HYDROMETEOROLOGICAL REPORT NO. 32

Characteristics of United States Hurricanes Pertinent to Levee Design for Lake Okeechobee, Florida

Washington

March 1954

HYDROMETEOROLOGICAL REPORTS

(Nos. 6–22 Numbered Retroactively)

No. 1. Maximum possible precipitation over the Ompompanoosuc Basin above Union Village, Vt. 1943.
No. 2. Maximum possible precipitation over the Ohio River Basin above Pittsburgh, Pa. 1942.
No. 3. Maximum possible precipitation over the Sacramento Basin of California. 1943.
No. 4. Maximum possible precipitation over the Panama Canal Basin. 1943.
No. 5. Thunderstorm rainfall. 1947.
No. 6. A preliminary report on the probable occurrence of excessive precipitation over Fort Supply Basin, Okla. 1938.*
No. 7. Worst probable meteorological condition on Mill Creek, Butler and Hamilton Counties, Ohio. 1937. (Unpublished.) Supplement, 1938.*
No. 8. A hydrometeorological analysis of possible maximum precipitation over St. Francis River Basin above Wappapello, Mo. 1938.*
No. 9. A report on the possible occurrence of maximum precipitation over White River Basin above Mud Mountain Dam site, Wash. 1939.*
No. 10. Maximum possible rainfall over the Arkansas River Basin above Caddoa, Colo. 1939.* Supplement, 1939.*
No. 11. A preliminary report on the maximum possible precipitation over the Dorena, Cottage Grove, and Fern Ridge Basins in the Willamette Basin, Oreg. 1939.*
No. 12. Maximum possible precipitation over the Red River Basin above Denison, Tex. 1939.*
No. 13. A report on the maximum possible precipitation over Cherry Creek Basin in Colorado. 1940.*
No. 14. The frequency of flood-producing rainfall over the Pajaro River Basin in California. 1940.*
No. 15. A report on depth-frequency relations of thunderstorm rainfall on the Sevier Basin, Utah. 1941.*
No. 16. A preliminary report on the maximum possible precipitation over the Potomac and Rappahannock River Basins. 1943.*
No. 17. Maximum possible precipitation over the Pecos Basin of New Mexico. 1944. (Unpublished.)
No. 18. Tentative estimates of maximum possible flood-producing meteorological conditions in the Columbia River Basin. 1945.
No. 19. Preliminary report on depth-duration-frequency characteristics of precipitation over the Muskingum Basin for 1- to 9-week periods. 1945.*
No. 20. An estimate of maximum possible flood-producing meteorological conditions in the Missouri River Basin above Garrison Dam site. 1945.
No. 21. A hydrometeorological study of the Los Angeles area. 1939.
No. 21A. Preliminary report on maximum possible precipitation, Los Angeles area, California. 1944.*
No. 21B. Revised report on maximum possible precipitation, Los Angeles area, California. 1945.*
No. 22. An estimate of maximum possible flood-producing meteorological conditions in the Missouri River Basin between Garrison and Fort Randall. 1946.
No. 23. Generalized estimates of maximum possible precipitation over the United States east of the 105th meridian, for areas of 10, 200, and 500 square miles. 1947.
No. 24. Maximum possible precipitation over the San Joaquin Basin, Calif. 1947.
No. 25. Representative 12-hour dewpoints in major United States storms east of the Continental Divide. 1947.*
No. 25A. Representative 12-hour dewpoints in major United States storms east of the Continental Divide. 2d edition. 1949.
No. 26. Analysis of winds over Lake Okeechobee during tropical storm of August 26–27, 1949. 1951.
No. 27. Estimate of maximum possible precipitation, Rio Grande Basin, Fort Quitman to Zapata. 1951.*
No. 28. Generalized estimate of maximum possible precipitation over New England and New York. 1952.*
No. 29. Seasonal variation of the standard project storm for areas of 200 and 1,000 square miles east of 105th meridian 1953.*
No. 30. Meteorology of floods at St. Louis. 1953. (Unpublished)
No. 31. Analysis and synthesis of hurricane wind patterns over Lake Okeechobee, Florida. (In preparation.)

*Out of print.

U. S. Department of Commerce
Weather Bureau

U. S. Department of Army
Corps of Engineers

Hydrometeorological Report No. 32

CHARACTERISTICS OF UNITED STATES HURRICANES PERTINENT TO LEVEE DESIGN FOR LAKE OKEECHOBEE, FLORIDA

Prepared by
Vance A. Myers
Division of Hydrologic Services
Hydrometeorological Section

Washington, D. C.
March 1954

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C. - Price 60 cents

CONTENTS

CONTENTS (cont.)

CONTENTS (cont.)

TABLES

FIGURES

FIGURES (cont.)

FIGURES (cont.)

INTRODUCTION

This is the third report published by the Hydrometeorological Section in collaboration with the Corps of Engineers on meteorological factors pertinent to levee design for Lake Okeechobee, Florida. The first, Hydrometeorological Report No. 26,[1] presented a detailed analysis of the winds and pressures in the hurricane of August 26-27, 1949, which crossed the Lake. The unexcelled hurricane data from the Corps of Engineers' observing network, formed the basis for the analysis. In Hydrometeorological Report No. 31, "Analysis and Synthesis of Hurricane Wind Patterns over Lake Okeechobee, Florida,"[2] the techniques of analysis of individual hurricanes in the previous report are extended, transposition of severe Florida hurricanes from their place of occurrence to a critical path over the Lake is carried out, and a basis is developed for synthesizing the hurricane that is sufficiently severe to be used for design of levees on the Lake. The last is a treatment of hurricane winds analogous to the treatments of precipitation with which the Section has dealt since its inception.

The present study expands the climatological basis for synthesizing the design hurricane by examining all hurricanes of significance that reached any part of the United States during a fifty-year period and investigates further the relation of actual hurricane winds to theoretical wind, the frictional dissipation of hurricanes over land, and certain other aspects.

The three published reports present that part of the Section's work on the Okeechobee problem that may be of general interest to the engineering and meteorological professions. Other aspects of less general interest have been transmitted to the Corps of Engineers separately.

Chapter I

RECONSTRUCTION OF HURRICANES

Basic purpose

Numerous compilations of extremes of observed wind and pressure in hurricanes have been published. A recent example is Gentry's discussion, for engineers, of highest known hurricane winds[3]. The direct detection by meteorological instruments of the maximum wind or the minimum pressure in any hurricane has depended, however, on the fortuitous location of the meteorological instruments with respect to the storm (prior to the era of aerial reconnaisance), and on the ability of the wind instruments to withstand high velocities. One specific goal set forth in the present study was to develop, not only for the use of the Corps of Engineers' designers of levees on Lake Okeechobee, but as a basic contribution to the climatology of hurricanes, frequency distributions of the lowest pressure and highest wind in all the principal U.S. hurricanes of the last half-century by estimating the extremes in each storm.

The wind data should be developed in such form that, in addition to maximum speeds at a point, extreme values of the speed integrated over an area equivalent to Lake Okeechobee and through a period of several hours could be readily extracted.

The hurricane model

The development of a hurricane model for the purpose of building synthetic design hurricanes from the elements of observed storms is described in Hydrometeorological Report No. 31. The same model is adapted in the present study to reconstruct historical storms from sparse data. In the model, the field of pressure is symmetrical about a central point, as is the wind field. Filling or deepening is negligible over a period of several hours or more. In fitting the data from a particular hurricane to the model, the pressure or wind data from scattered locations and over a period of time may be plotted against the single factor of distance from the center. The model radial profile of sea-level pressure is described by the expression

$$\frac{p - p_o}{p_n - p_o} = e^{-\frac{R}{r}} \qquad (1)$$

where p is the pressure at radius r, p_o the pressure at the center, p_n the pressure at some great distance from the center to which the profile is asymptotic, and R is the radius at which the wind speed is the greatest. Fitting a curve of this form to the observed pressure data yields an estimate of the pressure at all points in the storm, including the minimum pressure at the center. A first approximation of the wind field is obtained by computing the cyclostrophic or the gradient wind from equation (1). Equation (1) may be solved for the pressure gradient:

$$\frac{dp}{dr} = (p_n - p_o) \frac{R}{r^2} e^{\frac{-R}{r}} \tag{2}$$

Substituting in the general formula for the cyclostropic wind, in which the pressure-gradient force and the centrifugal force are in balance,

$$\frac{v_c^2}{r} = \frac{1}{\rho} \frac{dp}{dr} \tag{3}$$

we obtain

$$v_c^2 = \frac{1}{\rho} (p_n - p_o) \frac{R}{r} e^{\frac{-R}{r}} \tag{4}$$

where ρ is the air density. The corresponding expression for the gradient wind, in which the coriolis term is included in the balance of forces, is

$$\frac{v_g^2}{r} + 2 \omega \sin \phi \, v_g = \frac{1}{\rho} (p_n - p_o) \frac{R}{r} e^{\frac{-R}{r}} \tag{5}$$

In this study the gradient wind is usually employed as the model hurricane wind. Occasionally, the cyclostrophic wind is employed because of its greater simplicity. There is little numerical difference between the two theoretical wind speeds in the inner high-speed zone of the hurricane, but farther from the center the gradient wind corresponds better to the observed wind speed. See, for example, figure 21 on page 39. In computing the gradient wind a simpler method than direct substitution in equation (5) was employed. This method is described in appendix B.

Storm criteria

To facilitate a clear-cut interpretation of the frequency distributions of minimum pressures and maximum winds to be obtained by reconstruction of hurricanes, it was desirable to reconstruct every hurricane, or nearly every one, of a designated intensity that passed through a particular area during a stated period of time. Accordingly, specific criteria for selection of storms to be analyzed were set up. The area chosen was the coast of the United States, and waters immediately off-shore, from Texas to Maine. The West Indies were excluded, in spite of greater climatological similarity of that region, with respect to hurricanes, to our principal focus of interest at Lake Okeechobee, than the northeastern United States Coast. The available data from the West Indian Islands is too sparse to meet the requirement that nearly all hurricanes in the selected region be analyzed. The period chosen was 1900 through 1949. The year 1900 was decided upon for the beginning of the study by weighing the inaccuracies that would result from the very sparse data of earlier years against the desirability of a long record.

The primary intensity criterion was that the central pressure be less than 29.00 inches at the time the hurricane reached the United States Coast. That criterion was based on the consideration that the maximum cyclostrophic wind speed, computed from the Hydrometeorological Section model with a central pressure of 29.00 inches and asymptotic pressure of 30.00 inches, is 73 miles per hour. In some storms the intensity criterion could be applied immediately, for example, if a pressure reading in the eye was recorded. With many other storms the analysis had to proceed through various stages until the range of possible values of the central pressure could be narrowed down. An exception was made to the over-all principle that every storm meeting the established criteria be fully analyzed, in order to avoid expending an unwarranted fraction of the labor on lesser storms. Ten of the earlier storms in which it was reasonably certain that the central pressure was not below 28.50 inches, but in which there was no assurance that the central pressure was not below 29.00 inches, were omitted. The thirty-six storms fully analyzed with central pressures between 28.50 and 29.00 were judged to cover that range adequately. For one additional storm in the 28.50-29.00-inch range, that of November 4, 1935, no analysis was made, but the pressure observed at Miami when the calm center passed over, 28.73 inches, was incorporated in the central-pressure frequencies.

Virtual absence of pressure data made it necessary to omit one storm altogether, the Louisiana hurricane of August 6, 1918, which was sufficiently severe to put the anemometer at Lake Charles out of commission. The closest recorded pressure was some 90 nautical miles from the path of the storm center. An estimate of the central pressure from such a distance would be so unreliable as to be useless. The greatest distance from storm center to observed pressure in the storms analyzed was 60 nautical miles.

Dates of hurricanes

In his book, "Hurricanes", Tannehill[4] depicts tracks of Atlantic tropical cyclones during the years 1901 through 1949 on separate maps for each year. "Noteworthy" storms are shown by solid lines, lesser storms of tropical origin by dashed lines All noteworthy storms pictured as entering the United States on Tannehill's maps, or passing close enough to give strong winds on shore or over the Florida Keys, were condidates for analysis.

Of the 121 such storms, four were rejected as no longer of essentially tropical character at the time they reached the United States. Thirty-four were shown definitely to have central pressures greater than 29.00 inches upon reaching the coast. Eleven were omitted as discussed above. The dates of the omitted hurricanes in addition to the August 6, 1918 storm are, July 10, 1901, in Texas; June 14, 1902, in northwestern Florida; September 16, 1903, North Carolina to New York; August 28, 1909, October 16, 1912, and June 27, 1913, in Texas; July 19, 1916 off

North Carolina; November 15, 1916, Florida Keys and mainland; September 29, 1920, Florida west coast; and October 15, 1923, Louisiana. The remaining 72 hurricanes, all having central pressures below 29.00 inches, are listed in table 1, on pages 16 and 17. The conclusions of the study are based largely on this last group of hurricanes. Tannehill's first map is for 1901. The present study began with 1900, and the only important hurricane of that year, the disastrous Galveston hurricane of September 8, is included in table 1, giving a total of 73 storms.

Basic data

Previous analyses by the Section of several hurricanes passing over the Corps of Engineers' meteorological network around Lake Okeechobee were carried forward into the present study. The principal basic data for the reconstruction of all other hurricanes were original barograph traces from Weather Bureau, and in later years, Air Force, weather stations, autographic wind records from Weather Bureau stations, ("triple-register" sheets), and miscellaneous pressure and wind reports and textual descriptions in the Monthly Weather Review, Cline's "Tropical Cyclones",5/ and a few other sources. Damage reports in the Monthly Weather Review were considered carefully, and occasionally were helpful in one step of the analysis procedure, laying out the storm path. Possible data sources that were not tapped, so as to keep the study within the bounds of reasonable expenditure of time, were ship pressures and wind observations not published in the Monthly Weather Review, winds from airway stations established in recent years and not equipped with triple registers, and damage reports in old newspapers.

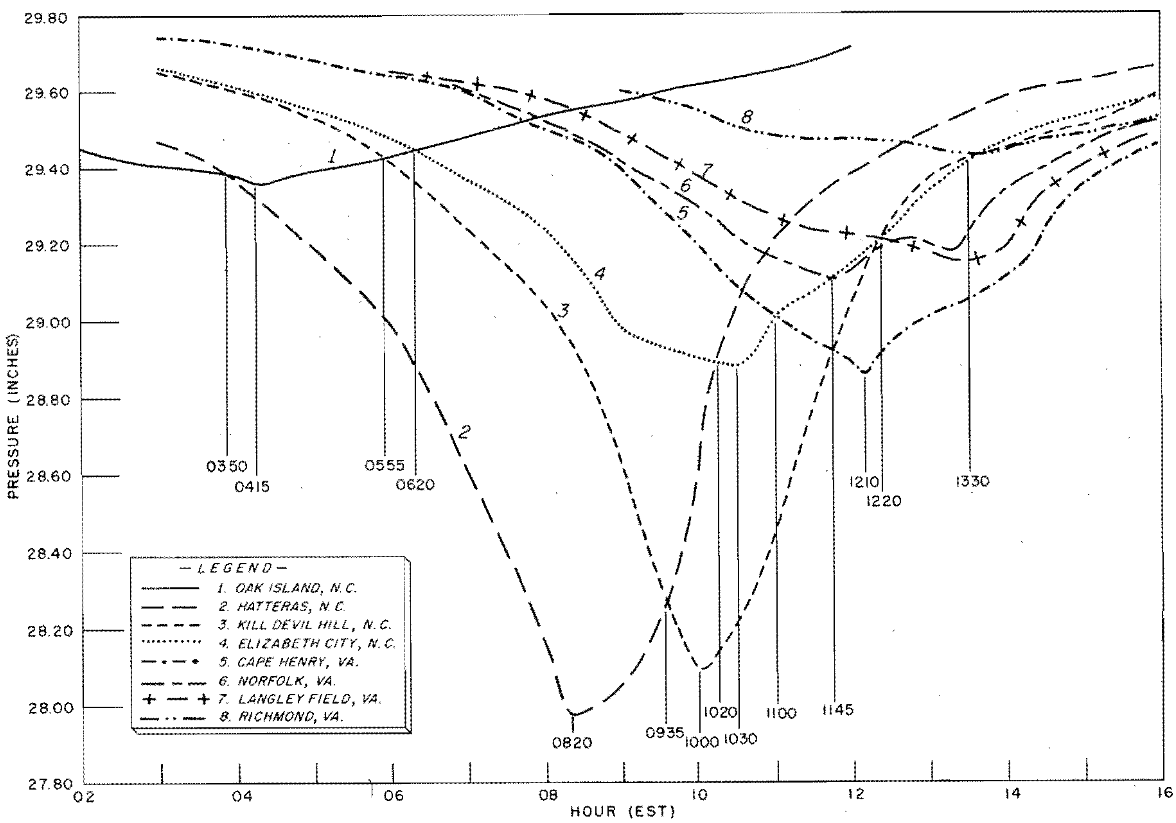
Basic analysis procedure

The model hurricane is defined by p_o, p_n, and R, of equation (1). These parameters were evaulated for each hurricane by plotting observed hourly pressures against distance from storm center, fitting a curve to the plotted points by eye, and, in turn, fitting to this visually-drawn profile a curve of the family defined by equation (1). For the foregoing, a path of the storm center is required to obtain distances from pressure-observing stations to the storm center. The final success of the method depends greatly on an accurate storm path, and considerable pains were employed to construct as accurate a storm path as the basic data would permit. The procedures by which the storm paths and the pressure profiles were obtained, including successive approximations of both, may, in part, have application in other studies of hurricanes and in hurricane forecasting and therefore will be described in some detail. The "Great Atlantic Hurricane" of September 1944, over the portion of its track off North Carolina, is taken as an example.

Sea-level barograms

Original barograph traces for all stations falling within about 100 nautical miles of the storm center at any time were reduced to sea level and transcribed to a common time-scale as in figure 1.

Instrumental corrections were applied if these had been entered on the original barograph trace. The times corresponding to the intersection of any two sea-level barograms and to the minimum points were recorded. These times are denoted by fine vertical lines in figure 1.



SEA-LEVEL BAROGRAMS -- SEPTEMBER 14, 1944

FIG. 1

Lines of position from pressures

Lines of position, based on the times recorded above, were laid out on a map on which the first approximation of the storm path was to be constructed. Perpendicular bisectors of chords joining stations were constructed (long-dashed lines in figure 2) and were labeled with the time of intersection of the corresponding barograms. The assumption that the hurricane is circular requires that the storm center lie on the bisectors at the designated times. Minimum pressures and their times of occurrence were plotted at stations, and perpendiculars to the track were run from the stations (short-dashed lines in figure 2).

The latter perpendiculars had to be constructed by successive approximations as the track was laid out. The center of the circular hurricane would lie at the end points of these lines at the time of the minimum pressures.

Wind-shift analysis

From any station within a hurricane the center of the storm lies in a direction roughly 90° clockwise from the direction from which the wind is blowing (northern hemisphere). Thus, a record of wind directions at a station may be interpreted as a record of approximate bearings on the storm center. From such bearings, if it is assumed that the hurricane is progressing at constant velocity, the direction of motion may be computed by geometry. If the forward speed can be estimated, the position as well as direction of the storm path is obtained.

Autographic wind-direction records were used in that fashion to estimate hurricane paths. All of the direction records were from Weather Bureau triple registers. This instrument registers the wind direction to eight points of the compass once a minute. The wind direction is known most precisely at the time the direction shifts from one cardinal point to the next. Bearings at these times were employed to lay out a storm path. For example, at the minute the wind shifted from E to NE it was assumed that the wind direction was ENE and that the bearing on the storm center was SSE.

The shifts in wind direction at Hatteras, N. C., as the hurricane of September 14, 1944, passed offshore, and the assumed bearings on the storm center are listed in the table below. The computation diagram is shown in figure 4.

WIND DATA AT HATTERAS, N.C.

September 14, 1944

Wind-direction shift	Time 75th mer.	Assumed exact wind direction	Assumed bearing on storm center
E to NE	0357	ENE	SSE
NE to N	0757	NNE	ESE
N to NW	0825	NNW	ENE
Anemometer failed	0856	Between NNW and WNW	Between ENE and NNE

From the pressure-based lines of position in figure 2 it was estimated that the forward speed of the storm near Hatteras was 20 knots. Time-checks were then marked on a vector representing the storm path, at a spacing corresponding to the distance of travel at the assumed 20 knots of the storm center between the several wind shifts. This path vector is shown at the bottom of figure 4.

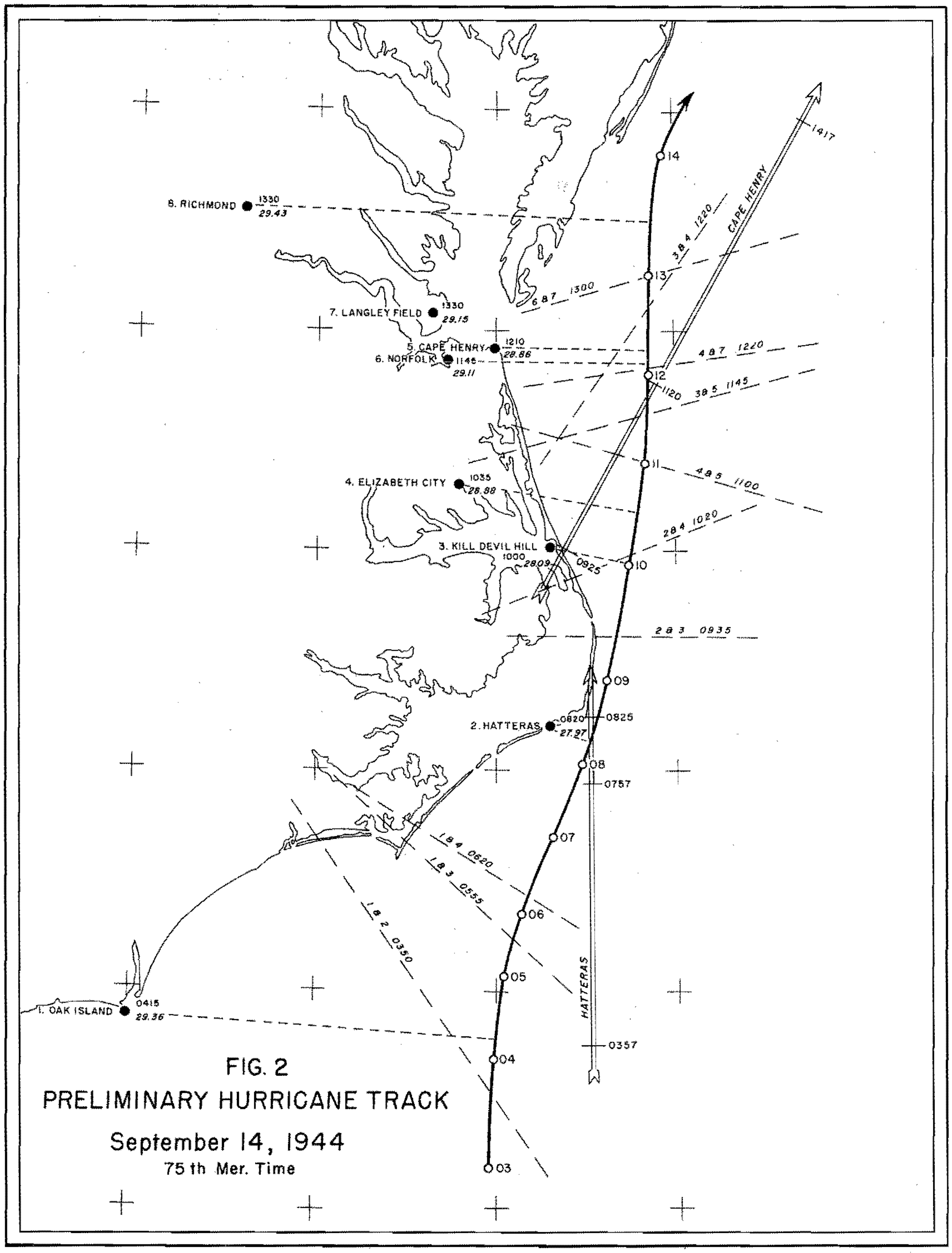


FIG. 2
PRELIMINARY HURRICANE TRACK
September 14, 1944
75 th Mer. Time

Numbers at stations are minimum pressure and time of occurrence. Short-dashed lines are perpendiculars from stations to track. Long-dashed lines are perpendicular bisectors between stations identified by numbers above the line. Double arrows are storm paths as estimated from the wind direction at designated stations.

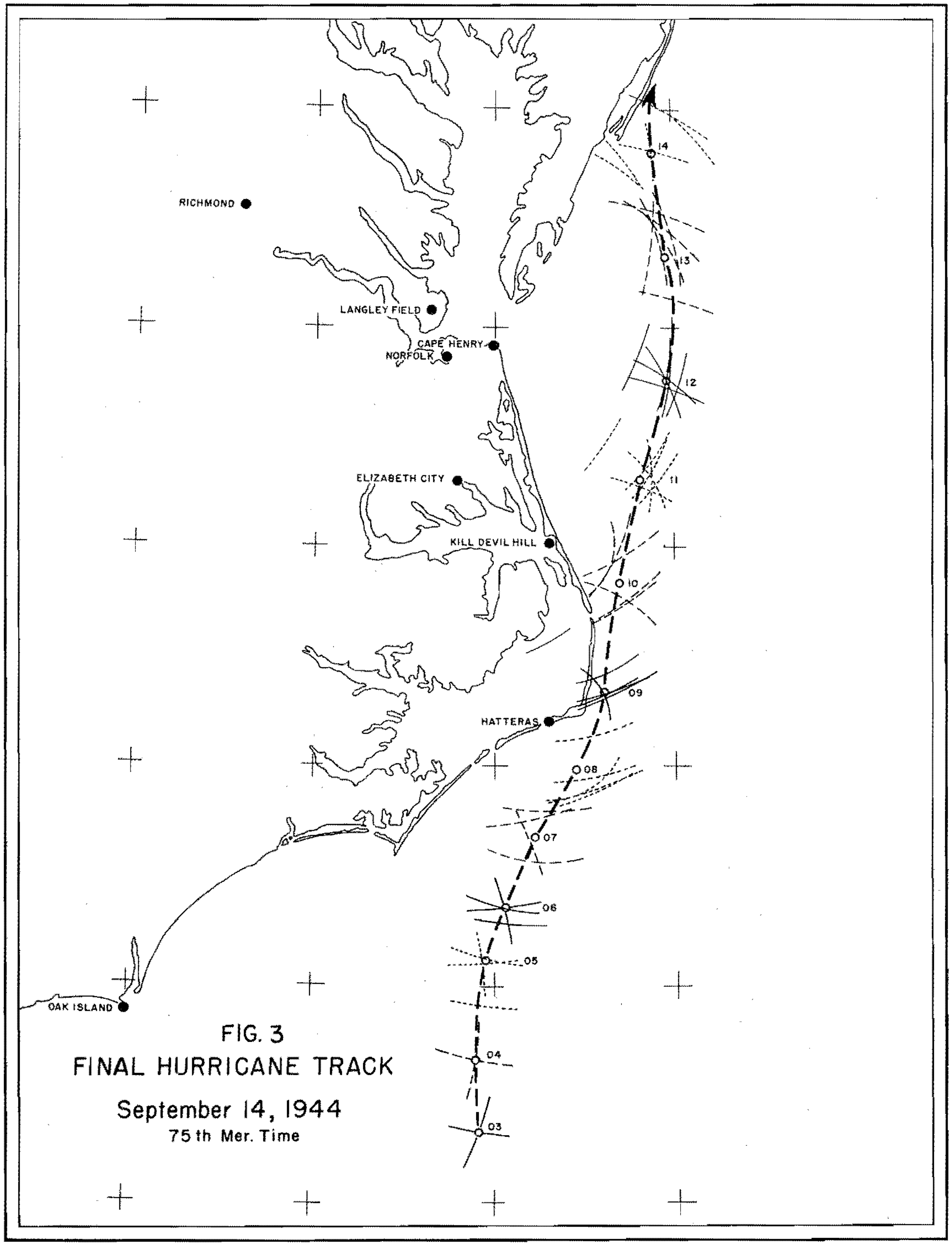


FIG. 3
FINAL HURRICANE TRACK
September 14, 1944
75th Mer. Time

Numbers along track on this and preceeding figure identify hourly positions of storm center. Arcs mark estimated distances of storm center from stations, which are at centers of arcs. Arcs for the same hour are drawn with the same line symbol.

