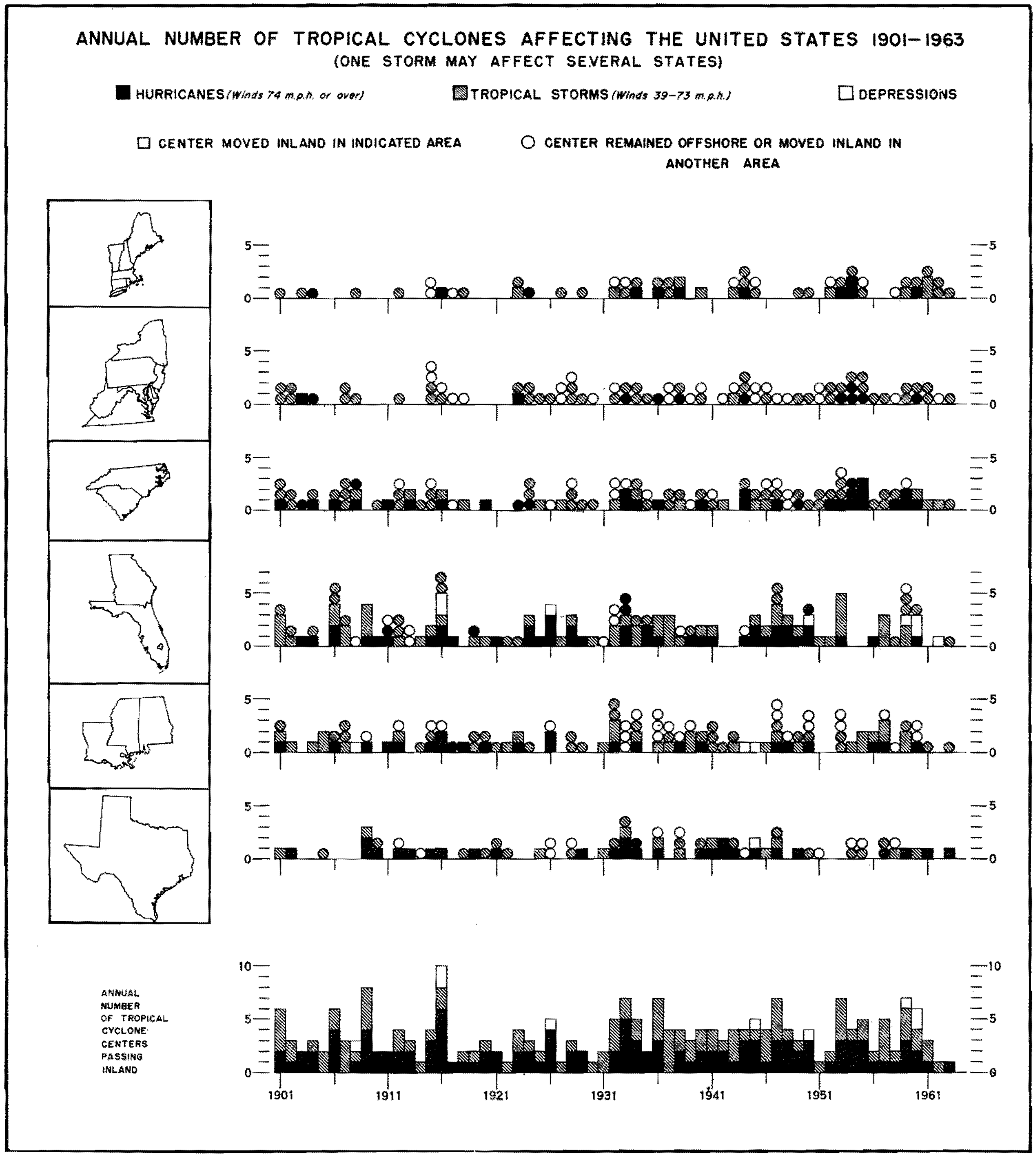

FIGURE 16.—Annual frequencies of tropical cyclones and hurricanes passing inland or significantly affecting various sections of the United States, 1901-1963. After Cry [4].