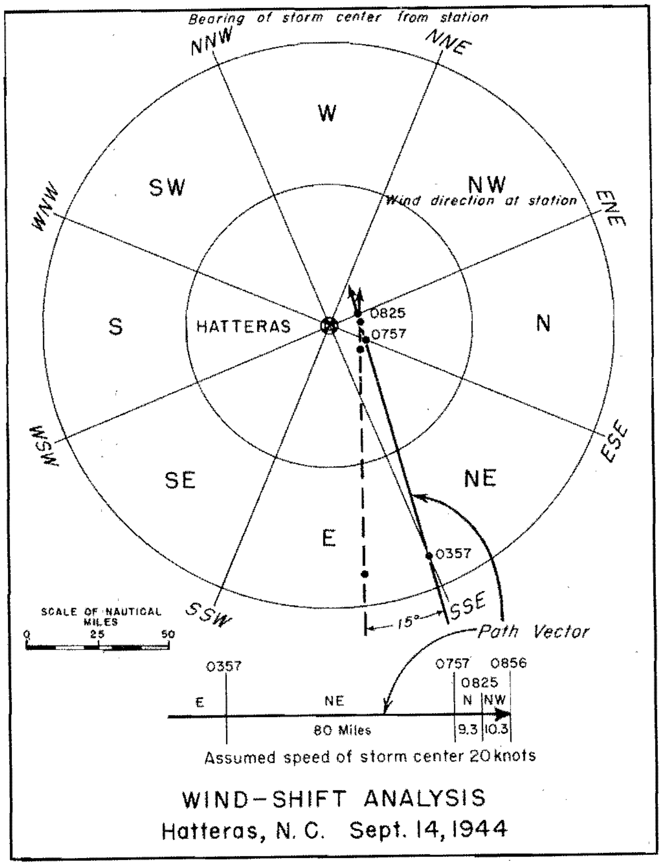


FIG. 4

The vector was laid out on the edge of a sheet of paper and then was superimposed on a polar diagram with the station at the center in such a fashion that the time-checks intersected the corresponding azimuth lines. The result of this step is illustrated by the solid arrow on the polar diagram of figure 4. In the example there are three time-checks and an exact fit is obtained. When there were four time-checks, an average best fit was made.

Next an approximate correction was made for the fact that the real angle between the direction of the anemometer-level wind and the bearing on the storm center is greater than 90° except very close to the center. Figure 5, which is reproduced from Hydrometeorological Report No. 26, depicts the average deflection angle of the wind from the tangential direction in a typical hurricane, the storm of August 26, 1949, as a function of distance from the wind center of the storm. From this figure was read the deflection angle that corresponded to the minimum distance from the station to the computed storm path. The arrow on the polar diagram (figure 4) was rotated about the center of the diagram by this angle and in the new position demarked the storm path that best fit the wind-direction record for a symmetrical storm with the assumed deflection angle. In our example the minimum distance and deflection angle were 11 nautical miles and 15°, respectively. The rotated arrow is shown as a dashed line in figure 4. Finally, the rotated arrow, with the time-checks retained on it, is transferred to the preliminary track map. The arrow from figure 4 is shown in figure 2 opposite Hatteras. The arrow based on the wind directions at Cape Henry, Va., is also shown.

The most important function of the foregoing wind-direction analysis was to establish in an objective way the minimum distance from pressure-observing station to storm track. This minimum distance has great influence on the central pressure to be obtained by extrapolation. The rotation for deflection angle in the last step of the wind-shift analysis does not change

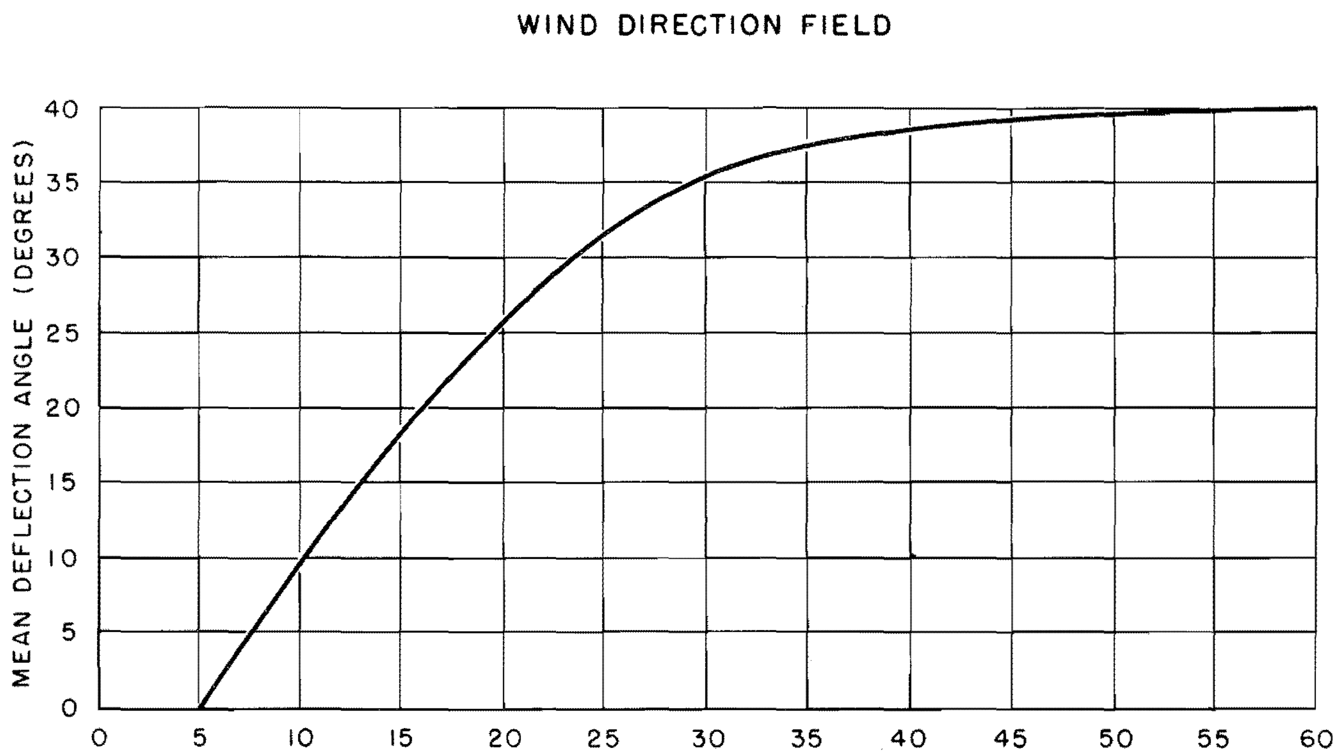


FIG. 5

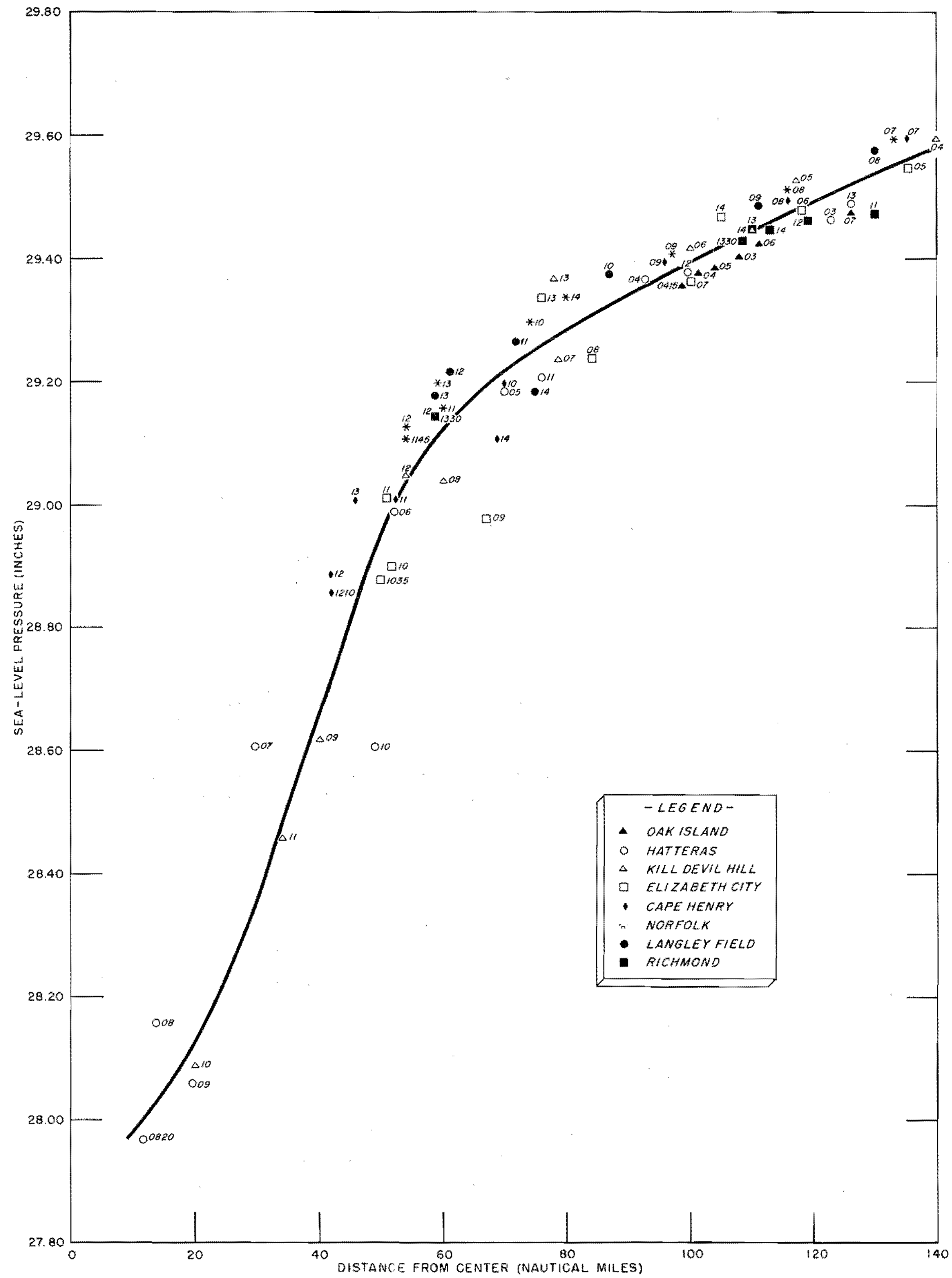
this critical distance. It can be noted in figure 2 that the lines of position based on the pressure data determine the position of the storm center in the north-south direction much more precisely than its distance offshore. The Hatteras wind arrow, on the other hand, gives the distance offshore (and from Hatteras). The complementary nature of the information from the two forms of data in this storm is typical.

Preliminary track

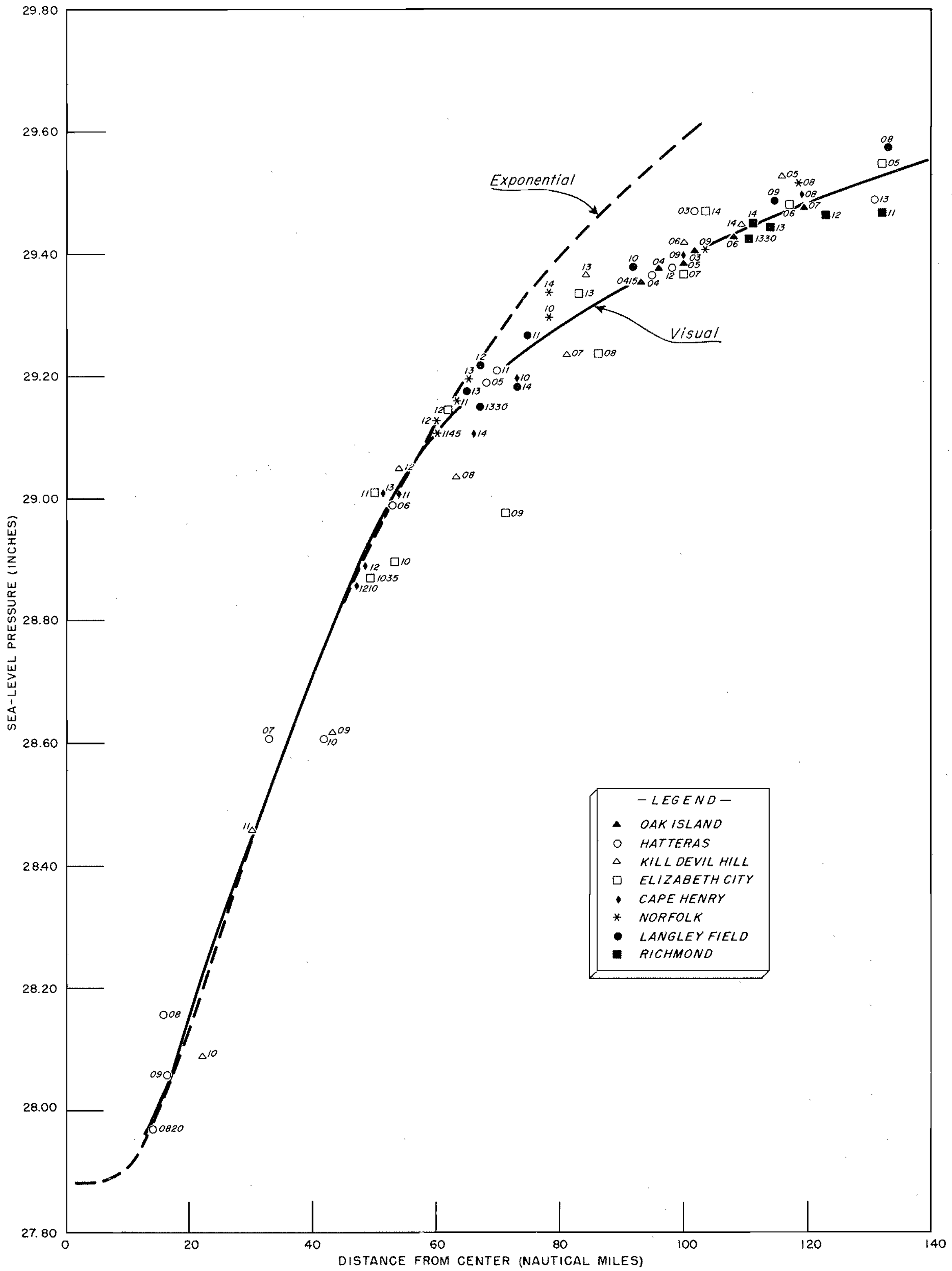
The track was drawn in, and on it were marked, as in figure 2, the hourly positions that most nearly fit the pressure-derived lines of position and the wind arrows. At this step the miscellaneous textual descriptions of shifting winds, calms, damage, etc., were considered and were given weight in laying out the track.

First approximation of pressure profile

Distances from pressure-reporting stations to hourly positions on the preliminary track were scaled off. Observed pressures at one-hour intervals were plotted against the corresponding distances. This step is illustrated in figure 6. Stations were identified by different symbols, and



FIRST APPROXIMATION OF SEA-LEVEL PRESSURE PROFILE
HURRICANE OF SEPT. 14, 1944
FIG. 6



FINAL SEA-LEVEL PRESSURE PROFILE
HURRICANE OF SEPT. 14, 1944
FIG. 7

the points were labeled with the time. The diagram was then inspected for filling or deepening, which would show as a tendency for points pertaining to the later hours to lie highest or lowest on the sheet. If filling or deepening was appreciable, a curve was fitted by eye to the points pertaining to a restricted time-interval; otherwise the curve was fitted to all the points. (In the example, figure 6, storm filling was judged as unimportant.) Mean positions for densely-spaced groups of points were computed as an aid in fitting the curve. The curve is the first approximation of the radial pressure profile.

Final track

A second approximation was made of both track and pressure profile. The preliminary pressure profile (figure 6) was entered with the observed hourly pressures and the corresponding distances read off. Arcs were then constructed on the final hurricane track map (figure 3) with these distances as radii and the pressure-observing stations as centers. New hourly positions were then located at the approximate intersection of the arcs and the final track laid out. The effect of this step is to weigh all of the pressure data in positioning the track, whereas only the minimum and intersection points of barograms had been considered before. A third approximation of the path could be made by repeating the process and drawing new arcs, but this was found to produce significant changes from the second approximation only in exceptional circumstances and was done for a very few storms.

Final pressure profiles

By scaling distances from the final storm-track map as before, plotting pressures, and fitting a curve, the final visually-fitted pressure profile was obtained (solid curve of figure 7). An exponential profile, defined by equation (1), was then fitted. A curve of that family is determined by three points. The exponential profile was computed that passed through the inner end-point of the final visually-fitted profile (which was not projected inward beyond data), the point on the profile 20 nautical miles farther out, and the point 20 miles beyond that. The exponential profile for the example storm is shown by the dashed curve in figure 7. The fit beyond a radius of 60 miles in this example is considerably poorer than average. The exponential profile was fitted to the inner portion of the visually-drawn profile, rather than less exactly to the entire profile, in order to minimize the error in p_o.

Pressure-profile parameters

The immediate goal of the storm analyses, to evaluate the pressure-profile parameters p_o, p_n, and R, was accomplished in fitting the exponential pressure profile. As a check, the R so obtained was compared with an estimate of the radius of maximum wind speed made directly from observed wind-speed data. This check, which will be described later, in some instances lead to modification of the parameters. The final values of the three parameters are listed in table 1. Also included in the table are the lowest pressures that were observed on barometers in the various storms and the place of observation. A hurricane entering the coast at two points, for instance crossing Florida and then striking Louisiana, is listed twice in the table, provided it was still of tropical character at both places and met the intensity criterion. The dates of the second parts of such hurricanes are marked with an asterisk. The convention in the table, and throughout the Report, is that the date of a hurricane will be listed as the day, local standard time, that the center entered the coast or passed closest to land.

Observed radius of maximum winds

The use of autographic records of pressure and of wind direction in the reconstruction of hurricanes and evaluation of the pressure-profile parameters has been described. In a final check, wind-speed records are introduced into the analysis. Values of R determined in fitting the empirical pressure profile are compared, where possible, with the radius of maximum observed wind speed. To accomplish this, average wind speeds for 15-minute intervals were read from the triple-register sheets. (The choice of a 15-minute interval was governed by the lines printed on the chart, which are at 5-minute intervals, with every third line differentiated.) The wind speeds were plotted on a time scale and a smooth curve drawn. A curve of distance from the storm center, as measured from the final track, was constructed on the same time scale. The two curves are shown for the September 1944 example storm in the upper panel of figure 8. An additional particularly clear-cut example is shown in the lower panel of the figure. If the wind-observing station passed within the band of maximum winds, two peaks in the wind graph resulted, as in the lower panel of figure 8. The "observed" radius of maximum winds would be the distance from the wind center (see next paragraph) at the time of these peaks. If the station did not pass within the radius of maximum winds, there would be only one peak in the wind profile. In this case, it was established that the radius of maximum winds was less than the perpendicular distance from station to storm track.

Displacement of wind center from pressure center

In measuring distances of wind-speed observations from a storm center, cognizance had to be taken of the fact that the apparent center of wind rotation and the pressure center in hurricanes are often not coincident. Willis E. Hurd, Chief of the Marine Division of the Weather Bureau for many years, in describing the eye of hurricanes as observed by mariners, notes that the calm center is frequently not coincident with the lowest pressure, and cites reports both of calms preceding minimum pressure, and the reverse sequence of events.6/ Deppermann7/ shows pressure and wind speeds on the same time scale at three stations in a Phillipine typhoon on November 28-29, 1934. At two stations at or near the coast a sharp wind minimum lags 30 to 40 minutes behind the pressure minimum. At the third station, in the interior and possible subject to topographical influences, some fifteen hours later, the wind minimum precedes the pressure minimum by 30 to 40 minutes. It was

Table 1

PRESSURE-PROFILE PARAMETERS - HURRICANES OF 1900-1949

Date	p_o	R	p_n	p_o'	p_a	Station	r	v_{gx}
Sept. 8, 1900	27.64	14	29.78		28.48	Galveston, Tex.	17	104
Aug. 14, 1901	28.72	33	30.16		29.42(a)	New Orleans, La.	45	83
Sept. 11, 1903	29.44	43	30.12	28.84	29.47	Tampa, Fla.	14	76
June 17, 1906	29.09	26	29.98	28.91	29.46	Jupiter, Fla.	29	72
Sept. 17, 1906	29.13	61	30.38	28.98	29.50	Columbia, S. C.	28	71
Sept. 27, 1906	28.50	57	30.07		28.50	Ship at Scranton, Miss.	5	83
Oct. 18, 1906	28.98	35	29.80	28.84	29.26	Jupiter, Fla.	33	67
July 21, 1909	28.41	19	30.27	28.31	29.00	Bay City, Tex.	16	99
Sept. 20, 1909	29.06	88	30.30	28.94	29.23	New Orleans, La.	43	73
Oct. 11, 1909	28.30	24	30.07		28.36	Sand Key, Fla.	7	94
Oct. 17, 1910	27.80	16	29.19		27.80	S.S. Jean 12 mi. S. Dry Tortugas, Fla.	0	84
*Oct. 18, 1910	28.50	48	29.77	28.33	28.94	Tampa, Fla.	45	81
Aug. 28, 1911	29.02	44	30.10	28.92	29.02	Savannah, Ga.	6	73
Sept. 3, 1913	29.36	41	29.98	28.81	29.36	Raleigh, N. C.	6	72
Aug. 16, 1915	28.14	32	29.57		28.14	Velasco, Tex.	4	83
Sept. 29, 1915	27.87	29	30.14		28.01	New Orleans, La.(Pauline St.wharf)	12	106
July 5, 1916	28.57	50	30.03		28.92	Mobile, Ala.	32	81
Aug. 18, 1916	28.00	35	30.77		28.00	Santa Gertrudis, Tex.	6	116
Oct. 18, 1916	28.76	44	30.20		28.76	Pensacola, Fla.	0	81
Sept. 28, 1917	28.48	31	29.88		28.51	Pensacola, Fla.	12	81
Sept. 9, 1919	27.44	15	29.73		27.44	Mean of 2 ships and Dry Tortugas, Fla.	0	108
*Sept. 14, 1919	28.65	75	29.54		28.65	Corpus Christi, Tex.	13	58
Sept. 21, 1920	28.93	28	29.90		28.99	Houma, La.	10	67
June 22, 1921	28.38	17	30.03	28.17	29.37	Houston, Tex.	33	97
Oct. 25, 1921	28.29	18	29.59		28.29	Tarpon Springs, Fla.	1	80
Aug. 25, 1924	28.70	89	30.33		28.80	Hatteras, N. C.	28	78
*Aug. 26, 1924	28.70	55	29.62		28.71	Nantucket, Mass.	12	59
Oct. 19, 1924	28.70	19	29.82		---	Nr Dry Tortugas, Fla.	(b)	75
*Oct. 20, 1924	29.10	25	29.62	28.83	29.10	Miami, Fla.	0	62
Dec. 2, 1925	28.95	49	29.90		29.17	Wilmington, N. C.	35	62
July 28, 1926	28.34	14	29.91		28.80	Meritt Island, Fla.	11	89
Aug. 25, 1926	28.31	27	30.35		28.31	Houma, La.	3	100
Sept. 18, 1926	27.59	24	29.99		27.61	Miami, Fla.	4	110
*Sept. 20, 1926	28.20	24	30.13		28.20	Perdido Beach, Ala.	1	98
Oct. 20, 1926	27.52	21	29.97		29.16	Key West, Fla.	60	112
Sept. 16, 1928	27.62	28	30.38		27.62	West Palm Beach, Fla. Everglades Exp. Sta.	3	117
June 28, 1929	28.62	13	29.97		29.12	Port O'Connor, Tex.	13	82
Sept. 28, 1929	28.15	28	30.08		28.18	Long Key, Fla.	7	98
*Sept. 30, 1929	28.80	58	29.96		28.80	Panama City, Fla.	6	70
Aug. 13, 1932	27.83	12	30.11		27.83	East Columbia, Tex.	0	108
Aug. 4, 1933	28.80	24	29.96		28.98	Brownsville, Tex.	15	76
Aug. 23, 1933	28.63	54	29.48		28.66	Cape Henry, Va.	16	58
Sept. 4, 1933	27.98	13	29.98		27.98	Jupiter, Fla.	0	101
Sept. 5, 1933	28.02	30	30.24		28.07	Brownsville, Tex.	2	105

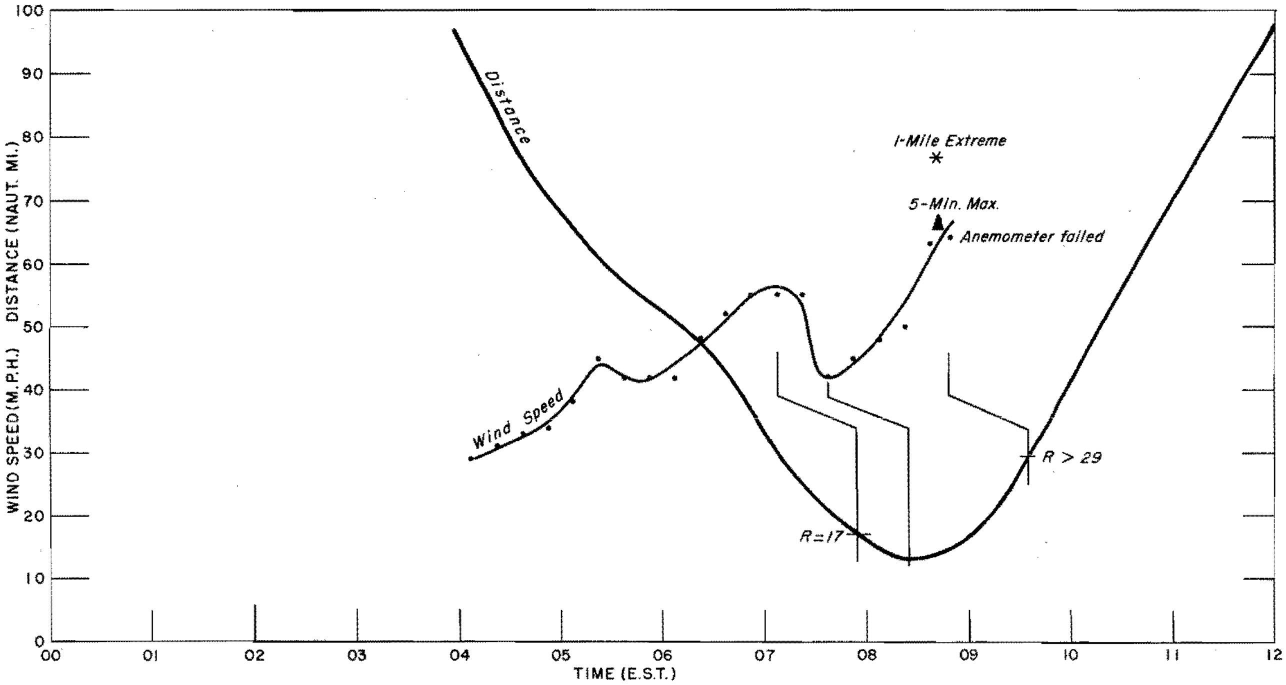
Date	p_o	R	p_n	p_o'	p_a	Station	r	v_{gx}
Sept. 16, 1933	28.25	42	29.82		28.25	Hatteras, N. C.	7	84
June 16, 1934	28.58	37	29.94		28.58	Jeanerette, La.	0	80
Sept. 2, 1935	26.35	6	29.92		26.35	Long Key, Fla.	0	137
*Sept. 4, 1935	29.11	51	29.89	28.71	29.18	Columbia, S. C.	30	71
Nov. 4, 1935	28.73	--	---		28.73	Miami, Fla.	0	79
July 31, 1936	28.73	19	30.00		28.73	Valpariso, Fla.	0	80
Sept. 18, 1936	28.53	34	29.42		28.52	Mean of 2 ships off Hatteras, N.C.	0	63
Sept. 21, 1938	28.00	35	29.52		28.04	Hartford, Conn.	7	83
Aug. 7, 1940	28.76	11	29.75		28.87	Port Arthur, Tex.	5	71
Aug. 11, 1940	28.78	26	30.02		28.78	Savannah, Ga. WBO	2	77
Sept. 23, 1941	28.66	21	29.66	28.31	28.66	Houston, Tex. WBO	0	81
Oct. 7, 1941	28.98	18	30.19		29.00	Carrabelle, Fla.	0	78
Aug. 30, 1942	28.07	18	29.64		28.10	Seadrift, Tex.	4	88
July 27, 1943	28.78	17	30.02		28.78	Ellington Field, Tex.	2	78
Sept. 14, 1944	27.88	49	30.66		27.97	Hatteras, N. C.	14	113
*Sept. 14, 1944	28.31	26	29.39		28.31	Point Judith, R. I.	3	71
Oct. 18, 1944	28.02	27	29.80		28.02	Dry Tortugas, Fla.	4	93
*Oct. 19, 1944	28.42	34	29.67		28.42	Sarasota, Fla.	1	77
Aug. 27, 1945	28.57	18	30.13		28.57	Palacios, Tex.	1	88
Sept. 15, 1945	28.09	12	30.00		28.09	Homestead, Fla.(Fla.E.Coast R.R.)	0	99
Sept. 17, 1947	27.76	19	29.83		27.97	Hillsboro, Fla.	8	102
Sept. 19, 1947	28.61	28	29.70		28.61	New Orleans, La. WBO	2	72
Oct. 15, 1947	28.59	13	29.65		28.76	Savannah, Ga. WBAS	7	73
Sept. 21, 1948	27.62	7	29.61		28.45	Key West, Fla. WBO	8	102
*Sept. 22, 1948	28.41	16	29.83		28.47	Clewiston, Fla.	8	85
Oct. 5, 1948	28.85	27	29.77		28.92	Miami, Fla., WBAS	2	67
Aug. 24, 1949	28.86	24	30.20		28.86	Diamond Shoals Lightship, N.C.	3	80
Aug. 26, 1949	28.16	22	30.12		28.17	West Palm Beach, Fla. WBAS	0	99
Oct. 4, 1949	28.88	28	30.13		28.88	Freeport, Tex.	0	78

Legend

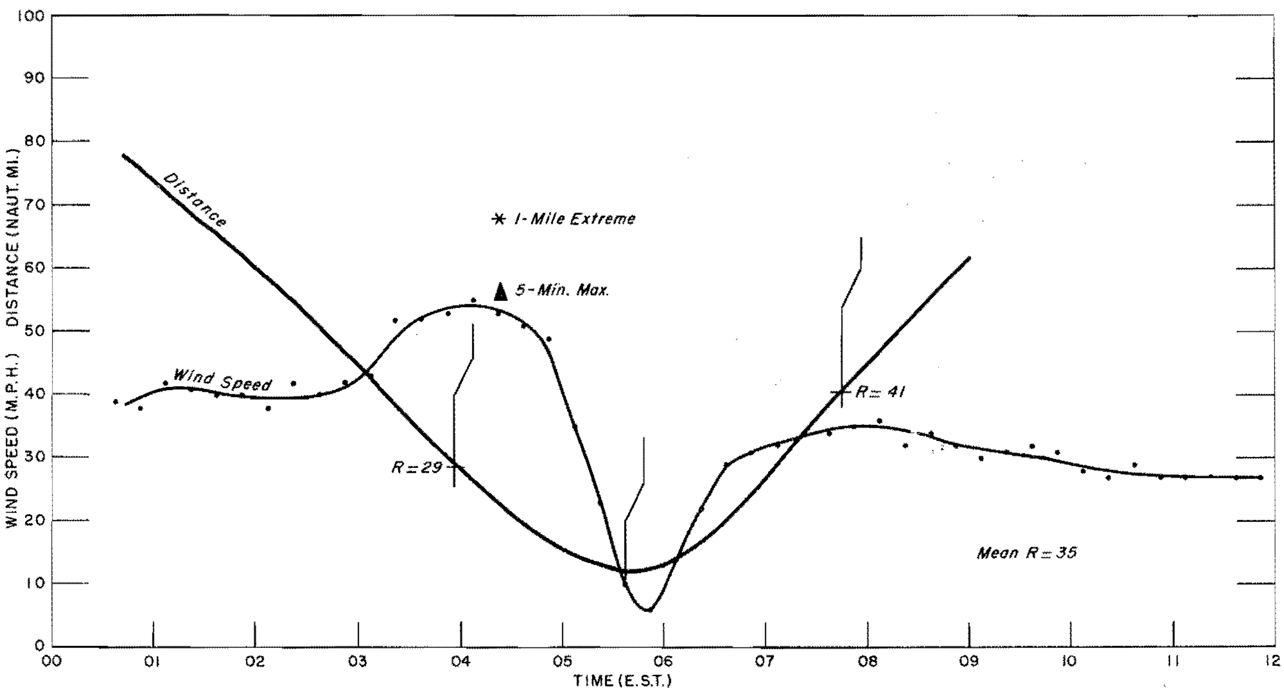
p_o - central pressure in inches.
R - radius of maximum winds in nautical miles.
p_n - assymptotic pressure in inches.
p_o' - central pressure adjusted to the coast.
p_a - lowest actually-observed pressure in inches.
Station - at which p_a was observed.
r - minimum distance in nautical miles from station to to storm center.
v_{gx} - maximum gradient wind speed, in m.p.h.