Table 6.—Some Extreme Winds Recorded in Atlantic Hurricanes

(After Dunn and Miller [9])

Date	Place	Wind speed	Duration
		m.p.h.	*minutes*
Sept. 18, 1926	Miami Beach, Fla.	138	2
		128	5
Sept. 13. 1928	San Juan, P. R.	150	5
		160 (estimated)	1
Oct. 18, 1944	Havana, Cuba	163	-
Sept. 17, 1947	Hillsboro Lighthouse, Fla.	155 (extreme)	
		121 (maximum)	
Aug. 26, 1949	Jupiter Lighthouse, Fla.	132	
		153 (extreme)	
Sept. 27-28, 1955	Chetumal, Mexico	175	

But as Dunn [7] noted, these storms must have been mostly past their prime, as is usual with hurricanes on the Gulf coast (except occasionally in June) and must have sustained the characteristic spread of isobars which occurs in older storms. The most extreme gradients are usually found when the hurricane is in the lower latitudes during the immature and early mature stages. Some fantastic pressure changes have been reported by ships near hurricanes. The SS *Virginia*, for instance, experienced a pressure drop of 45.38 mb. (1.34 in.) in 20 min. while in the central Caribbean on September 20, 1943. This is equivalent to a pressure gradient of 2.33 mb./km. (0.11 in./mile). Table 7 [9] gives some record low barometer readings in Atlantic hurricanes. In figure 17 the accumulated frequency of hurricanes occurring in various sectors of the Atlantic is plotted against the central pressure.

Rainfall and floods

Hurricanes derive their energy from the latent heat of water vapor. By some mechanism which is not yet fully understood, the heat released by the condensation of the water vapor is transformed into the mechanical energy of the storm. Since condensation is also a prime requisite for rainfall it is not surprising that some of the world's heaviest rainfall has occurred in connection with hurricanes. The greatest amounts are frequently measured when storms stall or when orographic effects are pronounced. Since both these factors occur after a storm has moved inland and started

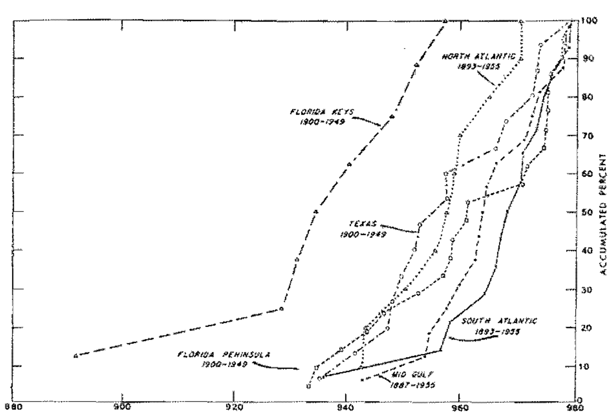

FIGURE 17.—Accumulated frequency of occurrence of hurricanes vs. central pressure (mb.) in different regions.

Table 7.—Record Low Barometer Readings

Location	Date	Pressure
		mb.
460 miles east of Luzon, Philippines (SS *Sapoeroea*)	Aug. 18, 1927	886.56
Matecumbe Key, Fla.	Sept. 2, 1935	892.31
Basilan, Frank Helm Bay, Philippines	Sept. 25, 1905	909.25
Cossack, Australia	Jan. 7, 1881	914.33
Chetumal, Mexico	Sept. 27-28, 1955	914.33
Western Caribbean (SS *Laisang*)	Nov. 5, 1932	914.66
26.7°N. 123.0°E. (SS *Phemius*)	Aug. 2, 1901	915.34
Havana, Cuba	Oct. 10-11, 1846	916.36
False Pt., India	Sept. 22, 1885	919.07
Miami, Fla.	Sept. 18, 1926	934.98
West Palm Beach, Fla.	Sept. 16, 1928	928.89
Long Island, N. Y.	Sept. 21, 1938	944.80

to dissipate, decaying storms can produce more rainfall in a given area than more intense storms with a fast rate of motion. Table 8 lists some record rainfalls measured in Atlantic hurricanes. These measurements, however, underestimate the true amounts because of the loss from rain gauges which may amount to 50 percent when the wind reaches 22.5 m./sec. (50 m.p.h.) or more [7].