Notes

* - Same hurricane as preceding line.
(a) - At stage when pressure profile parameters were computed. 29.31 inches observed at Mobile, Ala., later.
(b) - Parameters obtained by interpolation between ship off western end of Cuba and Miami, and apply to vicinity of Dry Tortugas.



HATTERAS, N. C. SEPT. 14, 1944



TAMPA, FLA. OCT. 18, 1944

HURRICANE SPEED-DISTANCE-TIME GRAPHS

FIG. 8

confirmed in the analysis of the August 26, 1949 hurricane by the Hydrometeorological Section,1/ that the apparent wind center was 6 to 7 miles to the rear and a fraction of a mile to the left of the pressure center. In fact, it can be shown on theoretical grounds that the wind and pressure centers in a moving circular storm should not be coincident.

Table 2

DISPLACEMENT OF WIND CENTER FROM PRESSURE CENTER

	Hours along Track	No. of Cases
Wind Center Ahead	2.1 - 2.5	1
	1.6 - 2.0	0
	1.1 - 1.5	2
	0.6 - 1.0	5
	0.1 - 0.5	7
	0	16
Wind Center Behind	0.1 - 0.5	22
	0.6 - 1.0	14
	1.1 - 1.5	6
	1.6 - 2.0	3
	2.1 - 2.5	0

Distances scaled from the track map pertain to the pressure center. An approximate allowance was made for the displacement of the wind center from the pressure center by shifting the distance curve on the time scale of the graphs like figure 8. If the station passed within the radius of maximum winds, the distance curve was shifted to the point where the minimum distance was coincident with the minimum speed between the two peaks of the speed curve; if the station did not pass within the radius of maximum winds, the distance curve was shifted so as to make the minimum distance coincident with the maximum speed. Both panels of figure 8 illustrate the former type of adjustment. Instead of actually redrawing a curve, elbowed light lines were constructed at the desired reference points as in figure 8. The upper ends pertain to the wind-speed curve, the lower ends to the distance curve. This adjustment compensates not only for real departures of the wind and pressure centers from coincidence, but also for analysis discrepancies and the like. The majority of the wind centers appeared to lag behind the pressure center, as in the lower panel of figure 8, while in a few instances, the wind center was in advance, as in the upper part. On many of the graphs the wind peaks were less definite, and there were possible alternative interpretations as to which peaks in the wind speed truly indicated the radius of maximum winds and which peaks and valleys were of the nature of fluctuations similar to gustiness. In the upper panel of figure 8 the minimum wind speed, for the 0730-0745 interval, would be subject to doubt on this basis if it were not for the associated fact that the most rapid backing of the wind occurs but a few minutes later. As a by-product of the analyses, a frequency distribution of the displacement of the centers is given in table 2, and shows that the wind center is most frequently to the rear of the pressure center.

Observed R vs parametric R

Values of R obtained as described above from the wind profiles are compared with the parametric values of R derived in fitting the pressure profile in figure 9. Where the station passed within the radius of maximum winds and a specific estimate of R was obtained from the wind-speed graph, a dot is plotted. Where the station did not pass within the radius of maximum winds and the only estimate from the wind-speed graph is that R is less than a certain value, a triangle is plotted. If the correspondence were perfect, all of the dots would fall on the 45° line and the triangles on or above the line.

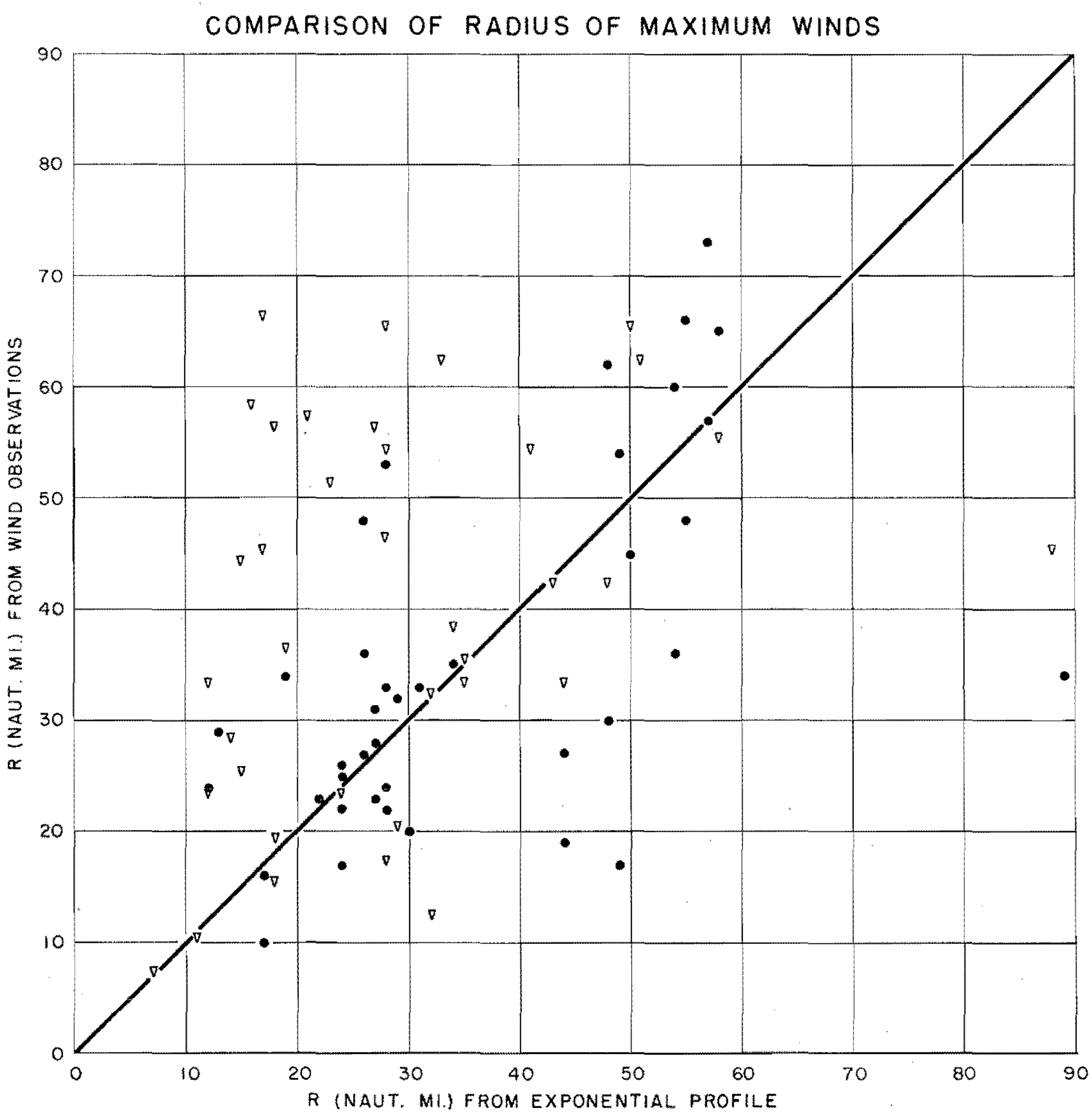


FIG. 9

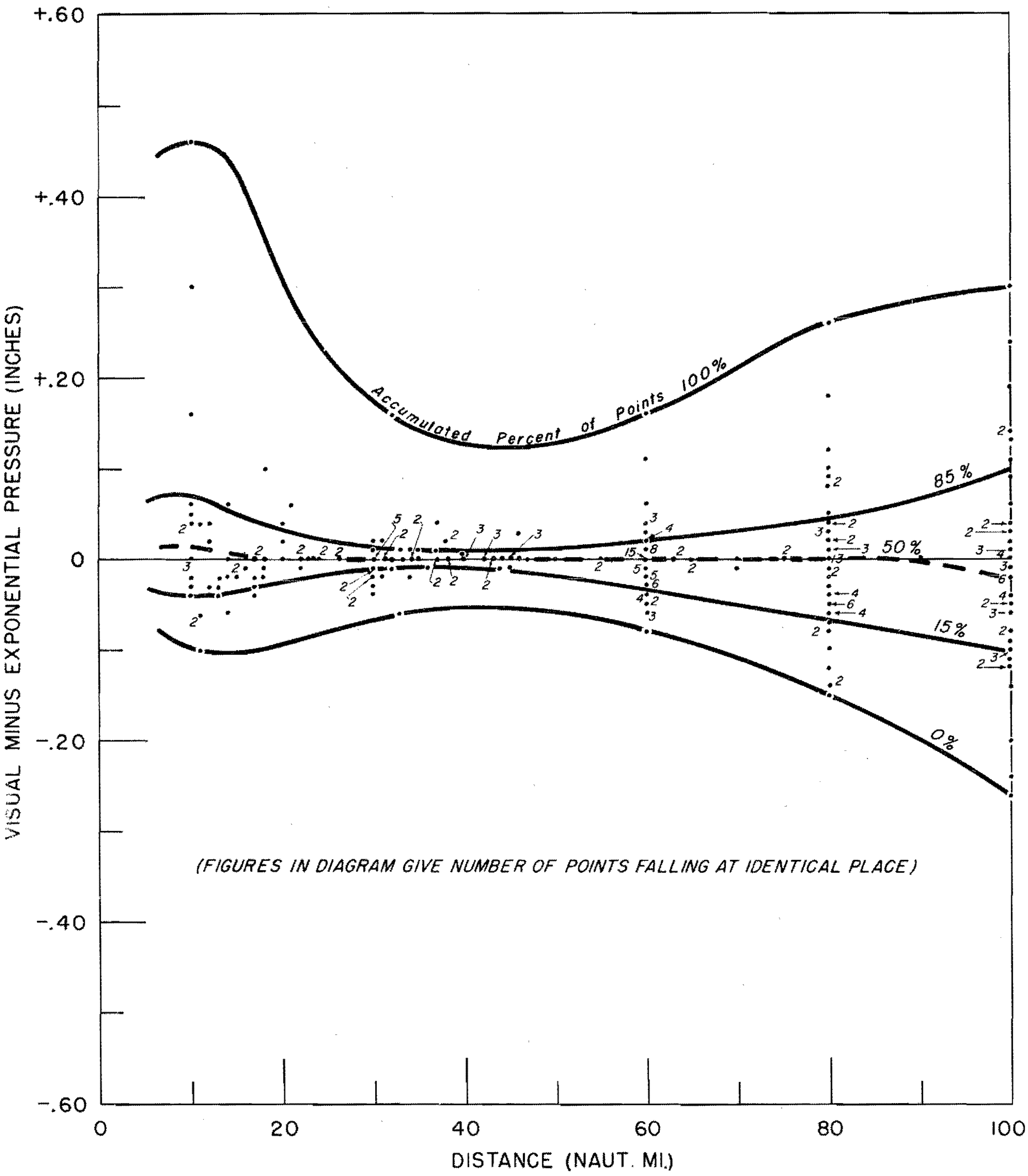
The comparison of the values of R served as a double check, on the analysis of each individual hurricane and on the hurricane model itself. Any marked lack of correspondence of the two R's lead to a re-evaluation of the analysis of the storm. At steps where alternate solutions confronted the analyst, that solution was given extra weight which would tend to bring the R's together. The final values of R are plotted in the figure. It is not surprising that even with this re-evaluation there is a considerable discrepancy between corresponding R's in a few instances. Our idealized circular model should be expected to fit some hurricanes less well than others. On the whole, the grouping of the dots in figure 9 about the 45° line is sufficiently close and sufficiently symmetrical to give confidence to the physical reality of the parameter R in our model. The correspondence is considered sufficiently good to warrant this conclusion in spite of the bias of the R's toward each other introduced by re-evaluation of analyses.

Test of fit of exponential pressure profiles

Figure 9 presented a test of the applicability of the Hydrometeorological Section pressure-profile formula, equation (1), to observed wind fields. A test of the correspondence of the formula to observed pressures is shown in figure 10. Differences, in inches, between the visually-drawn profile and the corresponding exponential pressure profile at selected radii for each storm are plotted. At the three points through which the exponential pressure profile was fitted, the difference would be zero. To obtain maximum differences, the distances at which the differences were taken were: halfway between the first and second fitted points, halfway between the second and third, and at 60, 80, and 100 miles outward if beyond the third fitted point. The bulge in the frequency lines to the left is due to the fact that in this region the slope of the pressure profiles is quite steep and the vertical distance between the profiles may be considerable, even though there appears to be a good fit. The spread of the frequency lines to the right is due to the fact that the fitting was to the innermost (lefthand) portion. The over-all correspondence of exponential to visually-fitted profile was considered quite satisfactory.

Test of path method

The validity of the analysis method when but few data are available was tested by using two storms in later years for which there were more data. These were the storms of September 23, 1941, in Texas and October 19, 1944, in Florida. Four barograms for the first storm and five or six for the second were given to each of three analysts familiar with the path method. No other information was provided. Tracks and pressure profiles, with standard first and second approximations, were computed independently by the three analysts for each of the two storms. The test tracks and final track for one of the storms are shown in figure 11. The test pressure-profile parameters obtained, as well as the final values based on all the data, are shown in table 3.



DIFFERENCES IN PRESSURE BETWEEN EXPONENTIAL PROFILES AND VISUALLY FITTED PROFILES

FIG. 10

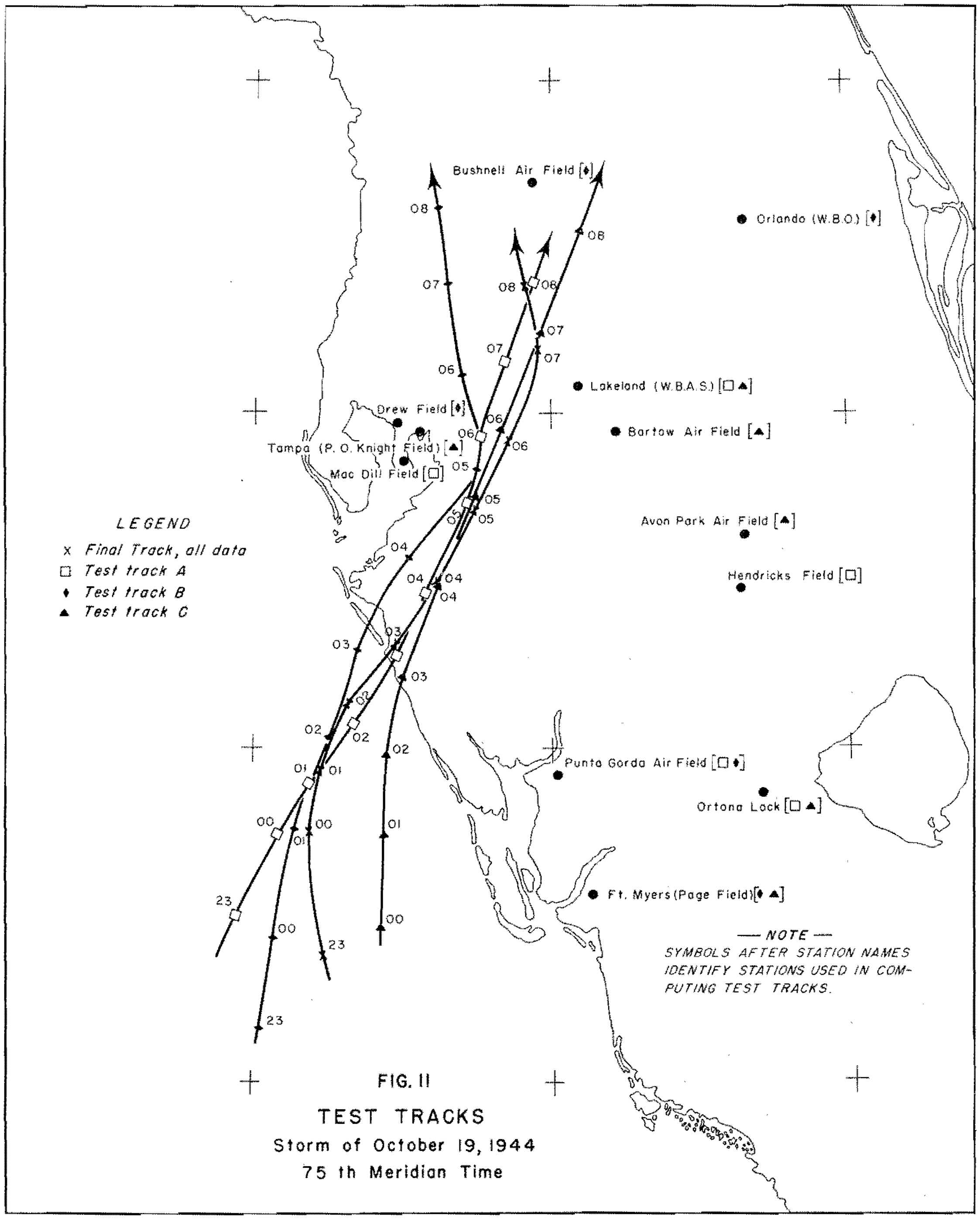


FIG. 11

TEST TRACKS

Storm of October 19, 1944

75 th Meridian Time

Table 3

PRESSURE-PROFILE PARAMETERS FOR TEST STORMS

	p_o (inches)	R (naut. mi.)	p_n (inches)
		September 23, 1941	
Test A	28.63	24	29.77
Test B	28.70	17	29.67
Test C	28.74	35	29.97
All Data	28.74	30	29.86
		October 19, 1944	
Test A	28.38	35	29.73
Test B	28.52	60	30.01
Test C	28.40	32	29.75
All Data	28.32	42	29.96

The tracks and parameters for "all data" are based on winds as well as pressures. Winds were not considered in the test analyses. It can be noted in the table that the central pressures correspond fairly well. The values of R leave something to be desired. Wind data, not used in the test analyses, would control this to some extent for those storms in which wind data were available. The maximum displacement of a test track from the final track for the 1944 storm was 20 miles (track B at 0700). The maximum displacement for the 1941 test tracks was 21 miles. The displacements were considerably less nearest the pressure-observing stations.

Paths of fifty years of hurricanes

The computed hurricane paths are reproduced in appendix C. Interest in sinuosities in hurricane paths has been stimulated by Yeh[8]. Since the analysis procedure could operate either to smooth out real irregularities in the hurricane paths or to introduce spurious ones, no definitive conclusions as to the reality or nature of sinuosities are warranted from the tracks, some of which are smooth curves and some of which are more irregular. Some analysts tended to smooth out irregularities more than others. It is the impression of the writer, however, that many hurricanes do indeed move quite smoothly and that others move irregularly both in path and speed. There were insufficient observations compared to the number of degrees of freedom to ascertain if the irregularities had any systematic oscillating pattern.

Chapter II

PRESSURES

Frequency distribution of central pressures

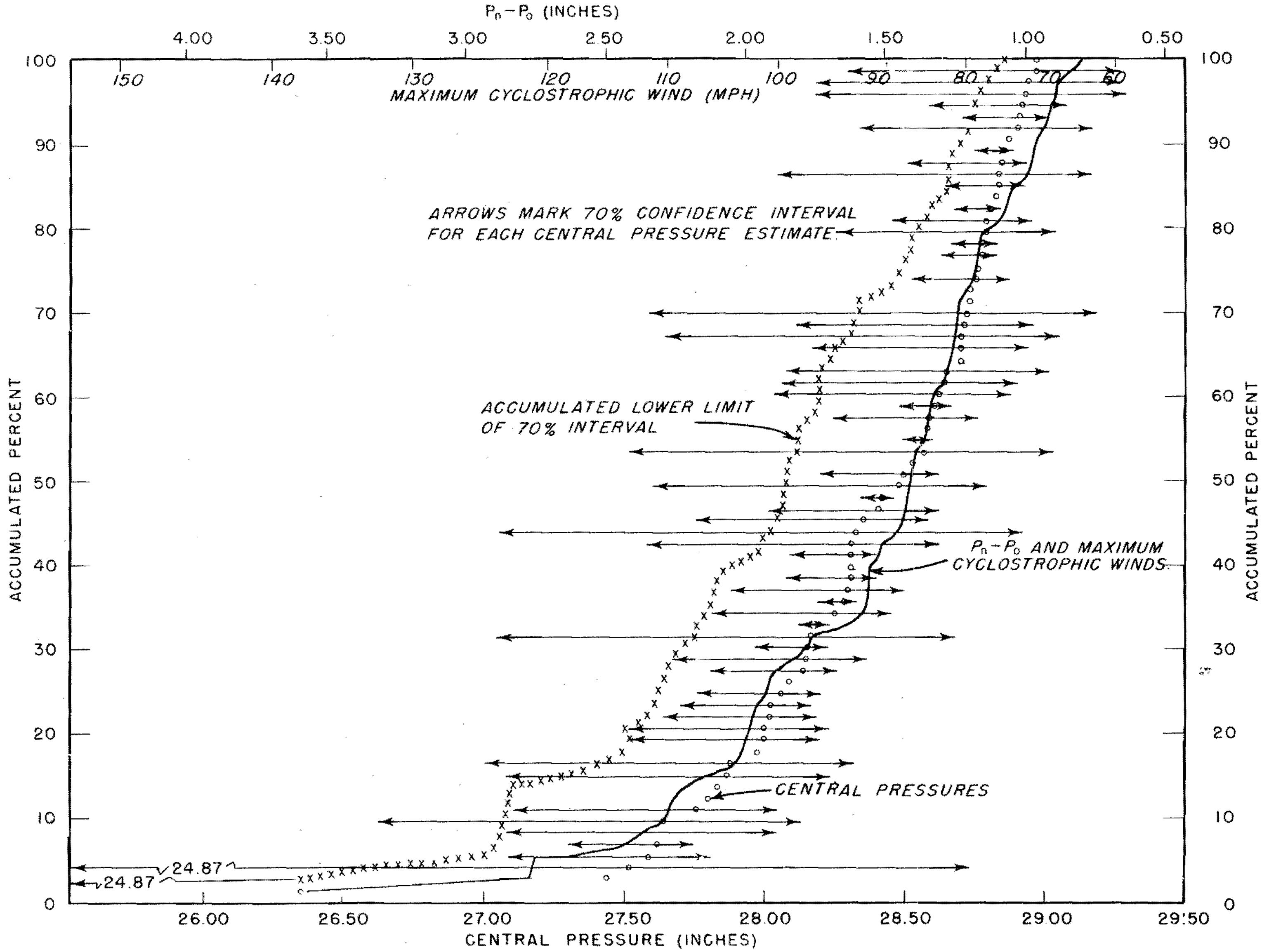
The values of the central pressure, p_o, for the hurricanes during the years 1900-1949, obtained by the analysis described in chapter I, are listed in table 1. The p_o's in the table pertain most closely to the moment in time and point in space at which the storm center was closest to the station that reported the lowest observed pressure for the storm. The lowest observed pressures, most of which are from stations on or near the coast, are also listed in table 1, with the reporting stations. To place all the central pressures on a common basis, those p_o's for which the lowest observed pressure in the storm was from a station well inland, such as Houston, Tex., or at a coastal station when the storm was emerging from land to sea, were adjusted back to the coast where the storm entered land. The adjustments were based on the average rate of filling developed in chapter V. The criterion was set up that an adjustment to coast would be made in p_o if the lowest observed pressure occurred after the storm center had been over land for more than two hours, after the center had moved inland a distance along its track of more than twenty nautical miles. The adjusted central pressures are listed in table 1 under the designation p_o'. Adjustments were required in 13 storms.

The central pressures, adjusted to the coast where required, are plotted as an accumulated frequency distribution in figure 12, (small circles). It is seen that there are but two values below 27.50 inches. Only twenty percent of the values are below 28.00 inches. The record low pressure of 26.35 inches lies far beyond all the other data, the next higher central-pressure estimate being 27.45, more than an inch higher. The figure brings out that for the pressure to fall as low as 26.35 inches in a hurricane near the United States is indeed a phenomenal event, and not that it is merely rare for such a pressure to be <u>detected</u>.

The central pressures were plotted on both logarithmic and normal probability paper. The points did not fall in a straight line on either type, and the linear presentation of figure 12 was considered the most satisfactory.

Pressure differences

Although the central pressure is one index of the intensity of a hurricane, a more precise index is the pressure difference, $p_n - p_o$. The relation of the pressure difference to storm intensity, as indicated



ACCUMULATED FREQUENCY OF HURRICANE CENTRAL PRESSURES, PRESSURE DIFFERENCES, AND MAXIMUM CYCLOSTROPHIC WINDS. 1900–1949

FIG. 12

by v_{cx}, the maximum speed of the cyclostrophic wind, is obtained by substituting $r = R$ in the general expression for the cyclostrophic wind, equation (4),

$$v_{cx}^2 = \frac{p_n - p_o}{\rho e} \qquad (6)$$

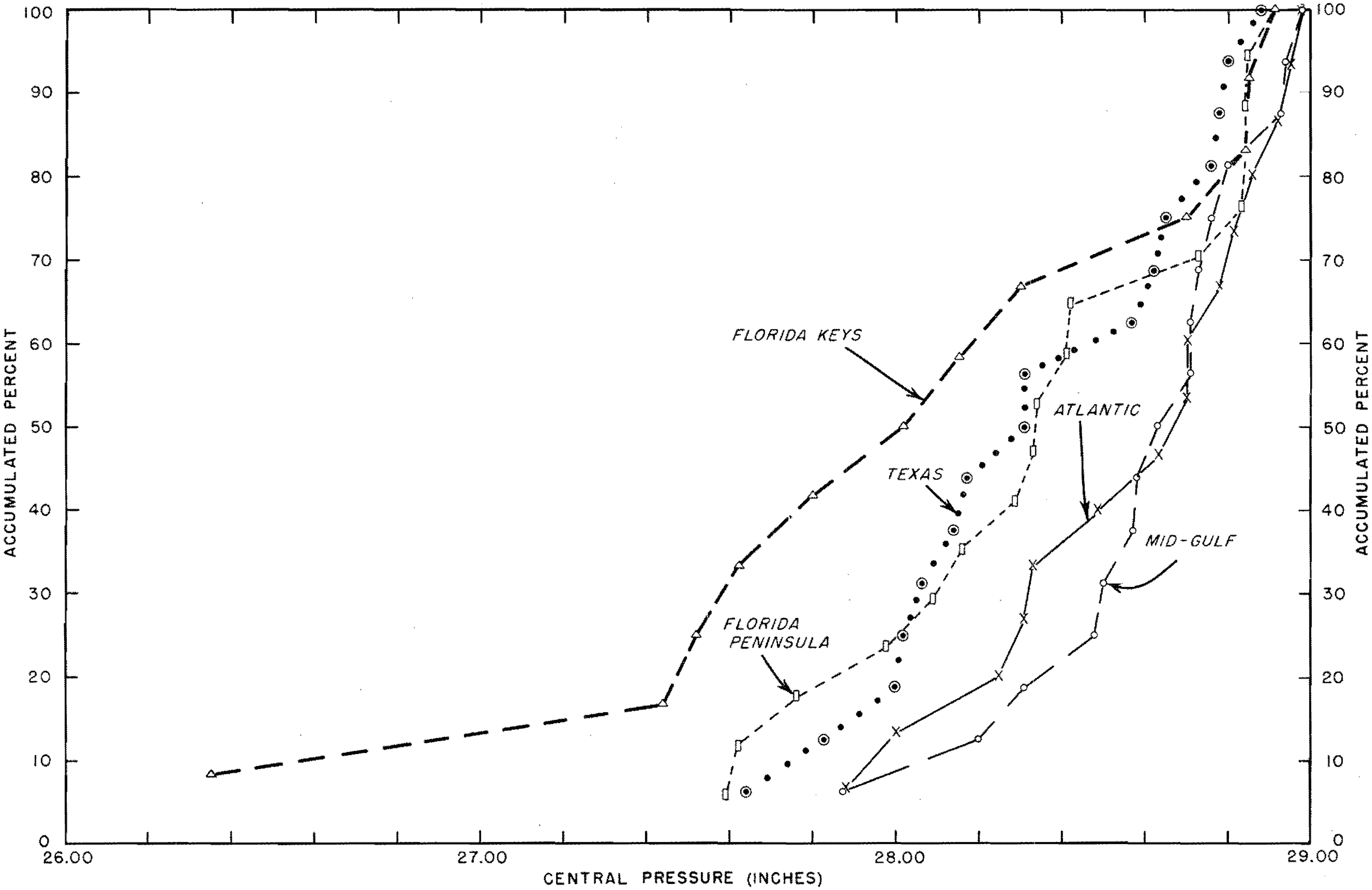
If variations in the density, ρ, are neglected, v_{cx} is completely dependent on $p_n - p_o$. It is worthy of note that v_{cx} is independent of the radius of maximum winds, R. The pressure differences, obtained by subtraction of values in table 1, are parametric values derived by fitting the exponential pressure profile to a 40-mile segment of the visually-drawn radial profile, and p_n may be greater or smaller than the real pressure at the outskirts of the storm. The average p_n was 29.94 inches, with a standard deviation of 0.30 inch.

The accumulated frequency distribution of values of $p_n - p_o$ is shown in figure 12 (solid curve). For storms in which an adjustment to the coast was made in the central pressure, the adjusted pressure difference was taken as the originally computed p_n minus the adjusted central pressure, p_o'. That is, it was assumed that there was no change in p_n over the interval of time for which the central pressure was adjusted. As would be expected, the pressure-difference curve closely parallels the central-pressure curve. (The pressure-difference and central-pressure scales are so aligned that if p_n equals the average value of 29.94 inches, points on one scale will coincide with points on the other). The most important departure between the two curves is that three storms drop closer to the record September 1935 values on the pressure-difference curve than on the central-pressure curve. The extreme pressure difference is 3.57 inches. The next three highest values are 2.78, 2.77, and 2.76 inches, all smaller than the extreme by less than an inch. This does not alter the previous conclusion that a central pressure on the order of 26.35 inches (or a pressure difference on the order of 3.5 inches) is an exceedingly rare event.

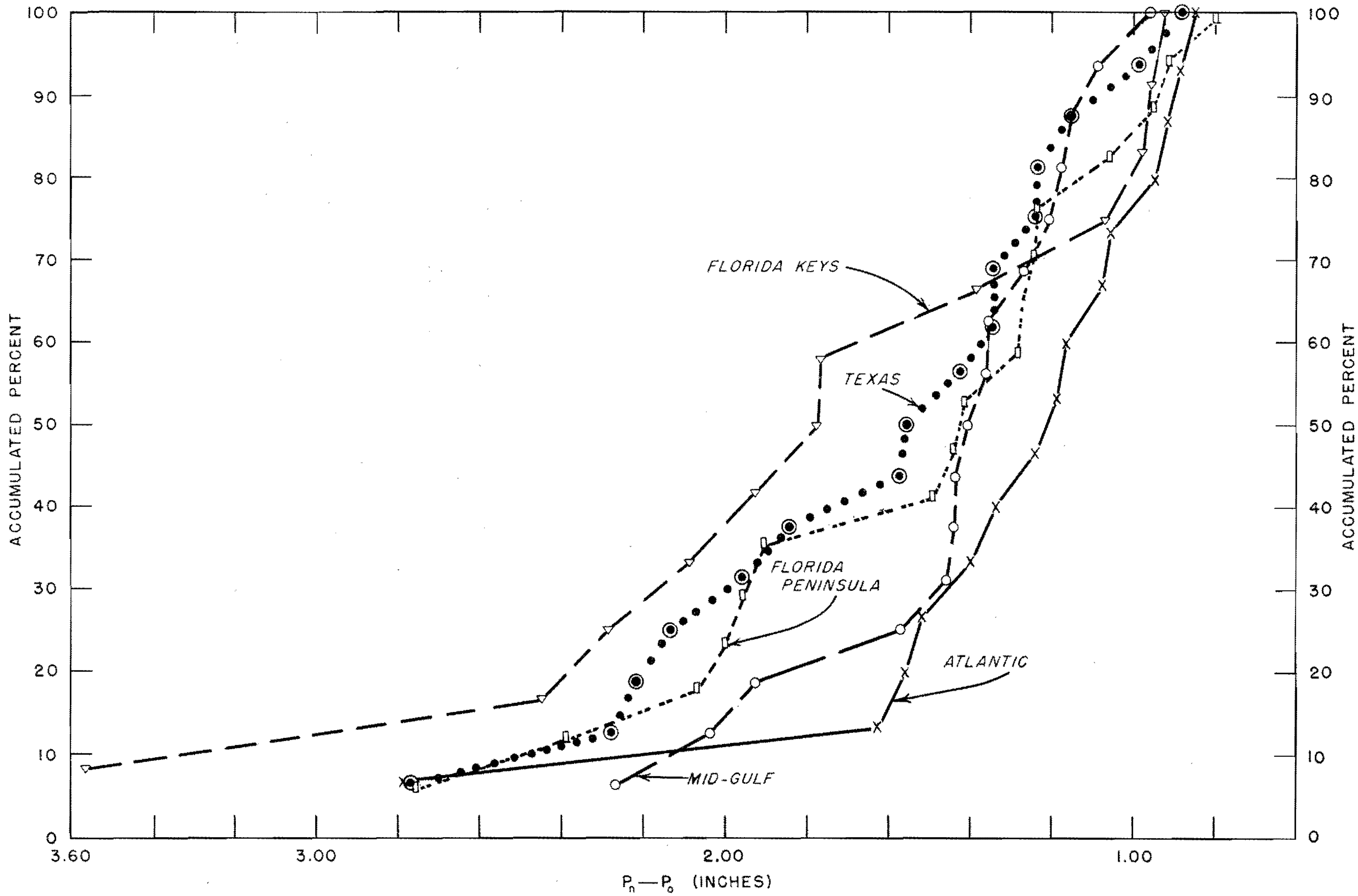
As shown by equation (6), the frequency curve for the pressure differences is also a frequency curve of the square of the maximum cyclostrophic wind speed. The pressure-difference scale was converted to the scale of maximum cyclostrophic speed shown in figure 12 by substituting in equation (6). With an air density of 1.175×10^{-3} gm/cm^3, the density of saturated air at a temperature of 68°F and a pressure of 1000 mb, and with a wind speed in miles per hour and pressure in inches of mercury, equation (6) reduces to:

$$v_{cx} = 72.8\,(p_n - p_o)^{\frac{1}{2}} \qquad (7)$$

The greatest departure from the adopted density at the radius of maximum winds in any hurricane was 10 percent in the record September 1935 storm.



ACCUMULATED FREQUENCY OF HURRICANE CENTRAL PRESSURES BY REGIONS
1900-1949
FIG. 13



ACCUMULATED FREQUENCY OF HURRICANE PRESSURE DIFFERENCES BY REGIONS. 1900—1949

FIG. 14

There is further discussion of the distribution of wind speeds in chapter IV.

Regional distribution of central pressures and pressure differences

Since the distribution of central pressures and pressure differences in particular regions, especially Florida, was of interest, the values were separated into five geographical groups, the Atlantic Coast north of Florida, the Florida Peninsula, the Florida Keys, the Gulf Coast from northern Florida to the Texas-Louisiana border, and the Texas coast. Accumulated frequency distributions of the central pressures and pressure differences for the various regions are shown in figures 13 and 14. It can be noted that the central pressure is not so low, nor the pressure difference so great, with increasing distance from the hurricane source region over tropical waters. There are no central pressures below 27.50 inches outside the Florida Keys, the area of the United States closest to the hurricane source region. Other areas, however, by virtue of a high value of p_n, contributed relatively larger values of the pressure difference, but none approached the record value in the Keys, 3.57 inches.

Test of p_o's

To check the reliability of the frequency distributions of figures 12-14, which are frequencies of estimated quantities, a test was set up to furnish an analysis of errors in estimating p_o. Variation in p_o is much greater than that in p_n. The reliability of $p_n - p_o$ is about the same as the reliability of p_o, and no specific test, as such, was made of $p_n - p_o$. The principal factors that influence the error in the central-pressure estimate are the extrapolation distance, that is, the distance from the closest observed pressure to the storm center, and the value of the central pressure itself.

The test of the p_o estimates was carried out on the hurricanes in which there was a pressure report within five miles of the storm center. The p_o's in these storms were considered the equivalent of observed values. Estimating p_o with the closest observed pressure 20 miles out from the center was then simulated by discarding the portion of each visually-drawn profile within 20 nautical miles of the center of each test storm and fitting the exponential profile objectively by standard procedures to the remainder. The differences between the p_o's for these test exponential profiles and the p_o's originally computed were taken as a representative body of errors in p_o with an extrapolation distance of 20 miles. The procedure was then carried out for 40 miles and 60 miles from the center, with the same storms. The three sets of errors were subjected to a statistical analysis.

Extrapolation distance vs. p_o error

The central-pressure errors are plotted against distance in figure 15. The increase in magnitude of the error with extrapolation distance can be noted. The distribution of the errors at any one distance is skewed, negative errors tending to be larger than positive errors. The fact that there is an upper limit to the central-pressure estimate, which can certainly be no higher than the lowest reliable observed pressure, while there is no such lower limit, is responsible for the skewness.

The primary purpose of figure 15 is to demonstrate the acceptability of the assumption that the standard deviation of the errors increases with increasing extrapolation distance while in other respects the distribution remains unchanged and has the same shape at all distances. The solid lines in the figure are frequency curves drawn strictly to the data. The dashed lines are the 15% and 85% frequency curves that best fit the data within the limits of the assumption. The moderate departure of the dashed curves from the corresponding solid curves is considered acceptable.

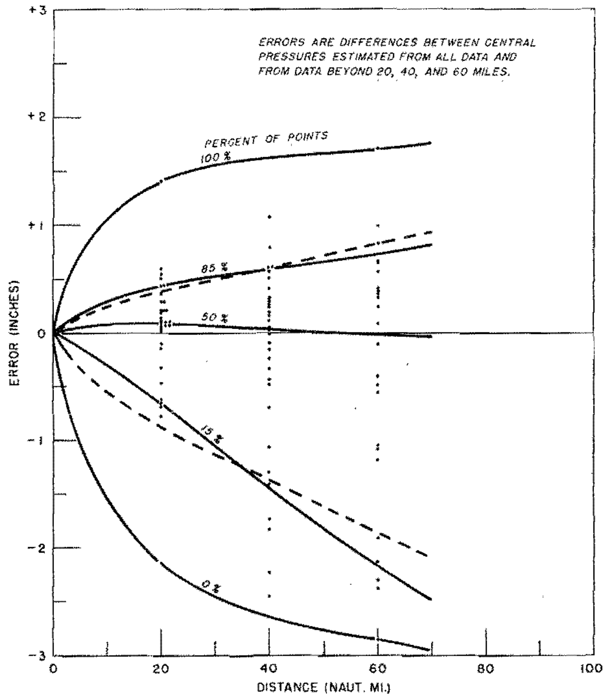
The standard deviations of the errors at 20, 40, and 60 miles, respectively, are plotted against distance in figure 16. That the three points lie in a straight line lends some confidence to extrapolation of the standard deviation beyond 60 miles and to the validity of the assumption stated in the preceding paragraph.

p_o vs. p_o error

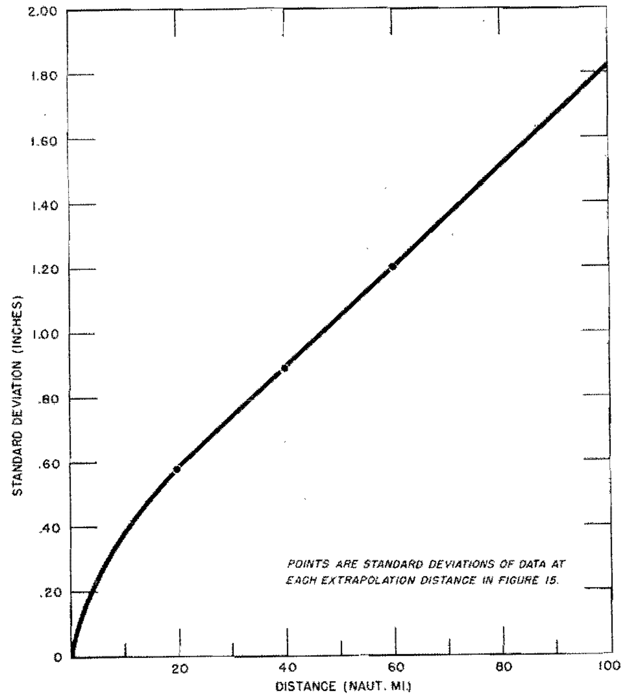
The three standard deviations plotted in figure 16 were used to adjust the errors in the three categories, from 20, 40, and 60 miles, to a common basis for examining the effect of p_o itself on the error in its estimation. Each error was divided by the corresponding standard deviation, and the resulting ratios (standard measure) were plotted against the corresponding originally computed p_o (figure 17). With the influence of the extrapolation distance thus removed, it is seen that the central-pressure error becomes greater as the central pressure becomes lower. The skewness in figure 15 is again found here. The frequency curves were fitted by eye. An attempt was made to fit a distribution with a mathematical basis, but the unusual nature of the data, with a variable and not well-specified upper limit and no lower limit, made the effort fruitless.

Confidence interval for central pressures

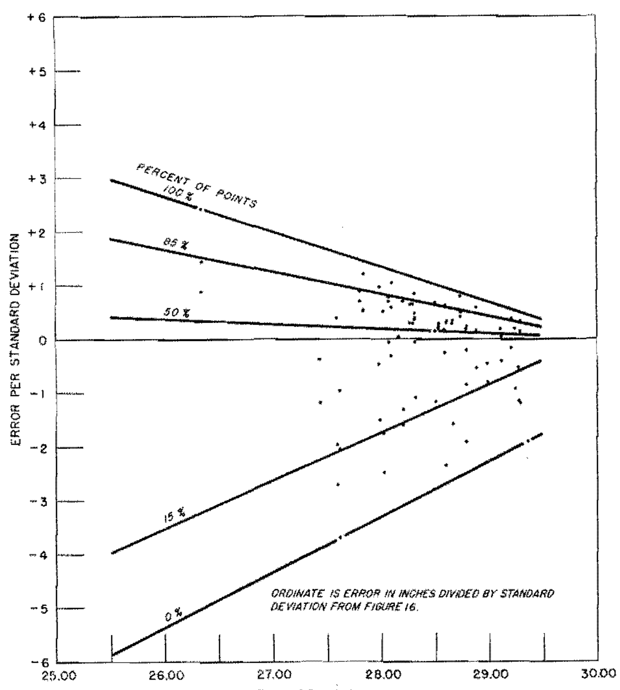
Figures 16 and 17 furnish the basis for placing a confidence interval about any central-pressure estimate. Figure 17 is entered at the central pressure. Opposite the upper and lower limits of the desired frequency range, values are read from the left-hand scale. Multiplying these values by the standard deviation taken from figure 16 at the pertinent extrapolation distance yields the magnitude of the negative and positive errors



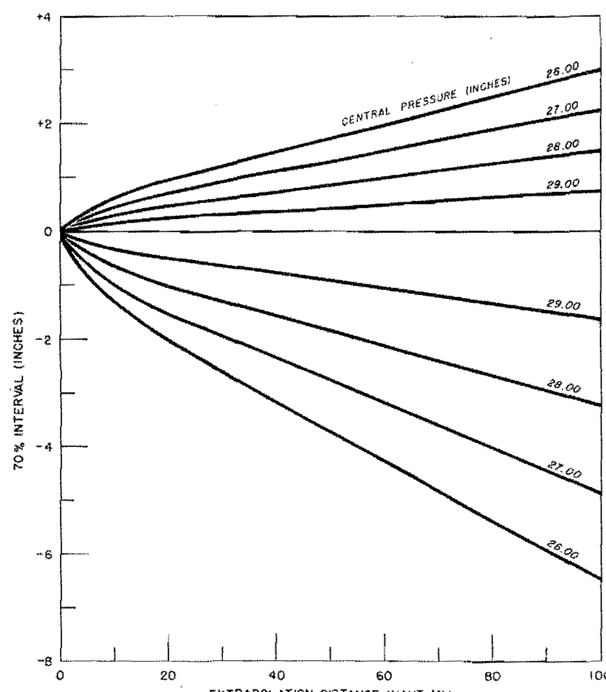
ERRORS IN ESTIMATES OF HURRICANE CENTRAL PRESSURE AS A FUNCTION OF EXTRAPOLATION DISTANCE
FIG. 15



STANDARD DEVIATION OF ERRORS IN ESTIMATES OF HURRICANE CENTRAL PRESSURE.
FIG. 16



ADJUSTED ERRORS IN ESTIMATES OF HURRICANE CENTRAL PRESSURE AS A FUNCTION OF THE CENTRAL PRESSURE
FIG. 17



70 % CONFIDENCE INTERVAL FOR HURRICANE CENTRAL PRESSURE ESTIMATES
FIG. 18

within the desired confidence band, in inches. By following this procedure the 70% confidence band (between frequencies of 15% and 85%) was computed for a large number of central pressures and extrapolation distances, and figure 18 was constructed. The latter figure gives directly the negative and positive error, in inches, within the 70% band. For example, if the central pressure is estimated at 27.00 inches from an extrapolation distance of 35 miles, there is a 70% probability that the true central pressure lies between 27.00-plus-1.00 inches and 27.00-minus-2.20 inches. As can be seen from figure 18, the reliability is low for large extrapolation distances and low central pressures. The principal interest of the study, however, is not in the individual p_o's, as such, but in the over-all distribution, and the reliability of an over-all distribution is higher than for the individual items.

The 70% confidence interval for each central-pressure estimate in table 1 was obtained from figure 18. These intervals are depicted by the horizontal arrows of figure 12. The extrapolation distance was zero for points without arrows. The very large variation in the reliability of the central pressures, as shown by the varying length of the arrows in the figure, prevents the placing of an over-all confidence band about the accumulated central-pressure frequency curve by any common statistical procedure. However, to facilitate an approximate judgment as to the reliability of the curve, abscissas of the left-hand end points of the arrows are replotted as x's in the figure in the order of magnitude. The curve formed by the x's represents what would be the true frequency distribution of the central pressures if the central pressure in every storm had been overestimated to the extent that the true central pressure lay at the lower end point of the 70% confidence interval. This accumulated lower limit lies, on the average, 0.39 inch below the original central-pressure curve. Considering the extreme unlikelihood that the former curve represents, it is seen that the chances are very small that the original central-pressure frequency curve is grossly in error.

The lower end points of the confidence intervals drop below 27.00 inches in three storms, one, of course, being the storm in which the central pressure was 26.35 inches. One point even drops below 25.00 inches. The conclusion remains unmodified, however, that a central pressure on the order of 26.35 inches or lower is an exceedingly rare event.

Chapter III

A WIND-REDUCTION PROCEDURE FOR LAKE OKEECHOBEE

According to the method that has evolved as the most feasible, the first step in synthesizing a design hurricane at Lake Okeechobee is to establish the design pressure profile. Chapter II was directed at expanding available knowledge for that purpose. The second step is to reduce the pressures to anemometer-level winds. The present chapter presents a method for accomplishing this.

Anemometer-level winds in three frictional categories are required, over open water, off-water at the shore, and off-land at the shore. The over-water winds are by far the most important ones in computing the total effect of the square of the wind speed along a fetch or the total kinetic energy over an area. The off-water and off-land shore effects decrease from the shore outward a few miles, where they are negligible. Moreover, the squaring of the wind speed decreases the influence of the frictionally decreased values. Thus, in computing the net effects in storms that have adequate pressure and/or over-water data, a highly refined procedure for computing the off-water and off-land effects is hardly required. However, in older storms the over-water winds must be derived from shore observations by the near-shore procedures in reverse. In these cases the values of the over-water wind are highly influenced by the procedures. For this reason, a good deal of effort has been expended in developing the near-shore procedures.

The hurricane of August 26, 1949, the most severe that has crossed the Lake since 1928, contributes most of the basic data to the wind reduction procedure. Some additional data is furnished by the storm of October 16, 1950. The fifty years of hurricanes from 1900 to 1949 as a whole, to which the report is mostly devoted, play the necessary role of confirming an important deduction from the August 1949 hurricane, namely, that the ratio of the free-air wind speed above the surface frictional layer to the cyclostrophic or gradient speed varies markedly with distance from the storm center.

Wind records at Lake Okeechobee

Since 1936 the Corps of Engineers has maintained a network of meteorological stations at Lake Okeechobee. The locations of the stations in operation in 1949 and 1950 are shown in figure 19. Six of the seven shore stations are equipped with Dines anemographs; the seventh, Lake Harbor, has a Friez Aerovane. A continuous graph of the wind speed is recorded at all stations. Three of the stations in the Lake were installed in the summer of 1949, and records were obtained from these in the August 1949 hurricane. The other two stations in the Lake were added the next year.

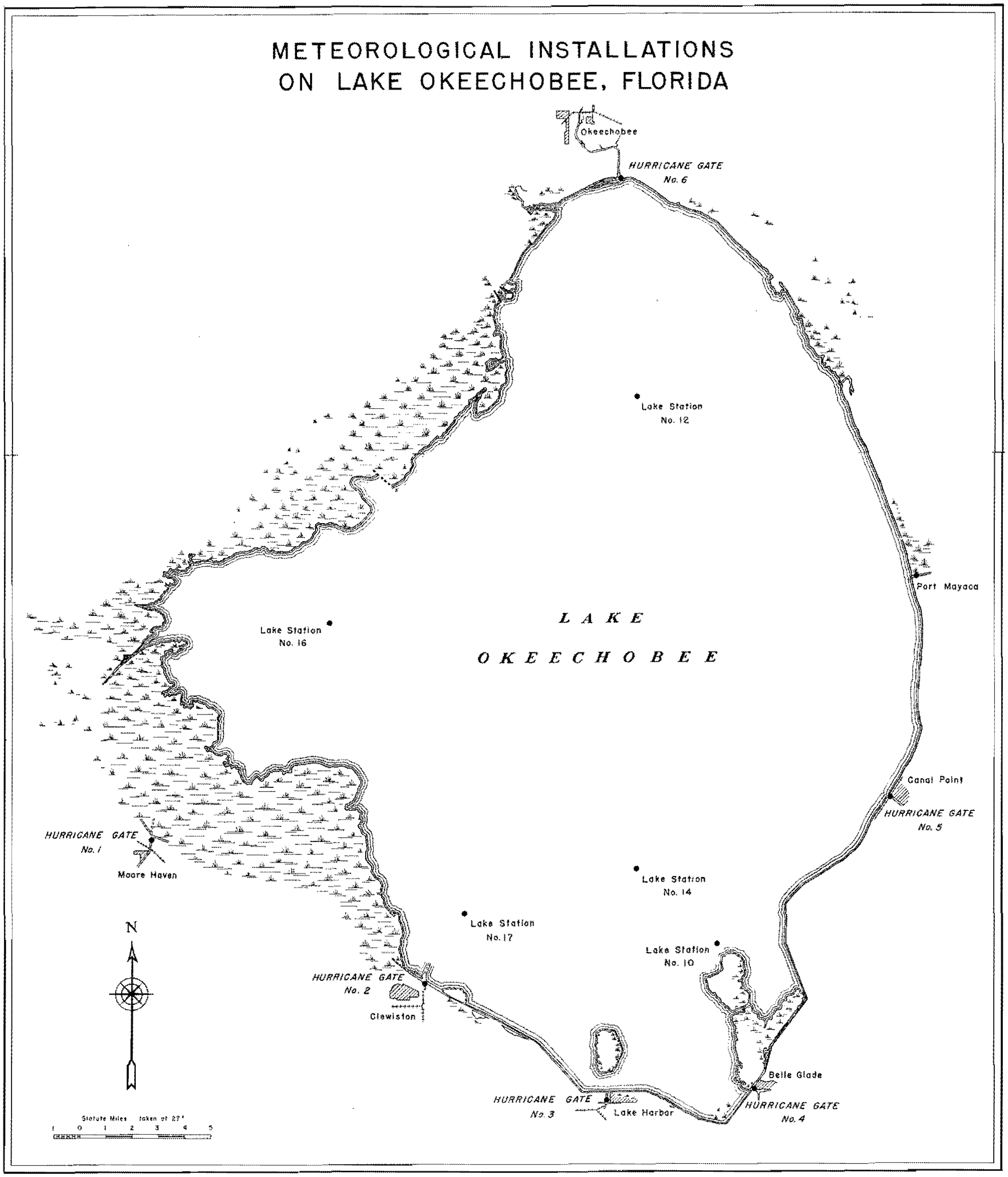

METEOROLOGICAL INSTALLATIONS
ON LAKE OKEECHOBEE, FLORIDA
Okeechobee
HURRICANE GATE
No. 6
Lake Station
No. 12
Port Mayaca
LAKE
OKEECHOBEE
Lake Station
No. 16
Canal Point
HURRICANE GATE
No. 5
HURRICANE GATE
No. 1
Moore Haven
Lake Station
No. 14
Lake Station
No. 17
Lake Station
No. 10
HURRICANE GATE
No. 2
Clewiston
N
Belle Glade
HURRICANE GATE
No. 3
Lake Harbor
HURRICANE GATE
No. 4

FIG. 19

The wind instrumentation for the stations in the Lake consists of Robinson 3-cup anemometers, vanes, and multiple-pen recorders, installed on Coast Guard navigation-light towers. The passage of each 1/10 mile of wind is recorded by a tick of one pen; another shows each 10 miles. Eight pens give the wind direction.

The average speed over ten minutes was the unit chosen as standard by the Corps of Engineers and the Hydrometeorological Section for hurricanes at Lake Okeechobee, both actual and synthesized. The wind direction is also averaged over 10 minutes. Average 10-minute speeds and directions were abstracted from original records by the Hydrometeorological Section and have been published by the Corps of Engineers for the hurricanes of August 26, 1949, and October 16, 1950, which passed over the Lake, and for several previous hurricanes which passed near the Lake. The standard 10-minute intervals were from 5 minutes after the hour to 15 minutes after, 15 to 25 minutes after, etc.

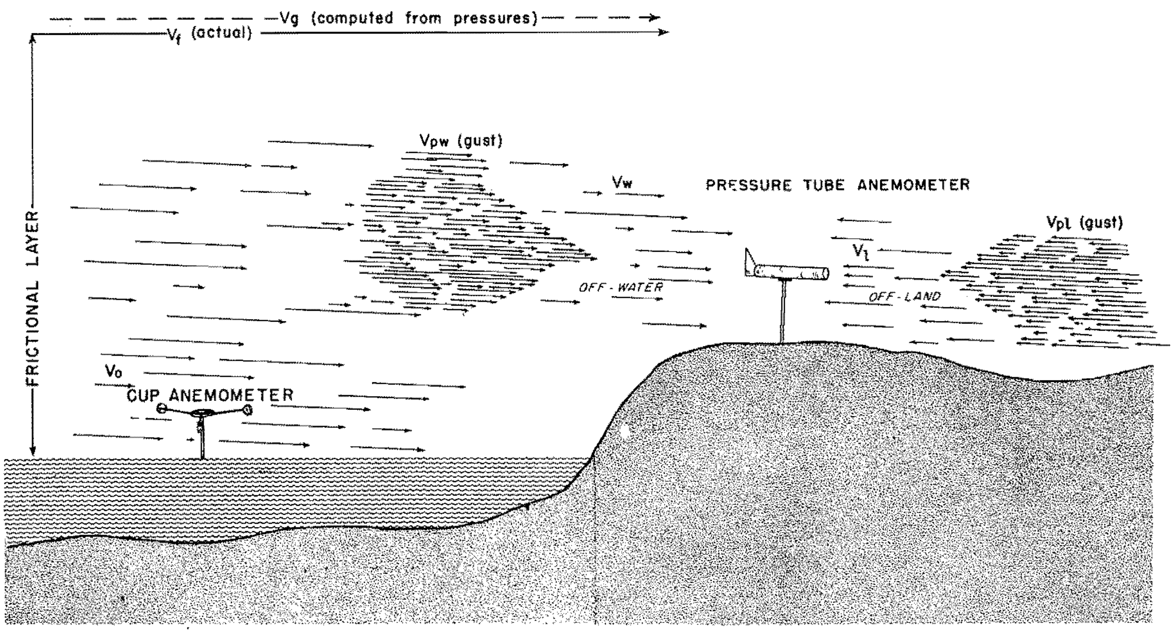


FIG. 20 SCHEMATIC REPRESENTATION OF CATEGORIES OF WIND

For the six shore stations equipped with anemographs, the peak gust within each 10-minute interval, that is the highest point of the wind trace, was extracted. The gust speeds at Lake Harbor, the shore station equipped with the Aerovane, were picked off for the October 1950 storm only. No comparable gust speeds could be obtained from the stations in the Lake, since they were equipped with cup anemometers. The gust speeds (which have not been published) were employed in the present study to investigate the relation of anemometer-level wind speeds to free-air wind speeds.