Table 8.—Some Heavy Rainfall Totals Associated With Atlantic Hurricanes

Date	Place	Rainfall
		mm.
June 15-16, 1886	Alexandria, La.	543.56
Nov. 1909 (4 days)	Silver Hill, Jamaica	2,451.10
July 14-15, 1916	Altapaso, N. C.	564.39
Sept. 9-10, 1921	Taylor, Tex.	589.99
Sept. 13-14, 1928	Adjuntas, P. R.	751.84
Aug. 6-10, 1940	Crowley, La.	501.90
Aug. 6-10, 1940	Abbeville, La.	804.16
Aug. 6-10, 1940	LaFayette, La.	753.11

Yet hurricanes do not always produce heavy rain. An extreme example of storms of this category, is one whose center passed within 20 km. of Miami on October 6, 1941. Only a meager 9 mm. of rain were collected in a locality where the winds reached 55 m./sec. (123 m.p.h.).

Schoner and Molansky [31] have compiled some representative rainfall totals as well as 12, 18, or 24 hr. amounts from hurricanes entering the United States at various points along the Atlantic and Gulf coasts. A climatological summary of the mean areal average and percentage frequency of precipitation amounts following passage of storms across the Gulf coast is given in figures 18 and 19. These figures show that the distribution of rainfall is not symmetrical with respect to the center of the storm and are in qualitative agreement with the findings of Cline [1] who noted that in storms along the Gulf coast the greatest intensity occurred about 100 to 130 km. (60-80 miles) in front of the center and mostly to the right of the hurricane track.

The above distribution is typical of hurricanes in the mature stage or after they have recurred. In immature storms, those observed in low latitudes and stationary storms, the rainfall is more or less symmetrical with some tendency for a maximum to occur to the rear of the center.

Radar observations have established that hurricane rainfall is concentrated along a series of spiral bands. Figure 20, prepared by Rockney [28], shows a schematic picture of the appearance of four major east coast hurricanes on radar. The concentration of the more solid bands in the forward semicircle, and the lack of precipitation to the rear, which is typical of these storms, is in evidence.

The torrential rains from hurricanes often result in floods: some minor, others devastating. In the period since 1886, more than 60 floods due to rains from hurricanes and other tropical cyclones are known to have affected the United States. Nearly every coastal state from Texas to Maine and even some interior states have been affected. Some of the most severe of these floods occurred in connection with hurricanes in the decaying state, as in the case of hurricane Diane which caused nearly 200 deaths and about one billion dollars of damage.

Elsewhere in the West Indies and Central America floods from hurricanes have been equally frequent and have killed thousands.

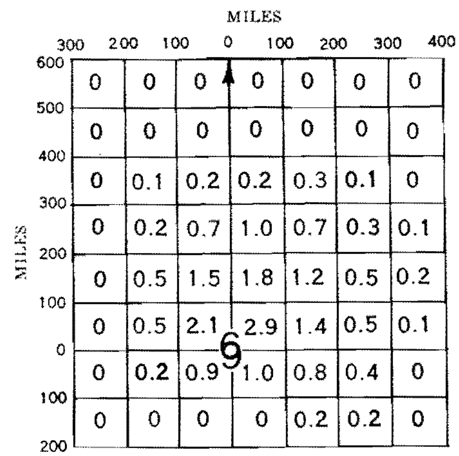

FIGURE 18.—Mean areal average precipitation amounts (in inches) for 35 tropical storms entering the Texas coast. All values are located relative to the position of storm as it crossed the coast and its motion (in direction of arrow) during the 24 hr. following coastal crossing. After Schoner [30].

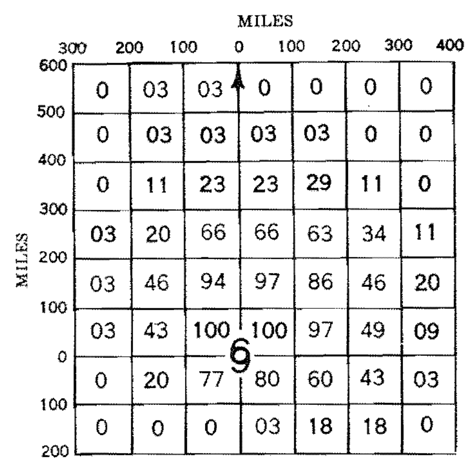

FIGURE 19.—Percentage frequencies of areal 24-hr. precipitation occurrence for 35 tropical storms entering the Texas coast. All percentages are located relative to the position of storm as it crossed the coast and its motion (in direction of arrow) during the 24 hr. following coastal crossing. After Schoner [30].