The speed recorded by an anemograph varies slightly with air density. However, in abstracting speeds no correction was made for density and, therefore, no allowance for density should be made in the reverse process of computing kinetic energies from the wind speeds for oceanographic purposes.

Definition of wind categories

For designation of various categories of wind speed, the following notation will be used in this chapter: v_l, 10-minute-average speed at the shore with wind direction off the land; v_w, 10-minute-average speed off-water; v_o, 10-minute-average speed over open water; v_{pl}, 10-minute peak gust off-land; v_{pw}, 10-minute peak gust off-water; v_g, gradient speed; and v_f, free-air speed. The free-air speed referred to is the true sustained speed at the height where reduction of speed by friction with the underlying ground or water surface becomes negligible. This may be on the order of 1,000 feet up.

The categories of wind speed are shown schematically in figure 20. The surface speeds are at the height of the installed anemometers at Lake Okeechobee. The heights are listed in appendix A.

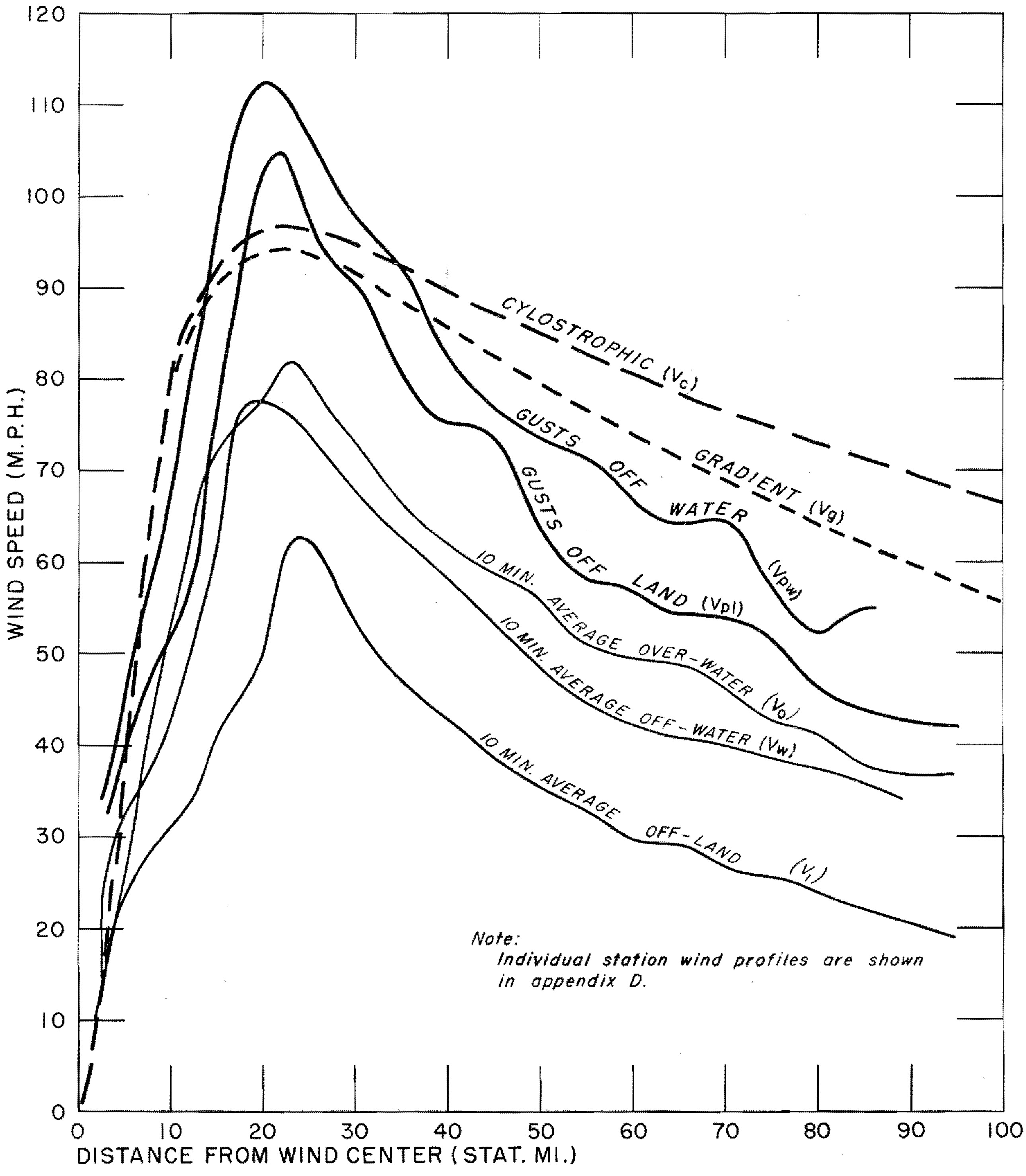
Procedure for Over-Water Winds from Gradient Winds

The wind at anemometer-level that may be expected from a given gradient wind, computed from the pressure field by assuming a balance of forces, depends on the departure--because of accelerations--from the gradient wind, v_g, of the free-air wind, v_f; the roughness of the underlying surface; and the strength of the turbulence. The last, at a given place, depends on the stability of the air (the vertical temperature gradient) and on the wind speed itself. The required relationship of anemometer-level wind to gradient wind is obtained if the factors named can be isolated or measured. It is permissible to assume that the vertical temperature gradient is nearly constant in the high-speed zone of all hurricanes that may reach Lake Okeechobee. This is based on the relatively constant temperature in hurricanes and on the fact that at high speed, perhaps above 40 mph, by virtue of the turbulence, the vertical temperature gradient will approach the adiabatic lapse rate. The other factors influencing the relationship of gradient wind to anemometer-level wind have not heretofore been evaluated quantitatively by meteorologists for lack of adequate data. Dunn, in his article, "Tropical Cyclones", in the Compendium of Meteorology[9] says "since the required dense network of observing stations has never been available, no rigorous study of surface wind velocity and directions and associated pressure gradients [in hurricanes] has ever been made." The data from the Corps of Engineers network in the August 26, 1949 hurricane enabled the Hydrometeorological Section to begin an attack on this problem. A chain of relationships among v_g, v_f, v_o, v_w, and v_l was developed which leads to an explicit procedure for computing the anemometer-level wind at Lake Okeechobee from the gradient wind. In chapter IV a similar procedure will be used to summarize the anemometer-level winds computed from gradient winds in the fifty years of hurricanes.

Relation of free-air to gradient wind

Practically no direct observations of the free-air wind speed by pilot balloons in the high-speed zone of hurricanes have been made because of the unsuitability of associated weather conditions. An indirect indication of the relation of free-air speed, v_f, to gradient speed, v_g, can be obtained by substituting the peak-gust speeds, v_{pl} and v_{pw}, for the free-air speed. There is evidence that gusts at anemometer-level consist largely of bubbles of air brought down by turbulence from fast moving layers above. These bubbles will not originate from above the frictional layer, by definition, nor will they reach anemometer-level with their momentum fully conserved. But, if peak gusts are selected, it is believed that the level of origin will be high enough and the loss of momentum small enough that the gust speeds will be quite close to the free-air speeds just above the frictional layer.

Profiles of the gradient and cyclostrophic speed and of the peak-gust speeds, v_{pl} and v_{pw} are shown together in figure 21 for the hurricane of August 26, 1949. The cyclostrophic and gradient profiles are computed from the parameters p_o = 28.20 inches, R = 22 statute miles, and p_n = 29.97 inches. These were previously determined as best fitting the data at the time the storm was over Lake Okeechobee, while the slightly different parameters listed for the storm in table 1 pertain to the time the storm center was at the Atlantic Coast. Mean gust profiles were constructed by plotting separate profiles for each station, then averaging the speeds at five-mile intervals, except at the peak. There, to avoid reducing the peak by smoothing, the average peak was located by averaging the positions of the peaks of the station profiles along both the distance scale and speed scale. To investigate the possible influence of lack of symmetry, separate mean gust profiles were first prepared for the forward and rear halves of the storm. No significant departure from circularity was found, however, and the final gust profiles (and other profiles) in figure 21 are based on all the data. In plotting the gust profiles, distances from the wind center were taken directly from the analysis of the storm previously made by the Section. To tie in most readily with this previous analysis, the distance unit in this chapter is the statute mile, whereas in most of the study the nautical mile, more convenient for laying out hurricane tracks, is the standard unit.

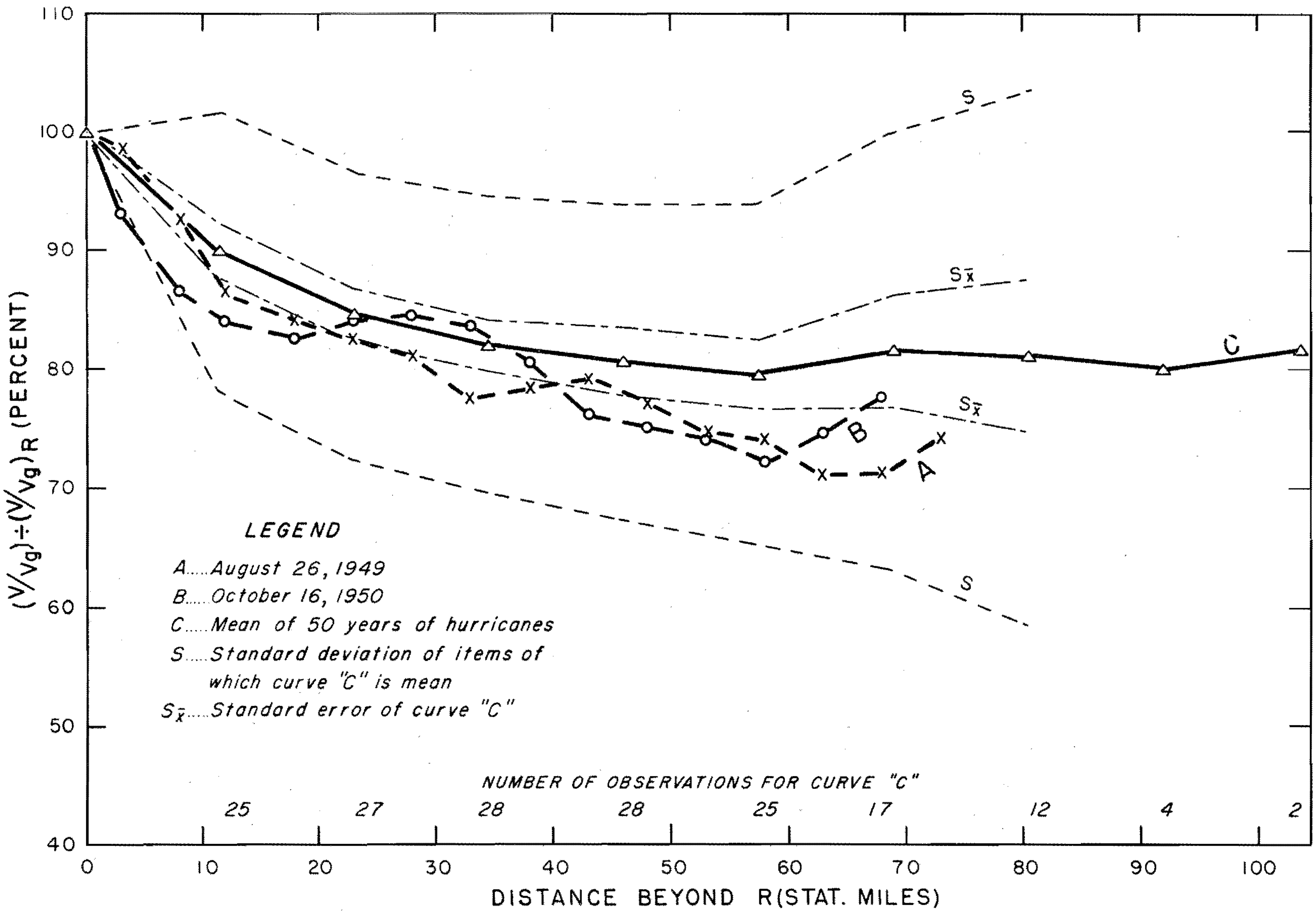


WIND-SPEED PROFILES, AUG. 26-27, 1949

FIG. 21

Comparison of the gust profiles with the gradient and cyclostrophic profiles in figure 21 shows that: the gusts speeds are considerably less than the gradient speed at some distance from the storm center, experience a relative increase as the radius of maximum winds, R, is approached, and appreciably exceed the gradient speed at the radius of maximum winds, while inside R the gust speeds drop below the gradient speed again. It can hardly be assumed otherwise than that the ratio of free-air speed to gradient speed follows the same trend. The free-air speed will not be less than the gust speeds. If the free-air speed is somewhat in excess of the gust speeds, an even greater exceedance over the gradient speed results at R. The interpretation of the observed trend is that in the outer portion of the hurricane the forces acting on an air particle are not in balance. The speed is not sufficient for the coriolis and centrifugal forces to equal the pressure-gradient force. The particle is accelerated inward across isobars, and as it moves closer to the storm center, not only does v in the centrifugal term v^2/r increase, but r decreases. As r becomes quite small, a balance of forces is quickly obtained, and then the pressure-gradient force is exceeded, as indicated by the super-gradient wind speed in figure 21, by the total of forces acting outward. The particle with a super-gradient speed will no longer be accelerated inward, will assume an essentially tangential direction, and, in fact, should turn slightly outward and be slowed down by the pressure gradient. In support of this, the reader is referred to figure 5, page 11, in which the average deflection angle of the anemometer-level wind inward across isobars is graphed as a function of distance from wind center for the 1949 hurricane. The angle decreases from 40° at a distance of 60 statute miles to zero at five miles. (Two stations within five miles of the center actually showed negative deflection angles.) It seems evident that the radius of maximum winds, R, is automatically at, or slightly inside, the radius at which the increasing v^2/r term becomes equal to the pressure-gradient term. At R, the coriolis term is almost negligible in comparison to the large v^2/r term.

Other data confirm the foregoing conclusions, which would not be completely above suspicion if there were no confirmation. Only a moderate error in evaluating the pressure-profile parameters--or in assuming that such parameters properly describe a real hurricane--would considerably influence the gradient-wind profile. The first confirmation is obtained from the hurricane of October 16, 1950. A figure similar to figure 21 was prepared and showed the same pattern of gust speeds, sub-gradient at the outer portion of the storm and becoming super-gradient at R. The exceedance of the gust speeds over gradient speeds at R is larger in the October 1950 storm than for the storm in figure 21 (the October 1950 storm was asymmetrical and data were restricted to the forward half). Final and important confirmation is from the fifty years of hurricanes as a whole. It was found that the average ratio of the sustained anemometer-level wind to the gradient wind increases as R is approached from the outskirts of the storm.



RATIO OF V/Vg AT VARIOUS DISTANCES TO V/Vg AT R

FIG. 22

Relation of over-water to gradient wind

The quantitative relationship of actual wind to gradient wind will be developed in terms of the sustained rather than the gust speed. Average radial profiles of the over-water 10-minute average anemometer-level wind, (v_o), were constructed for the August 1949 storm, figure 21, and for the October 1950 storm. As with the gust speeds, only the forward half of the October 1950 hurricane was used. The variation of the ratio v_o/v_g along a storm radius was brought out by plotting at selected distances, the quotients of v_o/v_g at each distance divided by v_o/v_g at R. See figure 22. A similar curve was prepared as an average for the fifty years of hurricanes, curve C of the figure. The winds were "off-water" instead of "over-water" for this last curve. The close similarity of curve C to curves A and B leaves no doubt that the decrease of the actual wind as compared with the gradient wind with increasing distance beyond R is typical of hurricanes reaching the United States. The details of deriving curve C are given in chapter IV.

Variation of the ratio of over-water to free-air wind with wind speed

To what extent is the observed variation in ratio of anemometer-level wind to gradient wind along a storm radius due to differences in accelerations at different distances from the storm center, and to what extent, if any, to variation in the turbulence structure as a function of wind speed? The magnitude of the latter variation will be investigated first, by examining the variation of v/v_f with wind speed, where v is any anemometer-level speed. It is not feasible to do this directly, and again recourse is made to gust speeds as indicators. The ratio of 10-minute average speeds to the peak gusts within the same 10-minute intervals was taken as an index of the turbulence structure. This is an attractive index, as the numerator and denominator are measured simultaneously by the same instrument.

Off-land gust ratios, v_l/v_{pl}, and off-water ratios, v_w/v_{pw}, were computed for four Lake Okeechobee hurricanes and were plotted separately against the average wind speeds, v_l and v_w, for each of the seven shore stations, a total of fourteen graphs. In segregating off-land and offshore winds, it was required that both be more than 10° away from a direction parallel to the shore. The shore-line of the shallow lake varies with the height of the water surface. It was verified by reference to Corps of Engineers water-level maps that for off-water winds the edge of the water surface was actually close to the station in all cases. During the highest-speed portion of each storm the ratios in each successive 10-minute interval were used. In the lower-speed portions, when the speed changes more slowly, only every second or third 10-minute interval was used to avoid a multiplicity of points at the same abscissa.

The startling result from the fourteen graphs was that v_w/v_{pw} for well-exposed stations is independent of wind speed, whereas v_l/v_{pl} is markedly dependent on wind speed. The two graphs for the well-exposed

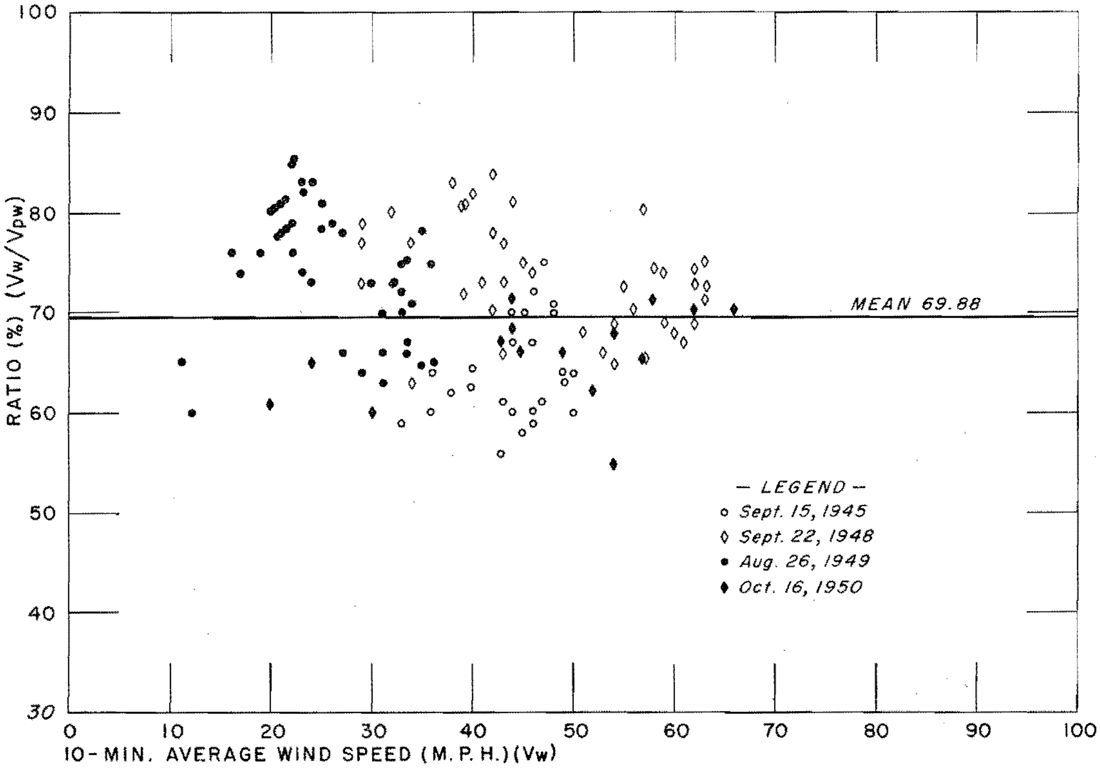


FIG. 23-RATIOS OF OFF-WATER 10-MINUTE-AVERAGE WIND SPEED TO GUST SPEEDS
CLEWISTON (H.G.S. No. 2)

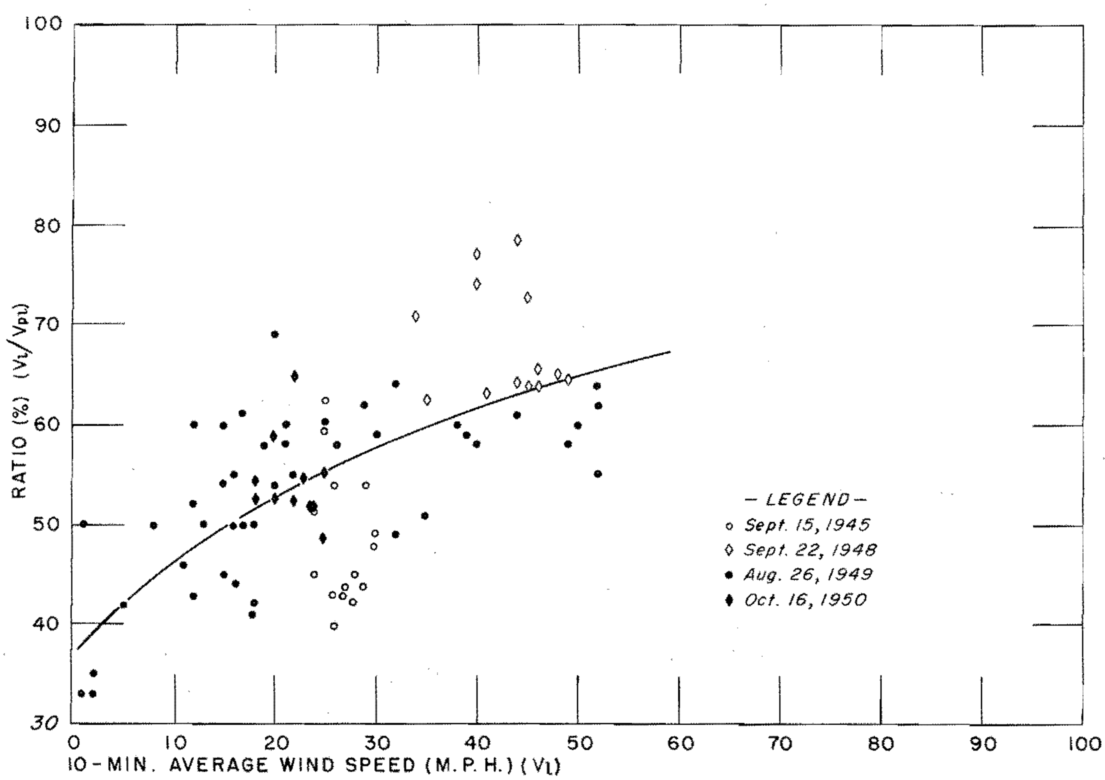


FIG. 24-RATIOS OF OFF-LAND 10-MINUTE-AVERAGE WIND SPEED TO GUST SPEEDS
CLEWISTON (H.G.S. No. 2)

station with the most data, Clewiston, are shown in figures 23 and 24. All of the off-land graphs are similar to figure 24, although the position and slope of the curves, fitted by eye, are not the same. The off-water graphs for Lake Harbor, Canal Point, Port Mayaca, and Okeechobee are like figure 23, showing no dependence of the ratio on wind speed. The off-water graph for Moore Haven, figure 25, looks like an off-land graph. This is presumably due to vegetation in the Lake off-shore. It was found previously in the analysis reported in Hydrometeorological Report No. 26 [1/] that Moore Haven does not have a true off-water exposure. The off-water curve for Belle Glade is intermediate between an off-water curve for a well-exposed station and an off-land curve. It is concluded that the islands off-shore from Belle Glade and vegetation in the Lake have a partial effect in reducing off-water winds at that station. To ascertain whether winds blowing directly over the islands were reduced more than winds over the adjacent water channels, the off-water ratios at Belle Glade were stratified by wind direction, but no systematic variation by wind direction could be isolated.

The finding that the gust ratio, v_w/v_{pw}, for a well-exposed shore is independent of wind speed leads to the following deductions: (1) the turbulence structure is essentially independent of the wind speed, (2) v_w/v_f must then be independent of wind speed, (3) if v_w/v_f is independent of speed, then v_o/v_f, with even less friction involved, is assuredly independent of speed also, (4) the observed variation of v_o/v_g along a storm radius (figure 22) is a function of the dynamics of the hurricane only, and is independent of speed. (This line of reasoning is not intended to apply to very low speeds, which were not investigated and at which v_w/v_f is probably not independent of the speed.)

Standard curve for the ratio of over-water to gradient speed

By a combined theoretical and empirical study, it should be possible to analyze the responsible forces and accelerations, at least for a model, and to describe the variation of v_f/v_g in terms of the three pressure-profile parameters, p_o, p_n, and R, and two additional parameters, speed of forward motion and intensity of the updraft. The present study stopped, however, at obtaining the observed variation of v_o/v_g along a radius in particular storms (figure 22) and demonstrating that the ratio is independent of wind speed. At present, then, to reduce v_g to v_o we are restricted to considering the ratio of v_o to v_g as a function of but one variable, distance outward in the storm, and to evaluating the ratio directly from the empirical data in figure 22.

Curve A based on the 1949 hurricane (figure 22) was chosen as the standard reduction curve in preference to curve B (1950 storm), or curve C (average of 50 years), or some combination of the three. The principal purpose is to compute the winds from the pressures in a near-maximum hurricane at Lake Okeechobee. The 1949 storm was a fairly intense, nearly circular storm, at the location of interest, and with R approximately that expected in the design hurricane. The October 1950 storm was decidely

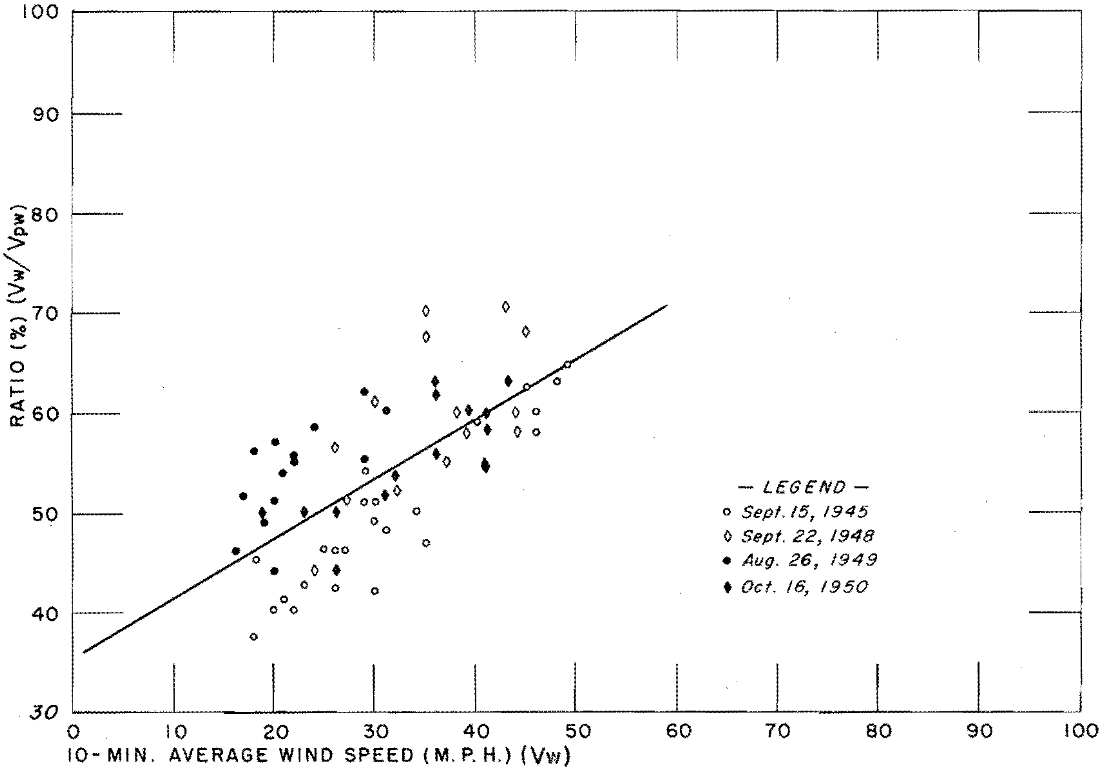


FIG. 25 RATIOS OF OFF-WATER 10-MINUTE-AVERAGE WIND SPEED TO GUST SPEEDS MOORE HAVEN (H. G. S. No. 1)

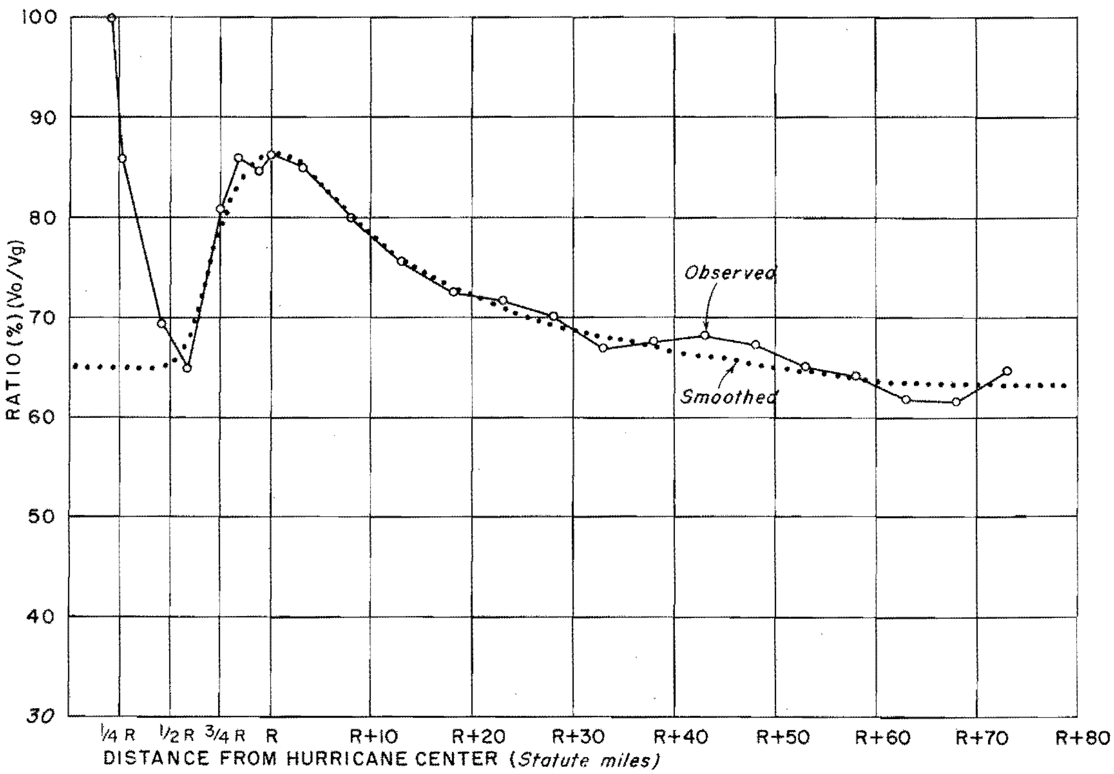


FIG. 26 RATIO OF 10-MINUTE-AVERAGE OVER-WATER WIND TO GRADIENT WIND AUGUST 26-27, 1949

asymmetrical and was weaker. The average curve for the fifty years of hurricanes is based on measurements at different locations, at different anemometer heights, with uncertain frictional effects. Individual analyses of the concurrent wind and pressure fields are less reliable and probably most important, much of the data is at fairly low speeds and is from storms with large R.

In order to reduce gradient wind to over-water wind through application of the selected curve, A, the actual v_o/v_g ratio at R (or at some other distance) is required. Available values for v_o/v_g at R are 86.5% for the 1949 hurricane, 99.2% for the 1950 hurricane, 73.2% for the mean of fifty years of hurricanes. The last value is obtained by making adjustments from the average height of the anemometers to the height of the Lake Okeechobee anemometers, and from off-water to over-water exposure. The ratio from the 1949 hurricane was selected as the standard by considering the same reasons as were used in choosing curve A and from the fact that this value lies halfway between the other two. Then, the observed value of v_o/v_g at each radius in the 1949 storm was chosen as the standard for wind reductions.

The observed v_o/v_g curve for the 1949 storm is shown by the solid line of figure 25. From R outward, values on this curve are ratios of the speeds on the mean v_o and v_g curves in figure 21. Inside R, special steps were required to compensate for the facts that, firstly, there were very few measurements of v_o inside R, and secondly, that the ratio of v_o to v_g is very sensitive in that region to small errors in distance. To increase the data, all off-land and off-water wind-speed measurements inside R in the storm were adjusted to the corresponding over-water values by relationships to be given in the next section. These synthetic over-water wind speeds, together with the few actual over-water winds, were plotted on an expanded distance scale and a profile fitted. The points inside R on the solid curve of figure 26 are based on values of v_o from that profile. The dotted curve in figure 26 is a smoothed version of the solid curve and is adopted as the standard for reducing v_g to v_o. There is little doubt that the upturning of the solid curve inside $\frac{1}{2}$R is a spurious effect of the sensitivity-to-distance errors referred to, and this upturning was rejected in constructing the dotted curve.

The question presented itself as to whether the v_o/v_g ratio at a given distance from R in the 1949 hurricane was most representative of the ratio at the same distance from R, or at the same fraction of R in another hurricane. The distance was judged best outside R and the fraction inside R. The horizontal scale in figure 26 is so labeled.

Procedure for Shore Winds

Having once obtained the anemometer-level wind over the open waters of the Lake by the procedures just described, the winds at the shore may in turn be computed from the over-water winds by evaluating the frictional differences. The relationships so developed are also applicable in reverse, to compute the over-water winds for oceanographic purposes in older storms in which wind observations are available from the shore stations but not over the Lake. The relationships of shore winds to over-water winds presented here are revisions of those described in Hydrometeorological Report No. 31 [2].

The problem is divided into determining the ratios of off-water wind speeds to over-water speeds and the ratios of off-land speeds to over-water speeds. Once more we are guided by the behavior of the gust ratios. From the fact that v_w/v_{pw} does not change with wind speed for well-exposed shore stations, we concluded previously that both v_w/v_f and v_o/v_f are independent of speed. A fortiori, then, v_w/v_o is independent of speed. The ratio of v_l/v_o is dependent on speed, as is indicated by the off-land gust ratios, v_l/v_{pl}. It remains to ascertain if v_w/v_o varies significantly from one station to another and to assign values, while the variation of v_l/v_o both with speed and location must be assessed.

Variation of off-water gust ratios between stations

The variation of v_w/v_o from one station to another could be investigated by comparing observed values of v_w for the respective stations at the same distance from the wind center of the storm, but the distances are obtained only be meticulous analysis. A more precise comparison, though more indirect, may be made by examining again the off-water gust ratios, v_w/v_{pw}. Greater friction at one location than another would reduce v_w more than v_{pw} and lower the ratio. This was demonstrated by an over-all comparison of v_l/v_w in the 1949 and 1950 hurricanes with v_{pl}/v_{pw}. The first was much the smaller ratio, showing, as would be anticipated, greater reduction of the sustained wind than the gusts by the greater friction over land. The values are listed in table 4.

Table 4

COMPARISON OF FRICTIONAL REDUCTION OF 10-MINUTE-AVERAGE AND GUST WINDS

	Ratio (percent)	
	August 1949	October 1950
v_l/v_w	75.0	73.3
v_{pl}/v_{pw}	87.2	89.7

Mean off-water gust ratios for the five stations with open exposures, table 5, vary a few percent from 70%. An application of the F test (Snedecor [10]) showed that there is less than 1% probability that the ratios of the first four stations listed in the table were drawn from the same population. An "F" of 4.52 was computed, whereas the value at the 1%

level was 3.87. The F test responds to variations in the standard deviation as well as variations of the mean, and the marked difference of the standard deviation at Clewiston from the others contributes to the large F. However, there is little doubt the means are significantly different, in the usual statistical sense. This would be inferred by comparing the variation of the means in the first column of the table with the standard errors in the last column. Lake Harbor was excluded from the F test because of the difference in instrumentation (Aerovane instead of Dines anemograph).

Table 5

RATIOS OF 10-MINUTE OFF-WATER SPEED (v_W) TO PEAK GUST SPEED (v_{pW})

Station	Mean v_W/v_{pW}	No. of Obs.	Standard Deviation	Standard error of mean
Clewiston (HGS 2)	69.88	128	7.22	0.52
Canal Point (HGS 5)	67.71	28	4.00	1.11
Port Mayaca	69.13	53	4.33	0.81
Okeechobee (HGS 6)	71.80	58	4.05	0.77
Lake Harbor (HGS 3)	67.36	11		

Several possible explanations for the differences between stations may be advanced. One is that there are small local differences in exposure, either the immediate surroundings of the weather house, vegetation in the Lake, or the configuration of the levee. Another is that the responsiveness of the anemographs is not identical, giving slight variations in the recorded peak gust speeds. A third possibility is that there is a more broad-scale influence, the topography of the land about the station and the general type of vegetal cover. It was judged that there is a sufficiently good chance that the differences in the means in table 5 are due to strictly local influences, either exposure effect or instrumental effect, that an over-all mean may best represent the average frictional influence along any considerable stretch of the shore better than the value from the station that happens to be the closest. Therefore, the station mean values were lumped together and a value of 70% for v_W/v_{pW} was assigned to all well-exposed beaches of the Lake. The corresponding assumption for v_W/v_O is that the ratio varies only slightly with location and should be regarded as constant for the well-exposed beaches.

Standard reduction of over-water to off-water speed

For the five well-exposed stations a mean v_W profile was computed for the 1949 storm and for the 1950 storm. Ratios of speeds from these mean profiles to v_O at the same distance, at $2\frac{1}{2}$-mile intervals from R outward, (figure 27) give confirmation that the ratio is independent of the wind speed. A mean ratio of v_W to v_O of 89% is obtained for both storms. The factor, 89%, is adopted as the standard for reducing over-water wind, not

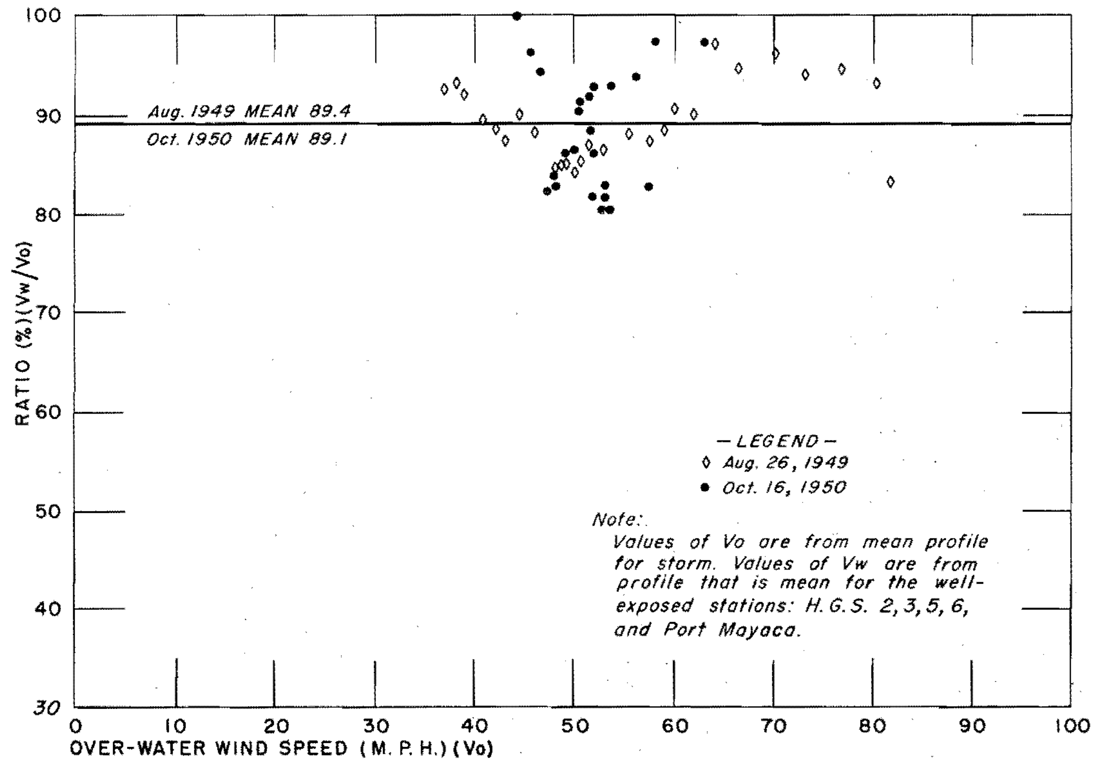


FIG. 27 RATIOS OF 10-MINUTE-AVERAGE OFF-WATER WINDS TO 10-MINUTE-AVERAGE OVER-WATER WINDS

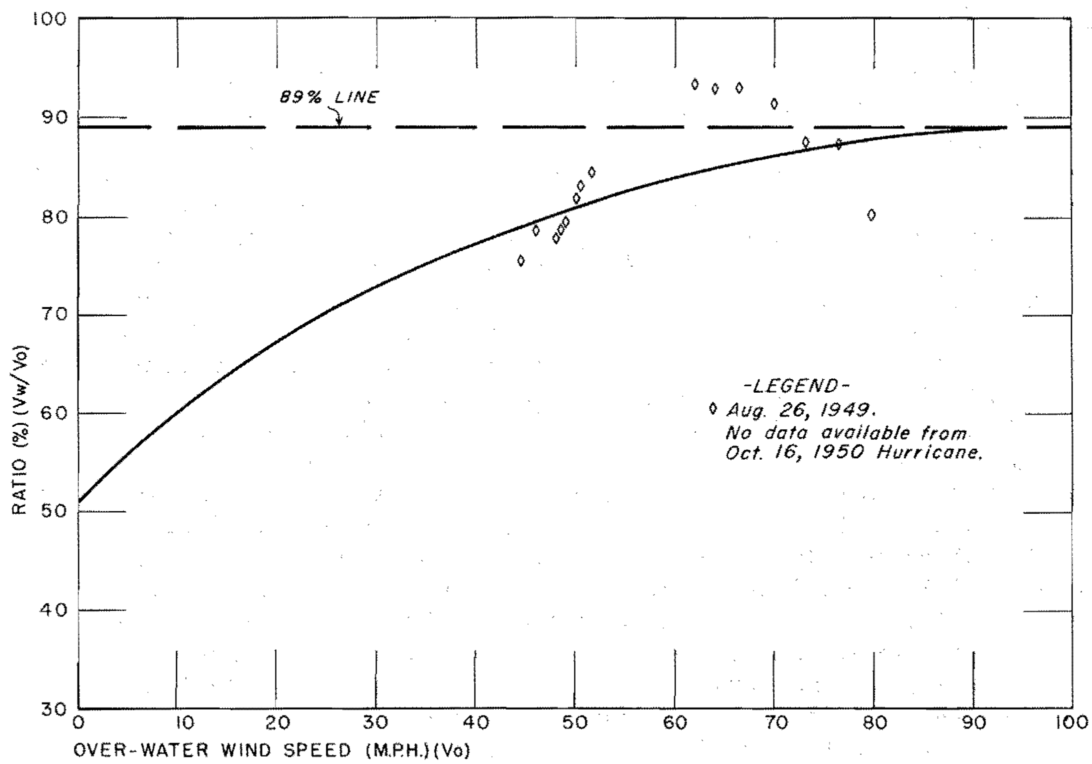


FIG. 28 RATIO OF 10-MINUTE-AVERAGE OFF-WATER WINDS AT BELLE GLADE (H.G.S. No. 4), TO 10-MINUTE-AVERAGE OVER-WATER WINDS

only at the five stations, but at any well-exposed beach.

For the two other shore stations, Belle Glade and Moore Haven, the v_w/v_o ratios confirmed the indications from the gust ratios that the frictional reduction of the off-water wind is greater than for the well-exposed stations. The v_w/v_o ratios for Belle Glade (figure 28) are intermediate in magnitude to the v_w/v_o ratios for well-exposed stations (figure 27) and v_l/v_o ratios for all stations (figure 30). The dependence of ratios on wind speed in figure 28 also appears to be intermediate to figures 27 and 30. The gust ratio, v_w/v_{pw}, at Belle Glade, with data available over a greater range of wind speeds, showed a variation of the ratio with wind speed more distinctly than figure 28, and also, as do the v_w/v_o ratios, indicated a frictional reduction of the off-water wind at Belle Glade intermediate to that for off-water winds at well-exposed stations and for off-land winds. Accordingly, a curve is fitted to the data in figure 28 that is intermediate to those of figures 27 and 30. The curve of figure 28 is made asymptotic to the 89% line of figure 27 at a v_o of 100 mph. Figure 28 is recommended as the best available relationship of Belle Glade off-water wind to the over-water wind. For convenience the curve of figure 28 is redrawn in figure 29, yielding the Belle Glade off-water wind directly from the over-water wind. The magnitude and dependence on wind speed of the Moore Haven v_w/v_o ratios was similar to off-land ratios, v_l/v_o. This behavior is again consistent with that observed for gust ratios. Accordingly, Moore Haven winds were treated as "off-land" for all directions.

Standard reduction of over-water to off-land speed

To establish an empirical relationship between over-water and off-land winds the most direct approach was carried out first--observed v_l/v_o ratios in the 1949 and 1950 hurricanes were plotted against over-water winds separately by stations. These plots proved to be too irregular to furnish reliable relationships. Of the two factors, station and speed, the most influential on the ratio was shown by these plots and by comparison of the collection of v_l/v_{pl} curves like figure 24 to be the speed. The next, and successful, procedure was to average out the station influence first. Ratios of wind speeds from a mean off-land profile to speeds from a mean over-water profile, at $2\frac{1}{2}$-mile intervals from R outward, are plotted in figure 30 against the over-water wind speeds for the hurricanes in 1949 and 1950. The curve was fitted to the 1949 data, which was considered superior to the 1950 data or to a mean of both. However, it can be noted that the 1950 data does not depart greatly from the curve. The following considerations determine that a curve concave downward should be fitted instead of a straight line. It is believed that with a decreasing pressure gradient an off-land wind would drop to zero, while an over-water wind still had a finite value. The ratio was drawn to zero at an over-water wind speed of one mph. On the other end the ratio cannot increase indefinitely as a straight line would require. The off-water reduction factor of 89% was taken as a limiting value, and the curve was drawn to this value at 150 mph. It is possible that the ratio of off-land winds to over-water winds would be <u>higher</u> than for off-water winds at some very high wind speed. The

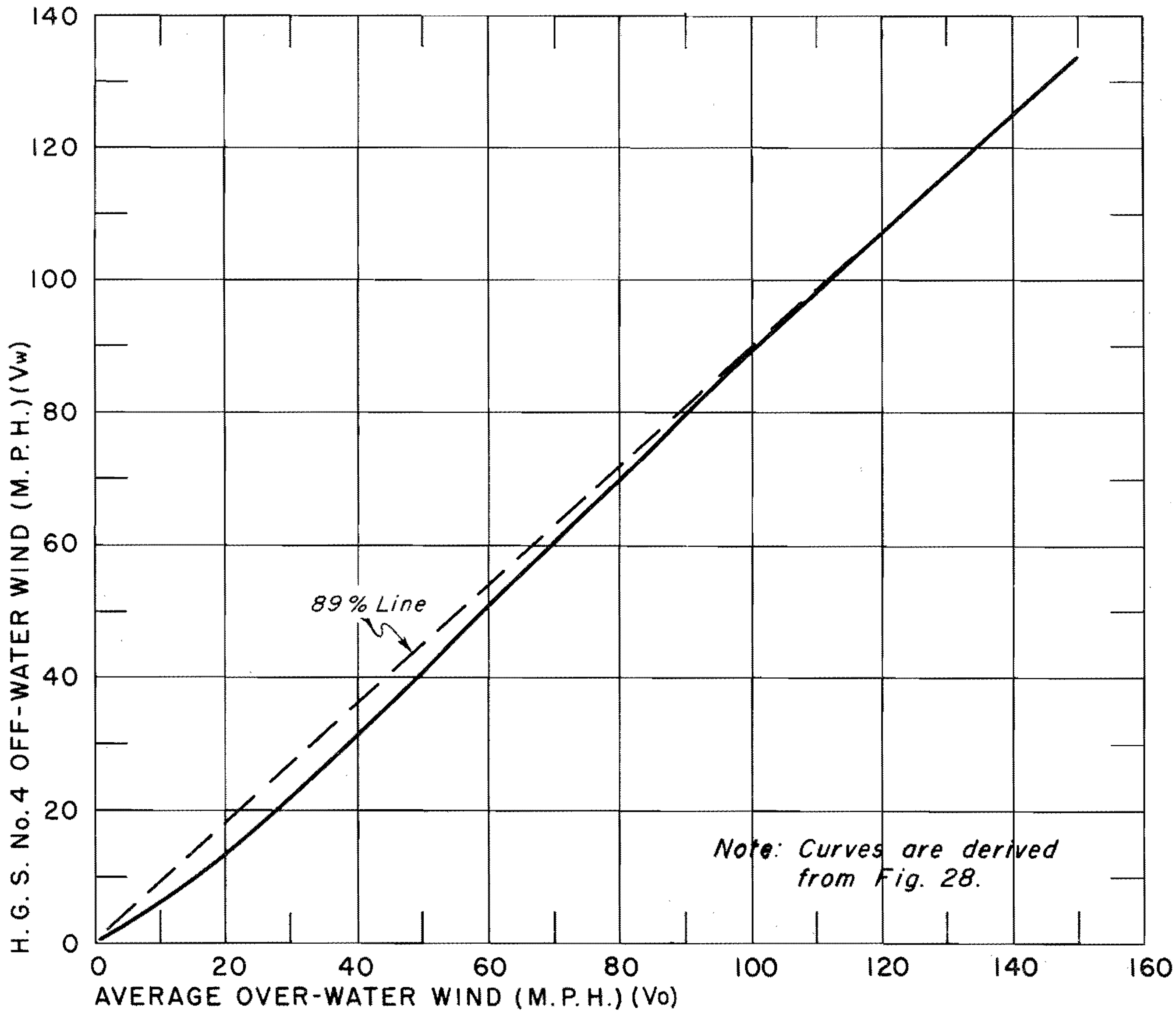


FIG. 29 RELATION OF OFF-WATER WIND AT BELLE GLADE (H. G. S. No. 4) TO AVERAGE OVER-WATER WIND

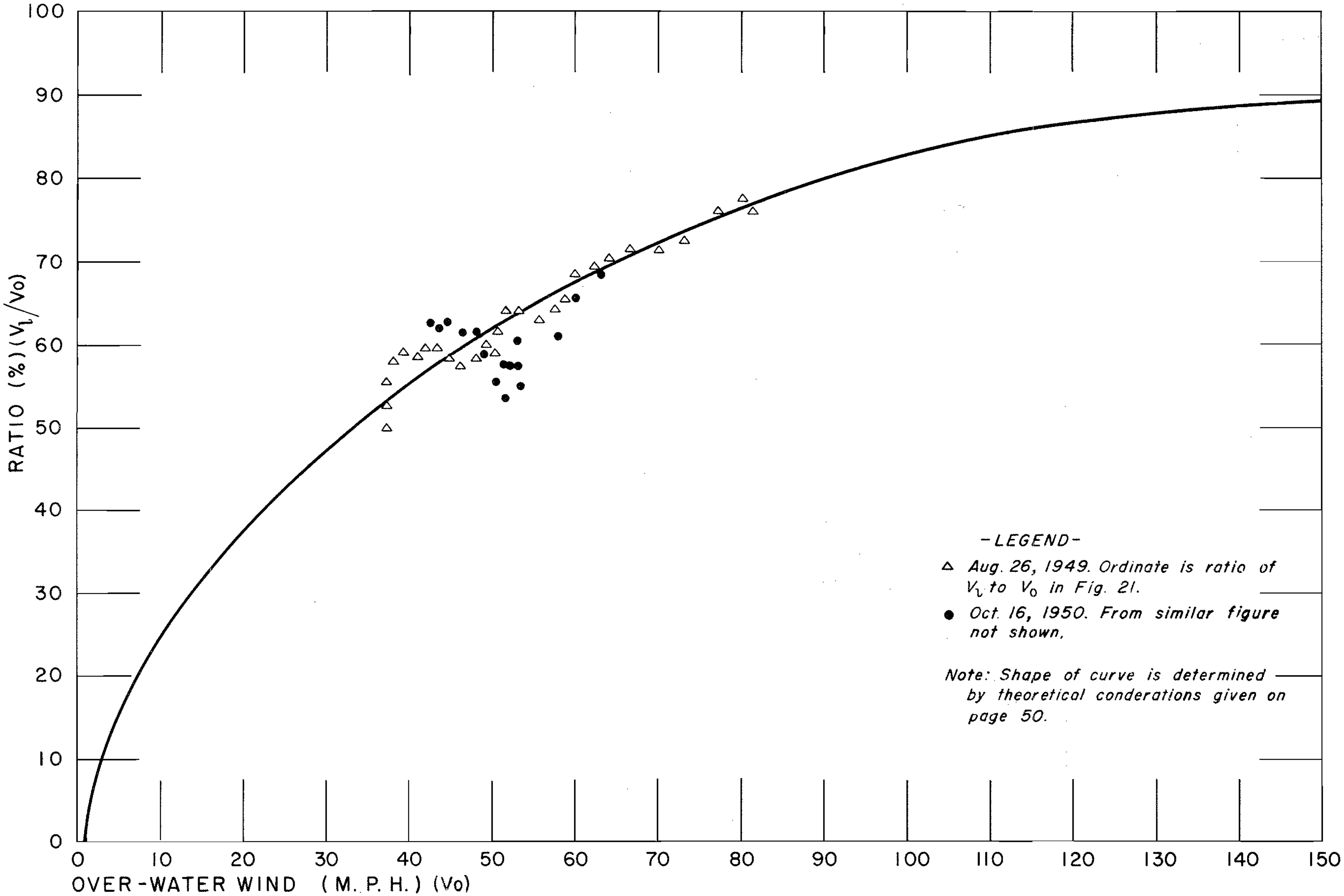


FIG. 30 RATIO OF AVERAGE OFF-LAND WIND TO AVERAGE OVER-WATER WIND

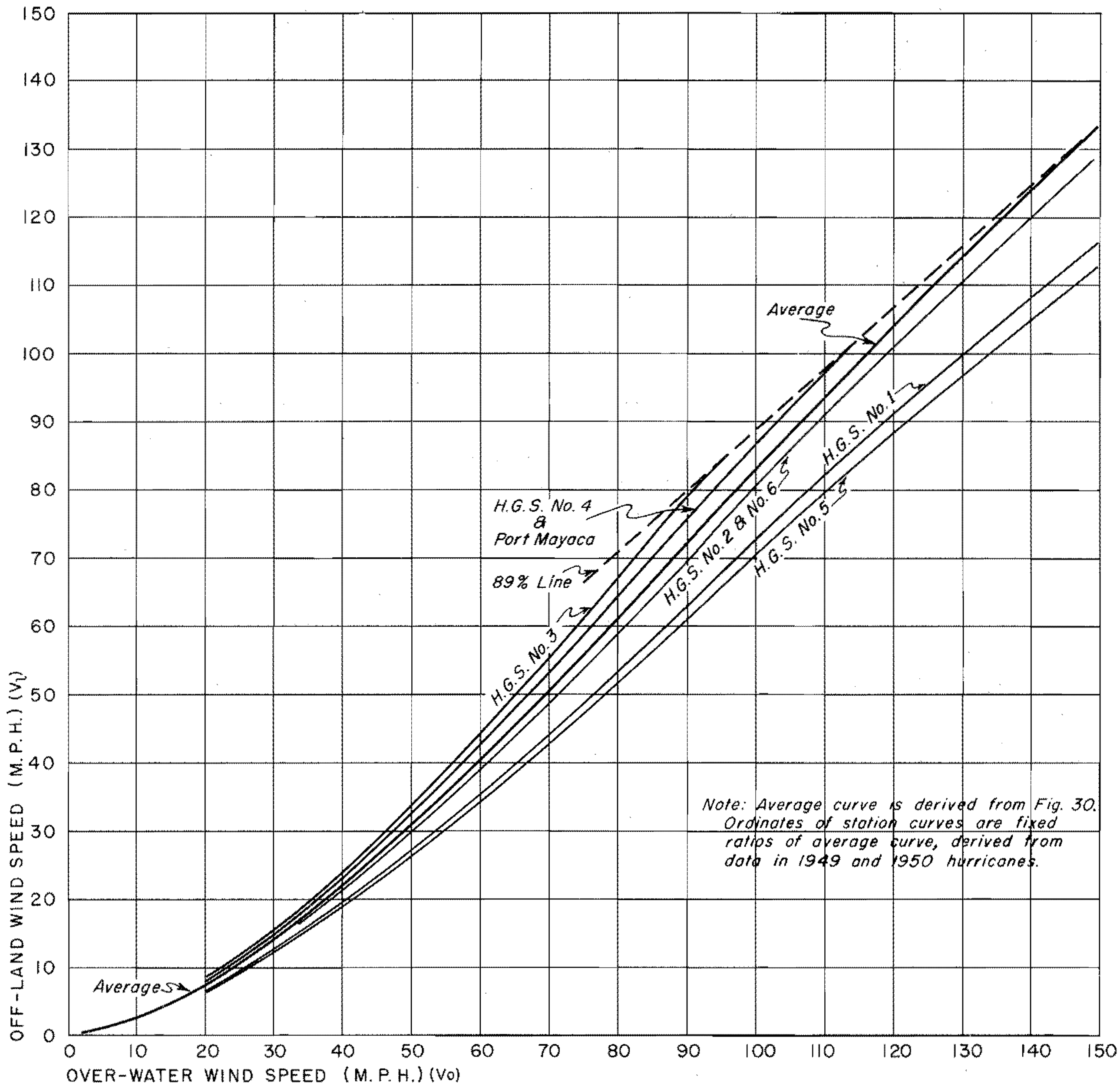


FIG. 31 OFF-LAND WIND SPEED FROM OVER-WATER WIND SPEED

greater roughness might result in more fast-moving air being brought down from above, while the flow might be more laminar off the water. However, without data to demonstrate otherwise, it seems wisest to place the off-water ratio as a limit to the off-land ratio.