The storm surge

The storm surge is a rapid rise in the water produced by onshore hurricane winds and falling barometric pressures. The surge may be as little as 3 or 4 ft. or less or it may be as much as 15 to 20 ft. or more. The most destructive situations occur when the surge coincides with high astronomical tides.

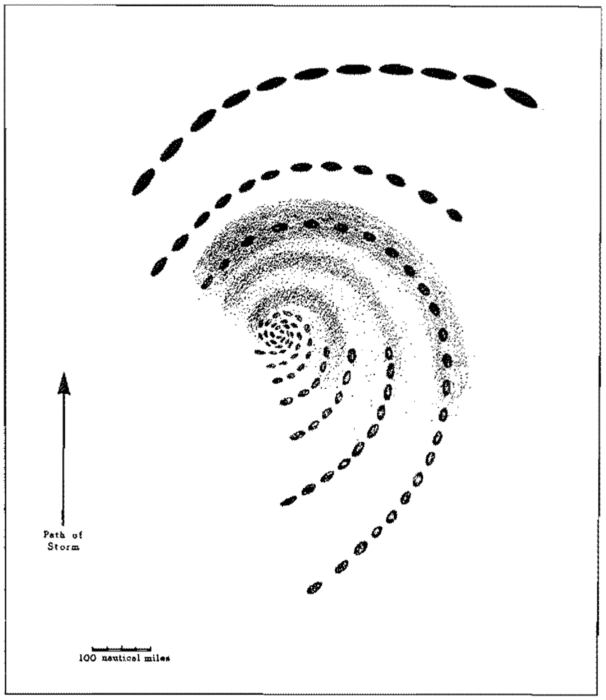

FIGURE 20.—Schematic illustration of the typical appearance of four major east coast hurricanes on radar. After Rockney [28].

The study of storm surges is not readily amenable to a climatological approach because of their dependence on a multitude of factors and their great variability within short distances. At least five distinct processes, associated with passage of a storm, have been recognized to alter the level in tide water regions [14]. These are: 1. the pressure effect; 2. the wind effect; 3. the effect of the earth's rotation; 4. the effect of ocean waves; and 5. the effect of rainfall. In addition such factors as the shape of the coast line and the topography of the continental shelf are also highly relevant.

In view of this multiplicity of causal factors, it would at first glance, appear hopeless to correlate any one of them with the observed water level. A correlation between peak water levels and minimum pressures associated with hurricanes has however been found [3], [15]; figure 21 illustrates this relationship. Some notably high tides associated with Gulf of Mexico hurricanes are listed in table 9. Detailed data and discussions of water levels in 27 hurricanes affecting the Atlantic and Gulf coasts during the years 1926 through 1961 were given by Harris [14].

Another characteristic which has been found to obtain in the generality of hurricanes is that the peak surge occurs to the right of the storm track. Hoover [15] found that the peak occurred on the average about 15 to 30 km. to the right of the track. However peak surges have been observed as far as 65 km. to the right and, occasionally, to the left of the hurricanes track.

Table 9.—Highest Tides and Lowest Central Pressures of Gulf of Mexico Hurricanes

Date	Location of highest tide on open coast	Lowest pressure	Maximum tide height
		mb.	*ft.*
Sept. 8, 1900	Galveston, Tex.	936	14.5 m.s.l.
Sept. 27, 1906	Ft. Barrancas, Fla.	965	10.8 m.s.l.
July 21, 1909	Galveston, Tex.	959	10.0 m.s.l.
Aug. 16, 1915	High Island, Tex.	953	13.9 m.s.l.
Sept. 14, 1919	Port Aransas, Tex.	948	11.1 m.s.l.
Aug. 25, 1926	Timbalier Bay, La.	959	10.0 m.s.l.
Sept. 5, 1933	Brownsville, Tex.	949	13.0 m.s.l.
Aug. 30, 1942	Matagorda, Tex.	951	14.8 m.s.l.
Sept. 19, 1947	Biloxi, Miss.	968	11.1 m.s.l.