For convenience, the curve of figure 30 is redrawn in figure 31 (the curve labeled "average") so as to give the average off-land speed, v_1, directly from the off-water speed rather than the ratio.

The supplementary curves of figure 31, give the off-land wind at each particular station directly from the over-water wind. Each of these curves was developed empirically from the 1949 and 1950 hurricane data by computing the average ratio of observed off-land wind speed at the particular station to the average off-land speed in the same hurricane at the same distance from the storm center. Multiplying the "average" curve of the figure by these average ratios yielded the station curves shown. An investigation determined that the supplementary curves should be ratios of, and not constant differences from, the average curve. It will be noted that the same curves were obtained for two pairs of stations, HGS 2 and HGS 6, and for HGS 4 and Port Mayaca. The curve labeled "HGS 1" is for Moore Haven off-land wind directions only. The off-water winds at this station were treated as if they were off-land winds for a separate station, and a ratio of 100.4% to the average curve of figure 31 was obtained. Hence, the average curve is used for reducing over-water winds to Moore Haven "off-water" winds. A limiting value of 89% of the over-water wind was placed on all off-land winds; at this value the off-land wind is equal to the off-water wind. A study of topography may permit computation of approximate wind values in synthetic or reconstructed hurricanes for off-land winds at points other than weather stations by analogy to the most similarly exposed weather station, if this refinement should be considered desirable.

Summary of procedure for reducing gradient wind to anemometer-level wind at Lake Okeechobee

1. Obtain the over-water wind profile by applying ratios of figure 26 to the gradient profile.

2. Obtain the shore winds by computing:

   (a) off-water profile for open exposures by multiplying the over-water wind by 0.89

   (b) off-water wind at Belle Glade from over-water wind by use of figure 29

   (c) off-water wind at Moore Haven from the over-water wind by use of the "average" curve of figure 31

   (d) off-land wind profiles for the various stations from the over-water wind by use of the appropriate curves of figure 31.

Chapter IV

WIND FREQUENCIES

The accumulated fury of hurricanes along the United States Coast during the years 1900-1949 is summarized by the pressure-profile parameters in table 1. These data will now be interpreted in terms of average recurrence intervals of certain high wind speeds at a coastal point. The point frequencies, computed from a comprehensive set of data by an indirect means, are intended to supplement the directly-observed but far-from-comprehensive records of maximum wind speeds available to the engineer charged with the design of a building, tower, or other structure at a geographical point in the hurricane zone. The wind speed frequencies are based on a reconstruction of the anemometer-level wind profile in each hurricane, adjusted to a standard anemometer height and frictional exposure.

Frequency Distribution of the Empirical Relationships Between Anemometer-level Winds and Hurricane Pressure Profiles

Observed pressure data are much more numerous and reliable than are observed wind data for all hurricanes, and especially for the older ones. Also the wind data show such wide variability that any curves of best fit would have a low degree of reliability. Therefore, the method analogous to the Lake Okeechobee procedure was adopted of developing a relationship between such wind observations as were available and the simultaneous pressure profiles, then applying this relationship to other pressure profiles---in this case the profiles of all the observed storms as defined by table 1---to reconstruct anemometer-level winds. Deriving the wind reduction relationship consisted of the same steps as before. The variation of v/v_g with distance, where v is the anemometer-level wind, was determined empirically and, coupled with values of v/v_g at R, furnished the basis for reducing any gradient wind profile to anemometer level. The empirical reduction factors were based on as many of the hurricanes as possible, in contrast to the Lake Okeechobee single-hurricane basis, since the goal now was to reconstruct winds that actually occurred in hurricanes of a wide range of intensity and location rather than to approximate the circumstances in a very intense hurricane at one place.

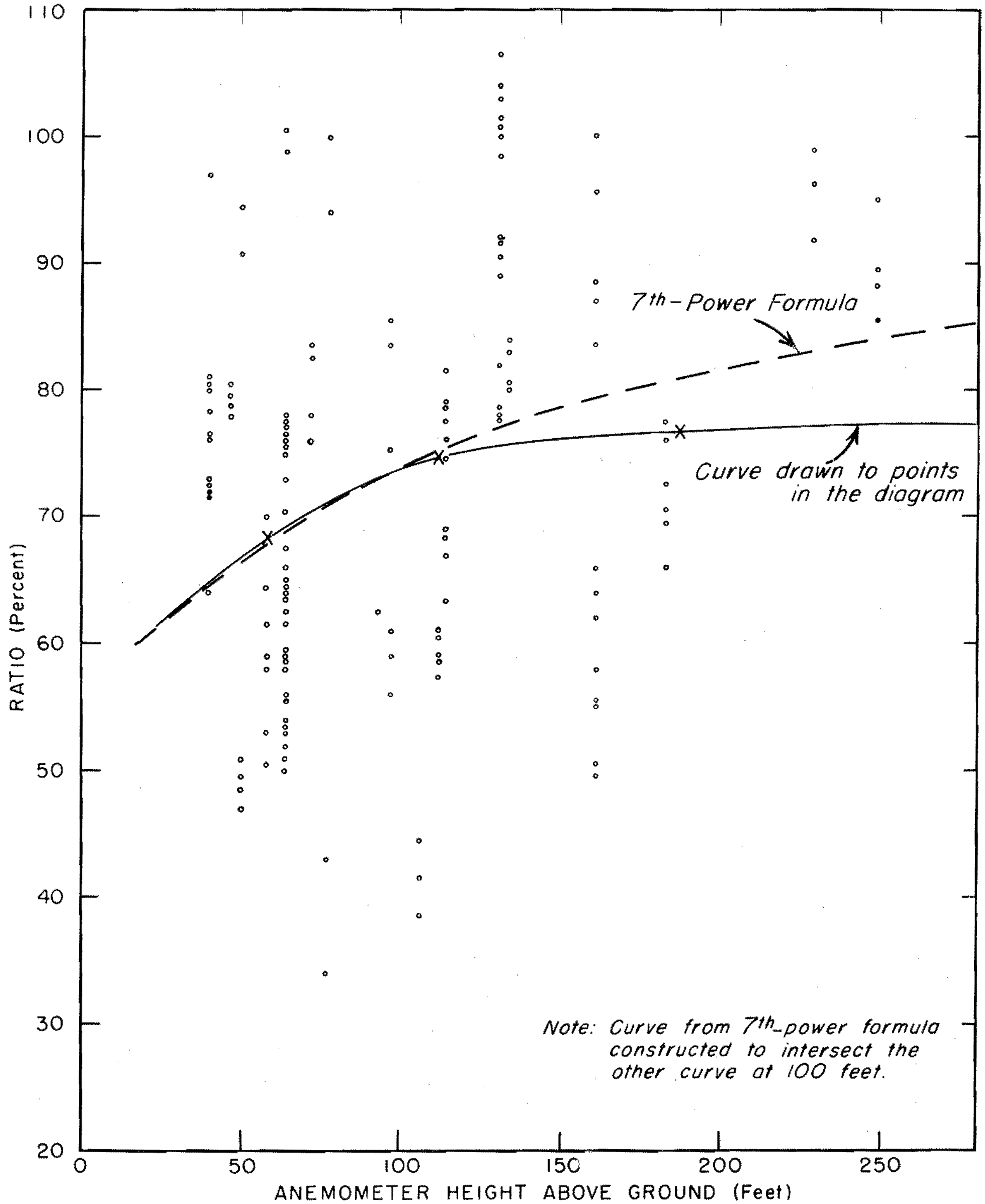
Variation with distance of ratio of anemometer-level to gradient wind

The average decrease of v/v_g with distance in the fifty years of hurricanes, curve C of figure 22, was derived by constructing for each storm a chart containing the profiles of observed wind speed (v) and the gradient profile (v_g), reading off ratios of v to v_g at specified distances, and combining the ratios into averages as detailed below. Observed speeds and distances (from the wind center) were taken from the previously prepared graphs like figure 8; gradient winds were computed from the parameters in table 1. The v/v_g values were read off, in the forward half of each storm only, at R, R + 10 miles, R + 20, etc., where R is the radius of maximum winds on the gradient profile. Curve C was computed from these v/v_g values in three stages. First, stepwise ratios were computed for each storm, being the ratio of v/v_g at R + 10 miles to v/v_g at R, v/v_g at R + 20 to v/v_g at R + 10, etc. Then these ratios were averaged across storms for each ten-mile interval. Finally, the resulting averages were multiplied in succession to yield curve C. The variation of the stepwise ratios at any one distance was large but was compensated by the sufficient number of observations, as indicated by the dashed curves of figure 22. The ordinates of these curves are: the ordinate of curve C plus or minus the standard deviation (s) of the stepwise ratios, and plus or minus the standard error of the means ($s_{\bar{x}}$) of the stepwise ratios. The standard error of the mean is sufficiently small to substantiate that curve C slopes up to the left and that for v/v_g to increase toward R is a real phenomenon typical of hurricanes in general.

The average increase of v/v_g with approach toward R is interpreted as a combination of the dynamic effect (increase of v_f/v_g due to changing accelerations) and frictional effect (increase of v/v_f due to lessening of percentage decrease in the wind by friction at higher speeds). This interpretation is made by analogy to similar exposures at Lake Okeechobee---all off-land winds and those off-water winds that are markedly influenced by friction. To separate the two effects is neither feasible nor necessary, and the over-all curve should be satisfactory for the purpose of obtaining frequency distributions of the anemometer-level winds from a number of gradient wind profiles. In the Lake Okeechobee procedure, by contrast, the highest degree of refinement was needed in order to properly extrapolate beyond all observed data to the design hurricane.

Adjustment of anemometer-level-to-gradient-wind ratio to 100-ft off-water value at R

Every observed v/v_g at any distance during the fifty years of hurricanes was adjusted to a standard 100-ft off-water value at R in order to introduce as much as possible of the greatly varying v/v_g data into the wind-reduction procedure. The first step was the adjustment to a standard anemometer-height, 100 feet. This adjustment was accomplished by use of empirical curves---off-water (figure 32) and off-land (not shown). Mean positions were computed for each third of the data (x's of figure 32), and a curve was drawn to the three points. The curve for figure 32 and the corresponding curve for the off-land winds are considered as reliable as any that can be obtained from the data. (All theoretical treatments, e.g. the Ekman spiral, show that the variation of wind with height above the ground is a curve concave down. Therefore, it is not appropriate to fit a linear regression line.) The observed v/v_g's were adjusted to 100 feet by multiplying by the ratio of the ordinates of the solid curve in figure 32 at the actual anemometer height and at 100 feet, and similarly



RATIO OF 15-MINUTE-AVERAGE OFF-WATER WINDS TO GRADIENT WINDS (1900-1949)

FIG. 32

for off-land winds. In stratifying, the off-water category included all cases in which the anemometer was within a mile or two of open water, and the wind direction was off the water. Large bays, such as Corpus Christi Bay and Mobile Bay, were considered open water. The off-land category included all other cases.

The second adjustment was from off-land wind to off-water wind, chosen as the standard frictional category. The off-land curve, alluded to above, fell at an ordinate of 0.88 of the corresponding ordinate on the off-water graph at all anemometer heights. Off-land v/v_g's at 100 feet were adjusted to off-water by dividing by that factor.

The third step was to divide each v/v_g adjusted to 100 feet and off-water by the ordinate of curve C at the pertinent distance, thus adjusting each ratio to distance, R. More than 150 adjusted values of v/v_g at R were obtained in this way.

<u>Application of frequency distribution of adjusted ratios at R to obtain probability distribution of anemometer-level wind from pressure profiles</u>

The adjusted values of v/v_g at R were arrayed in order of magnitude and the values were taken from the array at the 90%, 70%, 50%, 30%, and 10% frequency levels. Expressed as percentages, these values were 99.4, 83.6, 71.4, 61.0, and 50.5. Multiplying curve C of figure 22 by each of these percentages yielded five reduction curves for obtaining 100-foot off-water winds from gradient winds at varying distances from R. The gradient wind profile as computed from the coastal pressure profile in each hurricane was reduced by each of the five curves.

The purpose of using five reduction curves instead of a single mean reduction curve was to avoid minimizing the frequency of high speeds. The observed values of v/v_g were widely dispersed. Variations from a mean were due both to real variations in the relationship of the anemometer-level wind to the pressure gradient and to errors in measurement and analysis of both wind and pressure. In a particular storm the anemometer-level wind may have been either appreciably higher or appreciably lower than would have been obtained by computation from a mean reduction curve only. These departures would have tended to average out for speeds of frequent occurrence, but not for the extremes. For example, the highest gradient wind speed in any storm was 137 mph in the hurricane of September 2, 1935. Use of a mean value of v/v_g at R (73%) would have yielded a maximum anemometer-level wind of 100 mph, with a zero frequency for all speeds above 100 mph. This would neglect the fact that v/v_g may have had a higher value than 73% in that particular storm. To take cognizance of the variations of v/v_g, the values of v/v_g at the five frequency levels mentioned were employed and given equal weight. The five frequency levels were considered to be at the mid-points of five equal portions of the entire array of possible values of v/v_g.

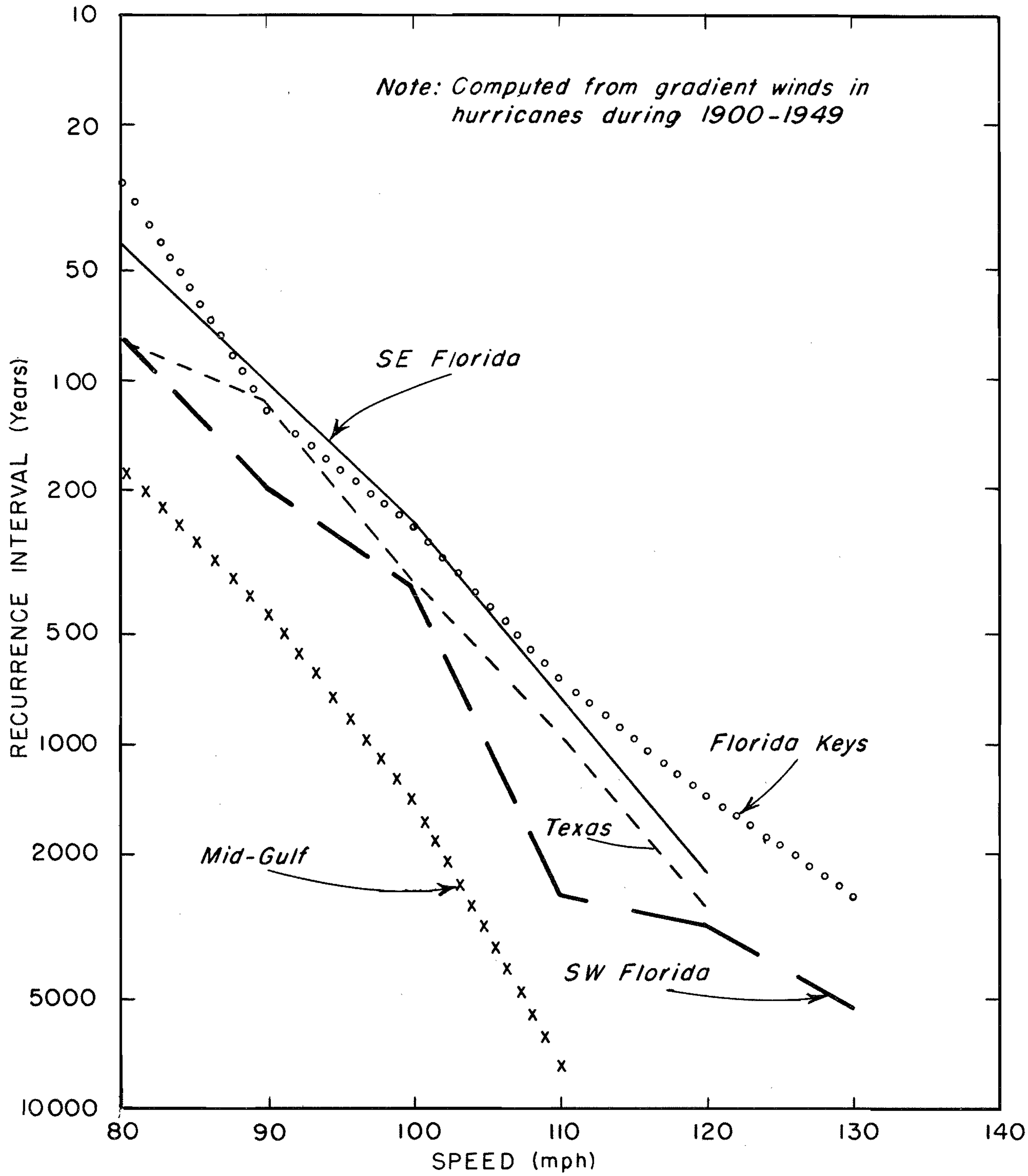
Derivation of Wind-Speed Frequencies

Frequency of 100-ft off-water winds

At a coastal point, the average frequency of hurricane winds in excess of 80 mph during the 1900-1949 period was synthesized in the following manner. (a) The outer of the two distances from storm center at which the speed was 80 mph was found on each of the five anemometer-level profiles (for the five frequency levels) that had been obtained for each hurricane by reducing the gradient wind profile. (b) These distances were scaled at right angles to the track of the storm center, and the length of coast lying within each of the five 80-mph zones was measured. (c) All such lengths were summed by geographical regions. (d) The sum was divided by five and by the total length of the coastline within the region, thus yielding the frequency, at a point, of a hurricane wind speed of 80 mph. (By this method, each storm yielding the critical value is counted as one occurrence, without regard to duration.)

The same procedure was followed for 90 mph, 100, etc. The resulting frequencies, in terms of recurrence interval, are shown in figure 33 for five geographical areas. In delineating these areas, the Florida Keys were construed as a "coast" of 160-nautical-mile length from Dry Tortugas to the northern end of Key Largo. "Southwest Florida" extends from the southern tip of the Peninsula, at 81°W, to a point at 28.5°N on the west coast (about halfway between Cedar Key and Tampa); "Southeast Florida" extends from the southern tip to Titusville. "Mid-Gulf" embraces the coast from the Texas-Louisiana border eastward to 84°W, in Apalachee Bay, (below the narrowest portion of Northwest Florida). There were no hurricanes of sufficient strength to enter figure 33 between Apalachee Bay and the northern limit of Southwest Florida during the 50 years. "Texas" is the coastline of that State. Along the Gulf and Florida Coasts the probability of a sustained wind 80 mph (the minimum speed in figure 33) for fifteen minutes in other than a hurricane is extremely remote, and figure 33, though based exclusively on hurricanes, is logically interpreted as a frequency distribution of all sustained winds above 80 mph. Along the Atlantic Coast there would be increasing contamination northward of the frequencies by non-hurricane high winds, and wind frequencies were not computed for the Atlantic north of Florida. Tornadoes were not considered. The hurricanes listed on page 4, which were omitted from analysis and which may have had central pressures as low as 28.50 inches, would have made but a negligible contribution to figure 33. By the method of computation employed, the average maximum sustained wind speed at the 100-ft level, for a central pressure of 28.50 inches, and average asymptotic pressure, is 65 mph.

The off-water exposure to which the frequencies in figure 33 pertain is a typical Weather Bureau City Office exposure at 100 feet above the ground, atop a downtown building with other buildings in the vicinity. The frequency of winds at the same height on a tower in open country would be higher. The frequencies from figure 33 were compared with an approximate frequency table given by Norton and Gray[11], which is also based on a fifty-year period, 1886-1935. Norton and Gray's frequencies of hurricane-force



AVERAGE RECURRENCE INTERVAL AT A POINT ON THE COAST OF 15-MINUTE-AVERAGE OFF-WATER WINDS 100 FEET ABOVE THE GROUND.

FIG. 33

winds for certain cities are compared with the frequencies of 75-mph (by extrapolation) and 80-mph 15-minute-average winds from figure 33 for the areas in which the cities lie. In Florida, the 75-mph frequencies from the present study compare well with Norton and Gray's frequencies. That their frequencies are consistently a little higher could easily be accounted for by a difference in wind category alone. The duration of 75 mph or more for 15 minutes is more restrictive than the usual definition of hurricane force. At Pensacola, Norton and Gray's average frequency of a hurricane wind is much greater than the average mid-Gulf frequencies found in the present study. This lack of correspondence may be evidence of one or more of three influences. A disproportionately large number of hurricanes may have passed very close to Pensacola, from 1886 to 1935, increasing the frequency in Norton and Gray's table. Secondly, the mid-Gulf coast may not be climatologically homogeneous with respect to hurricanes, having a real higher frequency in the vicinity of Pensacola and Mobile than to the west. Finally, the long and devious coastline of Louisiana, even though smoothed, may have artifically depressed the hurricane frequencies for the mid-Gulf curve when the lengths of coast subject to particular speeds were divided by the total length of coast.

Table 6

CHANCES OF HURRICANE WINDS IN ANY GIVEN YEAR
AS OBTAINED FROM FIFTY YEARS OF RECORD

	Norton and Gray 1886-1935	Figure 33 1900-1949	
		15-minute average	
	Hurricane force	75 mph (by extrap.)	80 mph
Jacksonville	1 in 50	--	--
West Palm Beach	1 in 20		
Miami	1 in 20		
Southeast Florida		1 in 26	1 in 42
Key West	1 in 10		
Florida Keys		1 in 13	1 in 28
Fort Myers	1 in 20		
Tampa	1 in 30		
Southwest Florida		1 in 48	1 in 75
Pensacola	1 in 10		
Mid-Gulf		1 in 114	1 in 185

The recurrence intervals in figure 33 may seem large in comparison with the published accounts of individual hurricanes, in which there are not a few reports of winds in excess of 100 mph. This is in part because the published accounts frequently cite bursts of wind of short duration, while figure 33 applies to winds averaged over 15 minutes. (Conversion of figure 33 to gust speeds is discussed later.) Also, prior to 1928 many published records are uncorrected for instrumental error. The standard correction for the Robinson 4-cup anemometer, the type in universal use by the Weather Bureau prior to 1928, is large. An indicated speed of 100 mph represents an actual speed of only 76 mph. Throughout the present report all wind speeds are corrected to true velocity, and the convention of dividing tropical storms from hurricanes at 75 mph did not have to be used.

Figure 33 is the end-product of the portion of the study devoted to the task of interpreting the large body of information about hurricanes--obtained in the course of meeting requirements for Lake Okeechobee--to point wind frequencies at a standard height, exposure, and interval of time over which the wind is measured. A comprehensive investigation of departures from the standard--other heights, exposures, and time intervals--lies outside the scope of the study. However, a few suggestions on possible adjustments from the standard, based largely on factors obtained for other purposes, are included in the remainder of the chapter.

Frequency of 100-ft off-land winds

Approximate average frequencies of off-land speeds can be obtained by multiplying the speeds of figure 33 by an average reduction factor. Comparison of the solid curve of figure 32 for off-water winds with the corresponding curve (not shown) for off-land winds yielded a reduction factor from off-water to off-land wind of 0.88 at all anemometer heights. It would be supposed that this ratio approaches 1.0 with increasing height, but no variation with height was discernible up to the highest anemometer height, 314 feet. The ratio should also vary with wind speed. However, it is probably not practicable to introduce a dependence of the ratio on height or speed without precise knowledge of the frictional effects at the particular location of interest. Multiplying the speeds of figure 33 by 0.88, or 0.9, is suggested as a conservative reduction to obtain a frequency distribution of hurricane wind speeds at the 100-ft height for off-land winds, either winds at the coast from a direction off the land or winds from any direction several miles, say 5 to 20, back from the coast. A rough check of the factor of 0.88 is obtained from the Lake Okeechobee wind data. In figure 31 the solid curves give off-land speeds for the various stations on the shore of the Lake for different over-water speeds. The dashed curve, labeled 89%, gives the corresponding off-water speeds. At an off-water speed of 80 mph, the corresponding off-land speed ranges from 61 mph at HGS No. 5 to 79 mph at HGS No. 3, a range from 76% to 99%.

Wind-speed frequencies at heights other than 100 feet

Figure 33 could be readily translated to heights of other than 100 feet if the variation of wind speed with height in hurricanes was known.

The variation of wind with height as obtained from the fifty years of hurricanes is depicted by the solid curve of figure 32, but the reliability of the curve is low, and it may well be that it would give speeds that are too low in comparison to 100 feet, both at lower heights and greater heights. We agree with R. H. Sherlock of the Structural Division Committee on Wind Forces of the American Society of Civil Engineers[12/] that for design purposes, "The equation for the relation between velocity and height should be based primarily on well validated rational considerations rather than upon statistical analysis of non-homogeneous . . . . . records." For obtaining design wind speeds, Sherlock has recommended the "seventh-power law" in which the wind at any height, v_h, is related to the wind at 30 feet, v_o, by the expression

$$v_h/v_o = (h/30)^{1/7}$$

The curve from this formula, computed to pass through the solid curve at 100 feet, is shown as dashed in figure 32 and fits the data reasonably well. It has been pointed out, however, for example by McCormick[13/], that, as was recognized by Sherlock, there is a wide variation in the exponent 1/7 and that caution is called for in applying exponents based on low-speed data to high speeds. It is questionable that the one-seventh-power expression should be referred to as a "law". However, the expression is at least as good as any other available and has gained acceptance. It can be used to transpose the speeds of figure 33 to another height with the recognition that the exponent of one-seventh is subject to fluctuations and has not been fully tested for high speeds. Use of the one-seventh power expression for variation of wind speeds up to 1000 feet has been recommended by Gentry[3/] in his recent discussion of hurricane winds.

Frequency of gusts

Nearly all climatological data on wind speeds published by the Weather Bureau are, like figure 33, in terms of speed averaged over a period of time. This is true even of the "fastest single mile" from the point of view of the engineer interested in the speed of gusts of only a few seconds' duration. The gust factor, that is, the ratio of gust speeds to average wind speeds, has been studied by Mattice[14/], Huss[15/], and Sherlock[12/]. Mattice compared gusts from a Dines anemograph with an anemometer on top of the Weather Bureau Central Office in Washington during the year 1936. The other two investigators analyzed wind records from specially designed anemometers mounted at different levels on towers. It is important to compare gust factors obtained from the Lake Okeechobee wind data with the others, as higher speeds were observed than in any of the other investigations. The highest speeds in each set of data are: Mattice, 47 mph (fastest single mile); Huss, 54 mph (5-minute average); Sherlock also 54 mph (5-minute average); and Lake Okeechobee, 81 mph (10-minute average). The Lake Okeechobee gust factors are obtained by taking reciprocals of the left-hand scales of figures 23-25 and similar figures (not shown) for other stations. The off-water factors are also the reciprocals of the v_w/v_{pw} values in table 5.

Table 7

GUST FACTORS AT LAKE OKEECHOBEE
(Ratio of peak gusts to 10-min-average winds)

	Off-water (all speeds)	Off-land 30 mph*	Off-land 60 mph*
HGS No. 1	**	1.78	-
HGS No. 2	1.43	1.89	-
HGS No. 3	1.48	1.33	-
HGS No. 4	**	1.72	1.47
HGS No. 5	1.48	2.23	1.65
Port Mayaca	1.44	1.87	1.66
HGS No. 6	1.39	1.80	-
Average	1.43***	1.80	1.59

Wind instruments about 23 feet above top of levee, about 40 feet above Lake and surrounding terrain. (See appendix A.) *10-minute average. **Factor at this station depends on speed. ***Reciprocal of previously mentioned standard value of v_w/v_{pw}, 70%.

Table 8

GUST FACTOR AFTER MATTICE, HUSS, AND SHERLOCK

Height above ground	Mattice** 20 mph*	Mattice** 47 mph*	Huss*** (selected high-speed periods)	Sherlock**** (selected high-speed periods)
85'	1.50	1.46		
30'			-	1.50
40'			1.63	1.47
100'			1.42	1.39
160'			1.37	1.35
220'			1.31	1.32
280'			1.30	1.30
350'			1.27	1.28

*fastest single mile
**from author's figure 2
***from author's table 8
****from author's equation (3)

Comparative gust factors are listed in tables 7 and 8 and show that over-all correspondence is good. If a precise comparison of gust factors is made, several contingencies must be given weight: (a) The gust factor decreases with height. (b) The gust factor increases with roughness. (c) The gust factor, decreases with increasing speed, as was shown by the Lake Okeechobee data. (d) Definitions of gust and average speed, and the instruments that measured them, differ. Heights and speeds at which the gust factors were measured are shown in tables 7 and 8. Table 9 lists the definitions of the speeds by the various authors and the instrumentation and exposure.