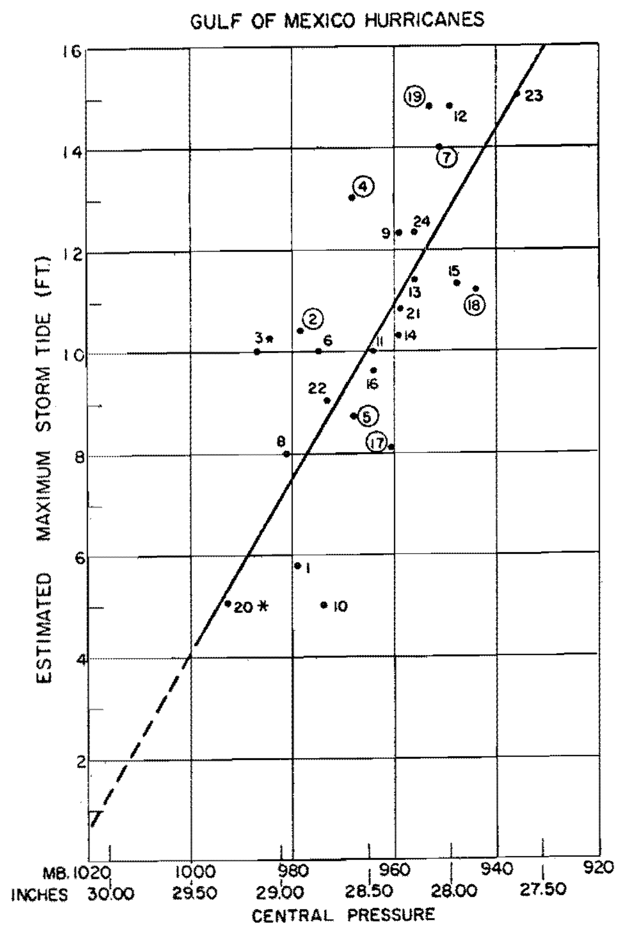

FIGURE 21.—Regression of maximum storm tide height on central pressure for hurricanes entering the United States Gulf of Mexico coastline west of Tallahassee, Fla. After Hoover [15].

Hurricane tornadoes

Although Tannehill [33] has noted that few authentic records existed of tornado activity in

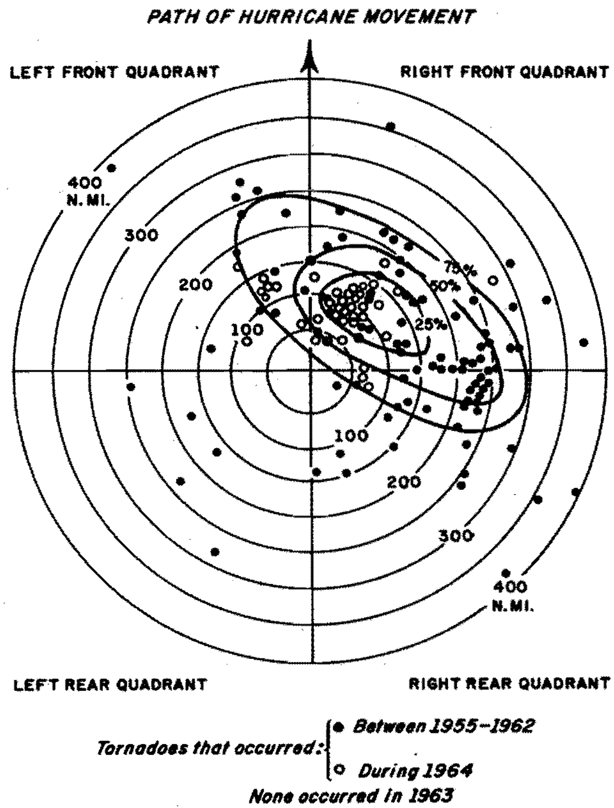

FIGURE 22.—Tornadoes associated with hurricanes, 1955-1964. After Pearson and Sadowsky [25].

hurricanes, and despite the fact that tornadoes are not normally considered tropical phenomena, there is increasing evidence of tornado occurrences associated with hurricanes. In a study of reported occurrences over the years, Malkin and Galway [18] found that tornadoes in hurricanes were observed only in the forward semicircle or along the periphery of the storm. Sadowski [29], on the other hand, showed that the 16 tornadoes which were reported in hurricane Carla of 1962, favored a location to the right of the hurricane track. In a study of a larger sample of tornado occurrences over the last ten years, Pearson and Sadowski [25] showed that both the above results were partially correct. Their finding, illustrated in figure 22, indicates the right front quadrant as the preferred location for tornado occurrences.

There is no indisputable evidence that tornadoes form during a preferred time of day. Nor, apparently, are they associated with hurricane winds. Out of a sample of 16 studied by Sadowski [29], none formed within hurricane force wind, but 13 formed in areas of gale wind.

ACKNOWLEDGEMENT

The author expresses his warm thanks to Mr. George Cry of the Environmental Data Service who made available the revised edition of U.S. Weather Bureau Technical Paper No. 55 [4] prior to its publication.

REFERENCES

1. Cline, I. M., *Tropical Cyclones,* The Macmillan Co., New York, 1926, 301 pp.
2. Colón, J. A., "A Study of Hurricane Tracks for Forecasting Purposes," *Monthly Weather Review,* Vol. 81, No. 3, March 1953, pp. 53-66.
3. Conner, W. C., Kraft, R. H., and Harris, D. L., "Empirical Methods for Forecasting the Maximum Storm Tide Due to Hurricanes and Other Tropical Storms," *Monthly Weather Review,* Vol. 85, No. 4, April 1957, pp. 113-116.
4. Cry, G. W., "Tropical Cyclones of the North Atlantic Ocean," *U.S. Weather Bureau Technical Paper No. 55,* Washington, D.C., 1965, 148 pp.
5. Cry, G. W. and Haggard, W. H., "North Atlantic Tropical Cyclone Activity, 1901-1960," *Monthly Weather Review,* Vol. 90, No. 8, August 1962, pp. 341-349.
6. Cry, G. W., Haggard, W. H. and White, H. S., "North Atlantic Tropical Cyclones—Tracks and Frequencies of Hurricanes and Tropical Storms 1886-1958," *U.S. Weather Bureau Technical Paper No. 36,* Washington, D.C., 1959, 214 pp.
7. Dunn, G. E., "Tropical Cyclones," in *Compendium of Meteorology* [T. F. Malone (ed.)], American Meteorological Society, Boston, 1951, pp. 887-901.
8. Dunn, G. E., "Areas of Hurricane Development." *Monthly Weather Review,* Vol. 84, No. 2, February 1956, pp. 47-51.
9. Dunn, G. E. and Miller, B. I., *Atlantic Hurricanes,* Louisiana State University Press, Baton Rouge, Louisiana, Revised Edition, 1964, 377 pp.
10. Fassig, O. L., "Hurricanes of the West Indies," *U.S. Weather Bureau Bulletin X,* Washington, D.C., 1913, 28 pp. + 25 plates.
11. Garriott, E. B., "West Indian Hurricanes," *U.S. Weather Bureau Bulletin H,* Washington, D.C., 1900, 69 pp. + 7 maps.
12. Gentry, R. C., "Historical Survey and Climatology of Hurricanes and Tropical Storms," in *Proceedings of the Inter-Regional Seminar on Tropical Cyclones in Tokyo, January 18-31, 1962,* (Sponsored by the World Meteorological Organization.) *Japan Meteorological Agency, Technical Report No. 21,* Tokyo, 1963, pp. 17-29.
13. Haggard, W. H., "The Birthplace of North Atlantic Tropical Storms," *Monthly Weather Review,* Vol. 86, No. 10, October 1958, pp. 397-404.
14. Harris, D. L., "Characteristics of the Hurricane Storm Surge," *U.S. Weather Bureau Technical Paper No. 48,* Washington, D.C., 1963, 139 pp.
15. Hoover, R. A., "Empirical Relationships of the Central Pressures in Hurricanes to the Maximum Surge and Storm Tide," *Monthly Weather Review,* Vol. 85, No. 5, May 1957, pp. 167-174.
16. Klein, W. H. and Winston, J. S., "The Path of the Atlantic Hurricane of September 1947 in Relation to the Hemispheric Circulation." *Bulletin of the American Meteorological Society,* Vol. 28, No. 10, December 1947, pp. 447-452.
17. Kutschenreuter, P. H., et al., "Survey of Meteorological Factors Pertinent to Reduction of Loss of Life and Property in Hurricane Situations." U.S. Weather Bureau, *National Hurricane Research Project Report No. 5,* Washington, D.C., 1957, 87 pp.
18. Malkin, W. and Galway, J. G., "Tornadoes Associated With Hurricanes—As Illustrated by Franconia, Va., Tornado, September 1, 1952," *Monthly Weather Review,* Vol. 81, No. 9, September 1953, pp. 299-303.
19. Mitchell, C. L., "West Indian Hurricanes and Other Tropical Cyclones of the North Atlantic Ocean," *Monthly Weather Review, Supplement No. 24,* Washington, D.C., 1924, 47 pp.
20. Mitchell, C. L. "West Indian Hurricanes and Other Tropical Cyclones of the North Atlantic Ocean," *Monthly Weather Review,* Vol. 60, No. 12, December 1932, pp. 253.
21. Namias, J., "Long Range Factors Affecting the Genesis and Paths of Tropical Cyclones," in *Proceedings of the UNESCO Symposium on Typhoons, November 9-12, 1954*—Tokyo, The Japanese National Commission for UNESCO with the Cooperation of the Organizing Committee for the UNESCO Symposium on Typhoons, 1955, pp. 213-219.
22. Namias, J., "Secular Fluctuations in Vulnerability to Tropical Cyclones in and off New England," *Monthly Weather Review,* Vol. 83, No. 8, August 1955, pp. 155-162.
23. Namias, J. and Dunn, G. E., "The Weather and Circulation of August 1955—Including the Climatological Background for Hurricanes Connie and Diane," *Monthly Weather Review,* Vol. 83, No. 8, August 1955, pp. 163-170.
24. Palmén, E., "On the Formation and Structure of Tropical Hurricanes," *Geophysica,* Vol. 3, 1948, pp. 26-38.
25. Pearson, A. D. and Sadowski, A. F., "Hurricane-Induced Tornadoes and Their Distribution," *Monthly Weather Review,* Vol. 93, No. 7, July 1965, pp. 461-464.
26. Riehl, H., "On the Formation of Typhoons," *Journal of Meteorology,* Vol. 5, No. 6, December 1948, pp. 247-264.
27. Riehl, H., *Tropical Meteorology,* McGraw-Hill, New York, 1954, 392 pp.
28. Rockney, V. D., "Hurricane Detection by Radar and Other Means," in *Proceedings of the Tropical Cyclone Symposium, Brisbane, December 1956,* Bureau of Meteorology, Commonwealth of Australia, Melbourne, 1956, pp. 179-197.
29. Sadowski, A., "Tornadoes Associated With Hurricane Carla, 1961," *Monthly Weather Review,* Vol. 90, No. 12, December 1962, pp. 514-516.
30. Schoner, R. W., "Frequency and Distribution of Areal Rainfall Averages Associated With Tropical Storms Entering the Coast of the United States (Texas to Maine)," Unpublished Research Report, U.S. Weather Bureau, Washington, D.C., 1957, 60 pp.
31. Schoner, R. W. and Molansky, S., "Rainfall Associated With Hurricanes (And Other Tropical Disturbances)," *National Hurricane Research Project Report No. 3,* U.S. Weather Bureau, Washington, D.C., 1956, 305 pp.
32. Tannehill, I. R., *Hurricanes—Their Nature and History,* Princeton University Press, Princeton, New Jersey, 1938, 257 pp.
33. Tannehill, I. R., *Hurricanes—Their Nature and History, Particularly Those of the West Indies and the Southern Coasts of the United States,* Princeton University Press, Princeton, New Jersey, 1956, 308 pp.
34. Willett, H. C., "A Study of the Tropical Hurricane Along the Atlantic and Gulf Coasts of the United States," Inter-Regional Insurance Conference, New York City, 1955, 63 pp.
35. Winston, J. S. (ed.), "Hurricane Forecasting," *U.S. Weather Bureau Forecasting Guide No. 3,* Washington, D.C., 1959, 108 pp.
36. Yanai, M., "Formation of Tropical Cyclones," *Reviews of Geophysics,* Vol. 2, No. 2, May 1964, pp. 367-414.

U.S. GOVERNMENT PRINTING OFFICE : 1968 O—312-879

37139—U.S.Dept.of Comm—DC—1968