Table 9

DEFINITIONS OF GUST AND AVERAGE SPEEDS
PERTAINING TO TABLES 7 AND 8

LAKE OKEECHOBEE		
Gust	:	peak of trace in each 10 minutes, duration of gust unspecified
Avg. speed	:	for 10 minutes
Instrument	:	Dines anemograph
Exposure	:	see appendix A
MATTICE		
Gust	:	selected peak of trace that is higher than adjacent peaks, duration of gust unspecified
Avg. speed	:	"fastest single mile" within a few minutes of the peak gust
Instrument	:	gusts from Dines anemograph, fastest single mile from Robinson 4-cup anemometer
Exposure	:	city; on top of Weather Bureau Central Office building in Washington, higher building nearby in one direction
HUSS		
Gust	:	selected "outstanding" peaks of trace, duration estimated by Huss from chart speed, etc., as 1 second
Avg. speed	:	average of highest 5-minutes that includes the gust
Instrument	:	light-weight anemometer
Exposure	:	open "off-land"; on steel radio tower
SHERLOCK		
Gust	:	highest 10-second gust for a storm
Avg. speed	:	maximum 5-minute average for the storm
Instrument	:	light-weight anemometer
Exposure	:	open "off-land"; on steel tower

The off-water gust factors at Lake Okeechobee are lower than at a corresponding height in Huss' data, which is consistent with lesser roughness at the Lake. Sherlock's factor is closer to the Lake values, which is consistent with the opposing influences of greater roughness but longer gust duration in his data. Duration of gusts from the Lake is not specified but there is no doubt that it is less than the 10 seconds on which Sherlock's data in table 8 are based. The Lake Okeechobee 60-mph off-land gust factors agree well with Huss' and Sherlock's factors in spite of differences in techniques. The 30-mph off-land factors, as would be expected, are larger. The over-all conclusion is that previous measurements of the gust factor and the Lake Okeechobee measurements appear to be consistent and that gust factors determined in other types of storms are applicable to hurricanes, with suitable allowance for the higher speeds, and conversely.

Recurrence interval of off-water gust speeds may be obtained by multiplying the speeds of figure 33 by the appropriate gust factor. Gust factors and their variation with height, with duration, and with other circumstances, discussed briefly above, are treated comprehensively by Sherlock12/. It is not the province of the present study to specify what the exact gust factor should be, but a first approximation of the recurrence interval of off-water gust speeds at 100 feet is obtained by multiplying the speeds of figure 33 by 1.4. This is based on the following considerations. The independence of wind speed of the off-water turbulence structure found at Lake Okeechobee does not carry over to the less open downtown location to which figure 33 is referred. Huss' gust factor of 1.42 at 100 feet should be adjusted (a) down for high speeds, (b) down for off-water instead of over-land exposure, and (c) up for downtown instead of open-tower location. The same three adjustments would apply to Sherlock's 100-ft gust factor of 1.39. In addition, Sherlock's factor would be adjusted up to a shorter gust duration comparable to Huss' and the Lake Okeechobee data. The Lake Okeechobee off-water factor of 1.43 would be adjusted (a) down for greater elevation and (b) up for greater friction. It is doubtful if any of the above adjustments individually exceed 10%, and 1.4 is an approximate mean adjusted value.

The corresponding factor to adjust the speeds of figure 33 to off-land gusts is 1.3 to 1.4. This is based on the following considerations. Huss' 100-ft factor of 1.42 should be adjusted (a) up for greater friction and (b) down for higher speed. Sherlock's factor of 1.39 would be similarly adjusted and, in addition, up for shorter gust duration. The Lake Okeechobee 60-mph off-land factor of 1.59 should be adjusted (a) down for elevation (to about 1.50 by Sherlock's formula) and (b) down for high speed (less than the others). A gust factor of 1.5 is considered as approximately representative of the Lake Okeechobee data and Sherlock's values, when adjusted to the 100-ft off-land downtown exposure. A final adjustment is required, not to the gust factor as such, but to convert the off-water speeds of figure 33 to off-land speeds. Employing 0.88 as the reduction factor from off-water to off-land as before, a total adjustment factor of 1.5 x 0.88 = 1.32 is obtained to convert the sustained off-water speeds of the figure to off-land gusts, or, roughly, 1.3 to 1.4.

The speeds obtained by applying the suggested approximate gust factors represent the gust speeds of frequent occurrence, every ten minutes or so, all around the hurricane in the high speed zone. Additional allowances would be required to obtain the extreme gust for a given sustained speed, and also for local exceedance of the sustained wind speed over the prevailing speed at the same storm radius.

The highest wind speed in the twentieth century in any hurricane near the United States was doubtless in the storm of September 2, 1935, although no measurements of the wind speed were obtained when the storm crossed the Florida Keys. The maximum gradient speed in the storm as computed in the present study by the standard procedure of assuming normal atmospheric density (1.175×10^{-3} gm/cm^3) is 137 mph. Corrected to the density for the reduced pressure at the radius of maximum winds (1.10×10^{-3} gm/cm^3), this is 142 mph. To examine the reliability of these maximum wind values which are computed from the pressure difference of 3.57, with p_o 26.35 inches and p_n 29.92 inches: the central pressure is accepted as an observed value; p_n is increased by one standard deviation (0.30 inch) with the same central pressure; a value of 143 mph instead of 137 mph is obtained for the maximum gradient wind, there being little change because the maximum gradient wind is proportional to the square root of the pressure difference. Harney[16/], in a comprehensive analysis of the storm from essentially the same basic data, obtained a maximum gradient speed of 151 mph. Accepting the 137-mph gradient wind value, a procedure for reduction to surface winds is to make an analogy to the August 26, 1949 hurricane at Lake Okeechobee. Comparative values of various categories of wind are shown in table 10. The speeds for the 1949 storm are observed values. Multiplying these by the ratio of the respective maximum gradient speeds yields the speeds

Table 10

ESTIMATES OF MAXIMUM WIND SPEEDS IN SEPTEMBER 2, 1935 HURRICANE BY ANALOGY TO AUGUST 26, 1949 HURRICANE

	August 1949 (observed)	September 1935 (estimated)
Maximum gradient speed	94.5	137
10-minute-average wind, Peak of mean profile		
Off-water	77.5	112
Over-water	82	119
10-minute-average wind, Highest single observation		
Off-water	81	117
Over-water	84	123
Off-water gusts		
Peak of mean profile	112.5	163
Highest single observation	124	180

Table 11

RADIUS OF MAXIMUM WINDS (NAUTICAL MILES)
IN U. S. HURRICANES 1900-1949

	Texas	Mid-Gulf	Florida Peninsula	Florida Keys	Atlantic (north of Fla.)
			p_o below 28.50		
	35	31	48	28	49
	32	29	34	27	42
	30	27	28	24	35
	21	24	24	21	26
	19		22	16	
	18		19	15	
	17		18	7	
	14		16	6	
	12		14		
			13		
			12		
Mean	22.0	27.7	22.5	18.0	38.0
			p_o between 28.50 and 29.00		
	75	88	43	19	89
	28	58	35		61
	24	57	27		55
	18	51	26		54
	17	50	25		49
	13	44			44
	11	37			41
		33			34
		28			26
		28			24
		19			13
		18			
Mean	26.6	42.6	31.2	19.0	44.5

listed for the 1935 storm. Since it is more than likely in the very intense and very small 1935 hurricane that the actual free-air winds exceeded the gradient wind by an even greater percentage than was the case in the 1949 hurricane, all speeds listed in the table for the 1935 storm may be underestimates. Thus, we see that a value near 200 mph is quite reasonable for the <u>extreme gust</u>. That such a speed was sustained for any length of time, however, is not confirmed by the present data.

Duration and area of high winds

For wave height and set-up (wind tide) at Lake Okeechobee, duration, area, and length of fetch, as well as speed, are of importance. For a building, the number of square miles covered by high winds is of no interest, and the duration is of distinctly secondary importance in comparison with the design speed. Figure 33 does not consider durations or areas but presents point frequencies. Several hours are required to bring the Lake surface to equilibrium with a sustained high speed. The presentation is not made here, but the basic data developed in this Report can be assembled in such a fashion as to portray the distribution of wind speeds in the various hurricanes, not only as point occurrences but in terms of areas and durations.

Frequency of radius of maximum winds

The values of R for individual storms, table 1, are listed in table 11 in order of magnitude, by geographical regions, and according to whether the storm central pressure was above or below 28.50 inches, R tends to increase with increasing distance from the hurricane source region--as the pressure difference tends to decrease (figure 14). R is also larger for the weaker storms, with central pressures above 28.50 than for the more intense storms.

Frequency of maximum gradient and cyclostrophic winds

Table 1 includes the maximum gradient winds which are computed from the pressure profile on the basis of a normal air density (.001175 gm/cm^3). The accumulated frequency of the maximum cyclostrophic winds (which are obtained directly from the pressure difference, $p_n - p_o$) in the 50 years of hurricanes is shown in figure 12 (solid curve). In but one storm (the 1935 storm already discussed) did the maximum cyclostrophic wind exceed 130 mph; four storms had values between 120 and 130 mph and 18 of the storms had values in excess of 100 mph. A very rough approximation of the frequency distribution of maximum values of various categories of anemometer-level winds may be obtained by analogy to the data for the August 1949 hurricane in table 10. The maximum cyclostrophic wind in the storm, at the time it was over Lake Okeechobee, was 96.5 mph.

Chapter V

FILLING

The filling problem

Hurricanes are maritime phenomena, and it is commonly conceded that when they pass over a land surface their force is diminished and they fill -- that is, the pressure rises. Since Lake Okeechobee lies 30 statute miles from the Atlantic Ocean, two questions arise. How much (if at all) should a great hurricane be expected to diminish in force in traversing that distance? And, is the reduction in wind speed inland restricted to the surface layer, or is the speed of the free-air wind above the frictional layer diminished also? If only the surface wind is diminished, a hurricane would be expected to regain its open-sea strength over the waters of the Lake; if the circulation above the surface is also diminished, it would not. The problem was investigated by considering the modification of pressure gradients as hurricanes moved inland.

Analysis of filling in individual hurricanes

Each of the hurricanes listed in table 1 for which sufficient pressure data were available was subjected to a filling analysis. In addition, a few storms with central pressures higher than 29.00 inches, and therefore not listed in the table, were included in the filling study. In these, it had been necessary to lay out the path and construct the pressure profile before it was determined that the central pressure was higher than the 29.00-inch critical value.

It was soon found that the rate of filling varies markedly with distance from the hurricane center. To portray the relation of the rate of filling both to distance from the storm center and to the passage of time, analysis of each hurricane proceeded in the following manner. Differences were taken between sea-level pressures observed at stations at one-hour intervals and pressures read at the same distances from the storm center from the mean radial visually-fitted pressure profile, the construction of which was described in chapter I. The differences, which will be termed pressure departures, were plotted as points in a coordinate diagram with the time of the pressure observation and the distance from the hurricane center as coordinates. The plotted points were labeled with the value of the pressure departure, in hundredths of an inch. Lines of equal pressure departure were constructed. Pressure-departure values were then read off this analysis for selected distances and times. Departures so obtained were interpreted as the mean change in pressure, at the distances to which they pertained, from approximately the middle of the time interval for which the original pressure profile had been constructed to the time of the particular departure value. The zero, or reference, time was then shifted to the hour the storm center crossed the coast by subtracting the pressure departures at that hour from the departures for all other hours.

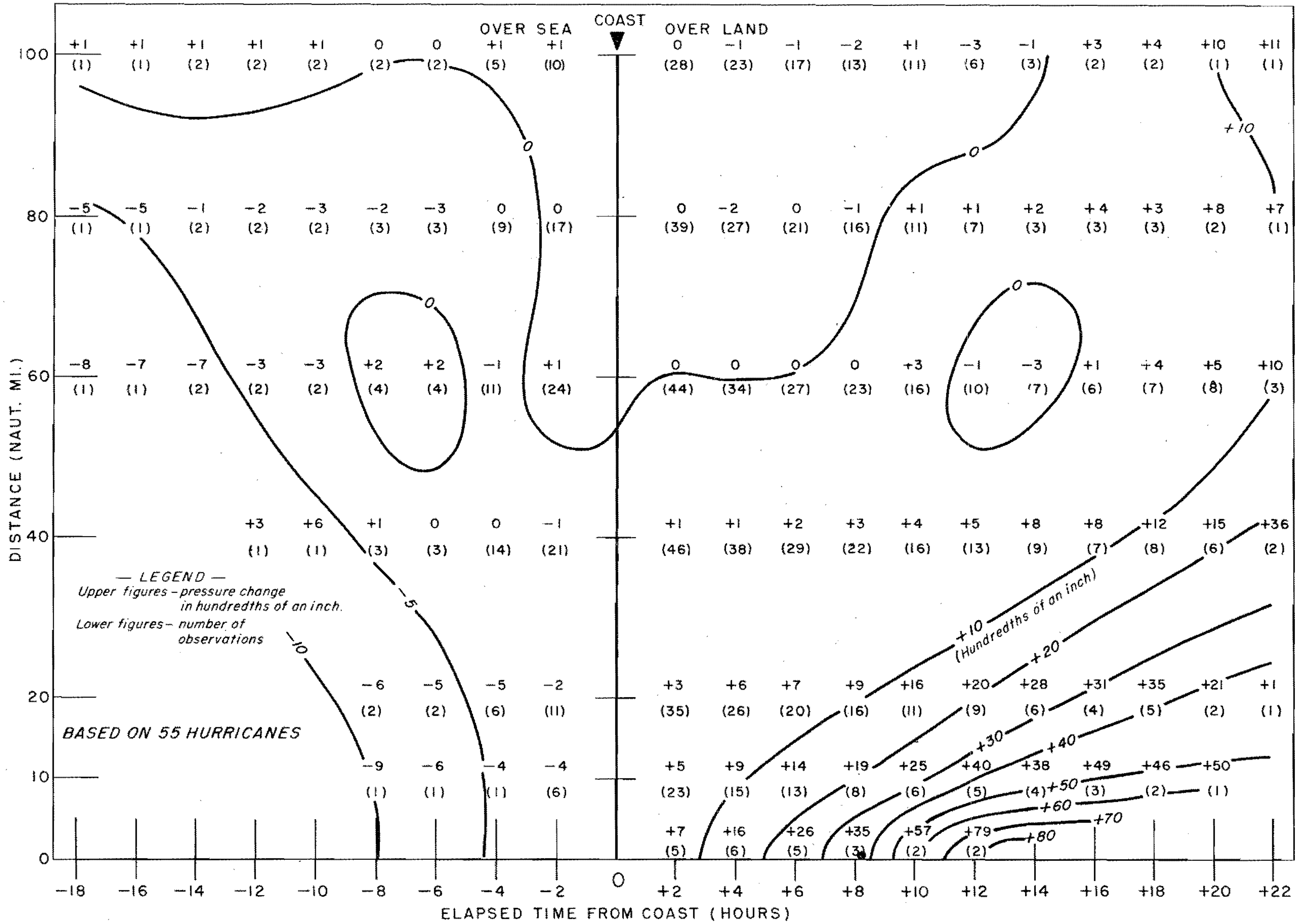
Average filling characteristics

Values of the pressure departures were averaged at standard distances and times -- for example, at 10 miles from the center two hours after entering the coast -- and the averages were plotted in a diagram, figure 34. The number of observations is also given in the diagram and varies from point to point because data were available in each hurricane for only a portion of the figure. The large variability of the number of observations makes strict quantitative interpretation of figure 34 unjustified. In fact, adding the pressure changes shown in the figure to the pressure profile of an average hurricane would give, within a few hours after it entered the coast, a higher pressure at the center than a few miles farther out, manifestly unreasonable for an average pattern. Nonetheless, the lines of average pressure departure in the right-hand portion of figure 34 make it evident that the following are typical characteristics of a hurricane moving inland. (1) The fastest rise in pressure is at the center of the storm (as indeed it must be if the over-all pressure gradient is to diminish). (2) With increasing distance from the center, the rate of pressure rise is greatly decreased, and in the first few hours rises of any magnitude are restricted to a core near the center not much larger than the eye of the storm (perhaps no larger). Farther out the pressure actually falls slightly. (4) During the first few hours the average pressure rises are so restricted in magnitude and in the area covered that it is not unreasonable to consider that an individual hurricane, which may fill even less than the average hurricane, can penetrate as far inland as Lake Okeechobee with its pressure gradients undiminished.

Filling over the sea seems to be taking place before the typical hurricane reaches the United States Coast -- similar to the filling that is characteristic of the passage overland, though at a slower rate. This is suggested by the left-hand portion of figure 34, which is roughly a mirror image of the right-hand portion. The filling prior to reaching land may be due to the storm encountering drier air or greater atmospheric stability in its progress. If so, the same factors, as well as the increased friction, should play a role in the filling over land.

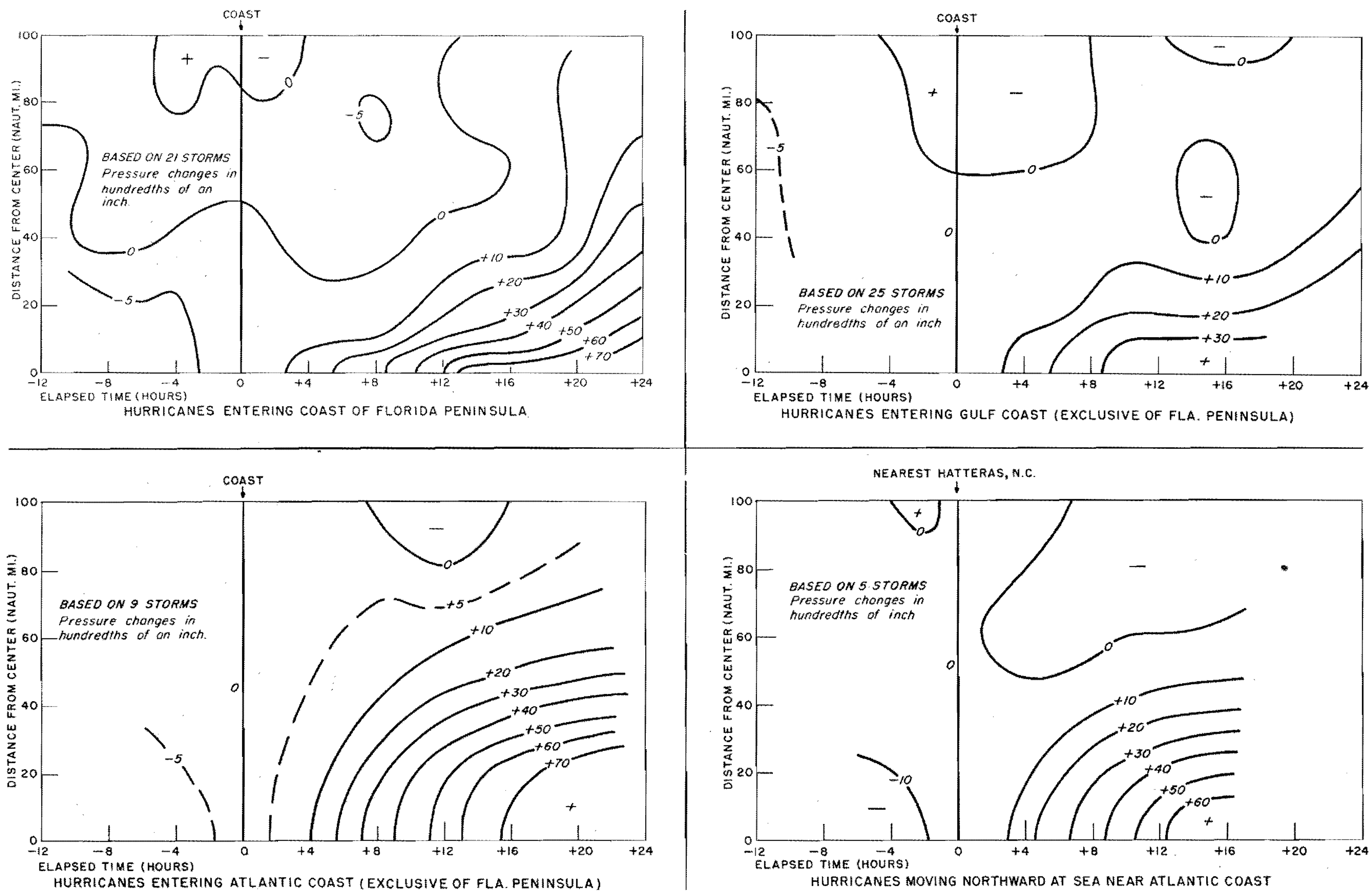
Regional distribution of filling

Filling diagrams similar to figure 34 are shown in figure 35 for the Florida peninsula, the Gulf Coast exclusive of the Florida Peninsula, and the Atlantic Coast north of Florida. The regional filling patterns are quite similar to the over-all average pattern in figure 34. Hurricanes that entered the Atlantic Coast filled more rapidly and to greater distances from the storm center than the others. Hurricanes moving northward at sea off the Atlantic Coast behaved similarly. This is shown by the lower right-hand panel of figure 35 which presents the pressure changes in five such storms. The reference time is that of location closest to Hatteras, N. C., rather than the time of entering the coast. These storms did not enter the coast and were not included in figure 34. The indicated pressure changes can be considered



AVERAGE SEA-LEVEL PRESSURE CHANGE IN HURRICANES ENTERING THE U. S. COAST 1900-1949

FIG. 34



SEA-LEVEL PRESSURE CHANGES IN HURRICANES BY REGIONS

FIG. 35

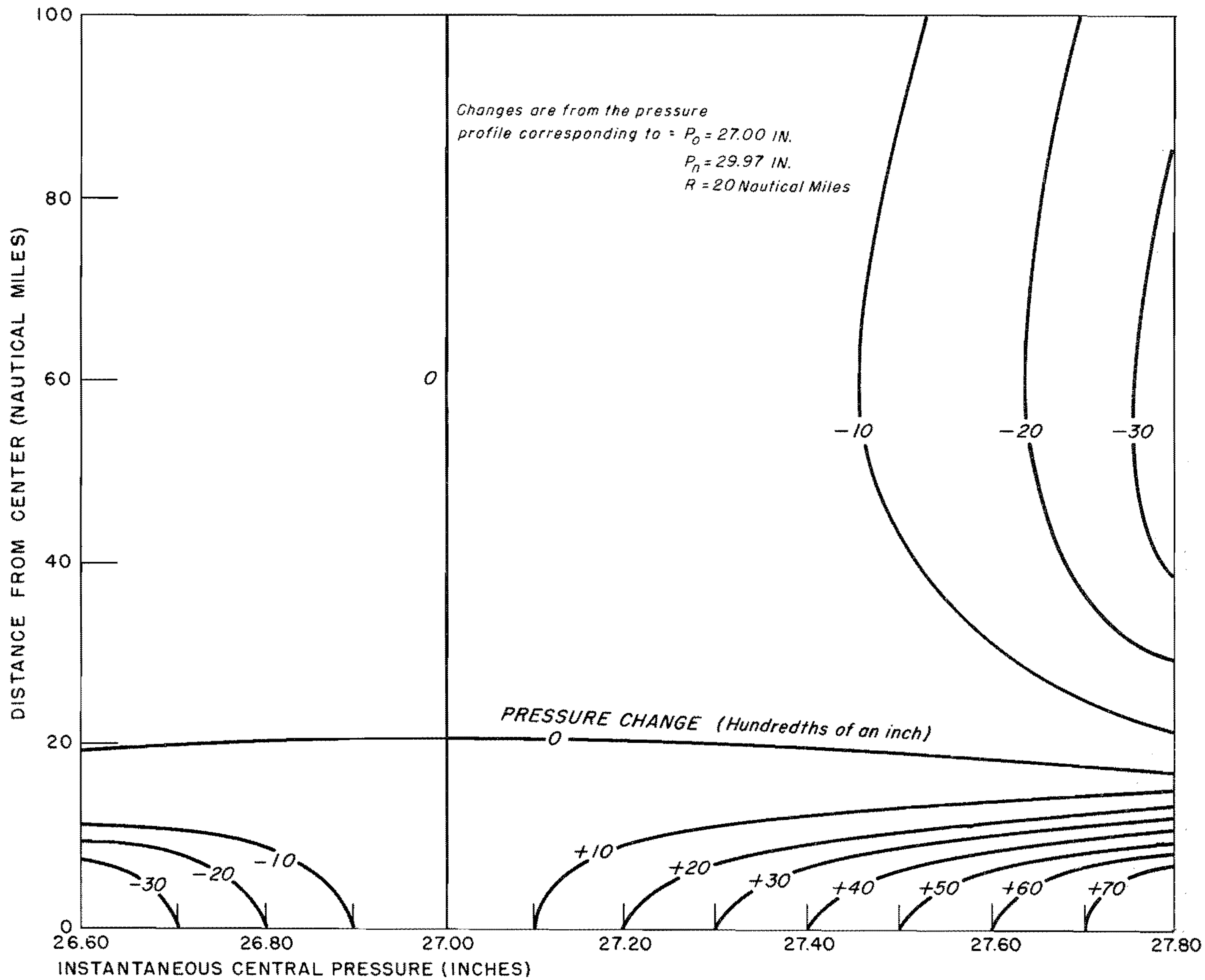
as typical of a maturing hurricane after recurvature northward. The similarity of the diagram to the others is further evidence that the typical filling pattern for a hurricane moving over land can be interpreted as a combination of the maturing process, which takes place over land or sea, and filling associated with movement over land. Greater influence of the maturing process, which would be expected to be more in evidence farther north, would account for the greater filling in storms entering the Atlantic Coast as compared with those passing into Florida or other Gulf States.

Redistribution of kinetic energy

The typical filling pattern operates in such a fashion that the loss in kinetic energy associated with the rise in central pressure is in part compensated by an expansion of the storm in such a way as to minimize the decrease in kinetic energy. A procedure will be described in the next chapter for computing the kinetic energy of the cyclostrophic wind in a hurricane from the center out to a specified radius. That procedure was applied to a hypothetical hurricane in which the initial central pressure was 27.00 inches, the radius of maximum winds 20 nautical miles, and the asymptotic pressure 29.97 inches. To simulate a filling hurricane, the central pressure of the hypothetical storm was then increased at a uniform rate while the asymptotic pressure was held constant, and the radius of maximum wind was varied in such a fashion that the kinetic energy within a radius of 100 nautical miles remained constant. A filling diagram analogous to figures 34 and 35, constructed for this hypothetical hurricane and its variations, is shown in figure 36. The similarity of the hypothetical filling pattern for constant kinetic energy in this figure to the filling patterns for actual hurricanes is striking and points up the fact that the rise in central pressure in a hurricane moving inland, or for that matter in a hurricane maturing as it invades a less tropical region, is, in part, associated with an increase in the radius of maximum winds and a redistribution of the kinetic energy of the storm outward. It is interesting to note in figure 36 that the pressure changes are opposite in sign inside and outside of the initial radius of maximum wind.

Comparison with other authors

McDonald[17/] cites evidence from ship observations of hurricane pressures in the West Indies during the 1933 season that "supports the view that tropical distribances often, or perhaps commonly, arise as intense vortices of small diameter, which expand in area and increase in intensity as they progress." Deppermann[18/], has said with respect to Phillipine typhoons, "While the minimum pressure diminishes steadily over land still the storm at times may widen out in the region of the 745th [29.33 inches] or the 750th isobars". Simpson[19/], in a detailed analysis of the hurricane which passed over Tampa in October 1946, describes the rise in central pressure accompanied by an expansion of the storm, a development which at the



PRESSURE CHANGES IN HYPOTHETICAL HURRICANE WITH KINETIC ENERGY CONSTANT WITHIN RADIUS OF 100 NAUTICAL MILES.

FIG. 36

time was puzzling. The findings of the present investigation give quantitative support to these qualitative descriptions of the expansion of hurricanes.

Chapter VI

KINETIC ENERGY

Size vs. intensity

In estimating the maximum hurricane-induced wave and set-up (tide), either in a large inland body of water such as Lake Okeechobee, or along the coast, the area covered by high winds as well as their speed must be considered. An answer is required to the question, is there a relationship between the highest wind speed that may be expected in a great hurricane and the lateral extent of the hurricane winds? In the literature there are suggestions of a tendency for hurricanes with the lowest pressure (and the highest wind) to be of limited lateral extent. Any specific high maximum speed represents less of a threat to the Lake if this relationship is real than if there is no relationship of hurricane size to intensity.

Deppermann[18/] has tabulated the durations of calms for some 59 typhoons in the Phillipines as follows:

Central pressure (in.)	No. of cases	Mean duration of calm (min.)
Below 27.56	4	18
27.56 - 27.95	7	16
27.95 - 28.35	5	37
28.35 - 28.74	11	32
28.74 - 29.14	15	39
29.14 - 29.53	17	64

The table is evidence for larger areas of near-calm with high central pressures than with low, and the radius of maximum winds, in turn, can be assumed to vary about as the diameter of the eye.

The hurricane of September 2, 1935, also suggests the inverse relationship. In that storm, with the lowest sea-level pressure ever observed near North America and the highest wind in the fifty years of hurricanes, the energy for producing tides was much less than in many other hurricanes because of the very small diameter. The radius of maximum winds was but six miles, the smallest for the fifty years of hurricanes.

From the results on filling in chapter V, one would conclude that in any particular hurricane there is a tendency for the pressure difference, $p_n - p_o$, and the highest wind to diminish when the lateral extent increases. Other evidences of an inverse relationship between size and intensity are figure 14 and table 11. The figure shows that the pressure difference tends to decrease with increasing distance from the hurricane source region, and the table indicates that R (index of size) tends to increase. This inverse relationship is investigated in the present chapter in greater detail.

Kinetic energy of the cyclostrophic wind

Combining the expression for speed of the cyclostrophic wind, equation (4), page 3, with the expression for kinetic energy, $E = \frac{1}{2} mv^2$, leads to the following expression for the total kinetic energy of the cyclostrophic wind in a horizontal, circular layer of a hurricane one centimeter deep extending from the center to radius r_1:

$$\int_o^{r_1} dE = (p_n - p_o)\pi R \int_o^{r_1} e^{-R/r} \, dr \qquad (8)$$

The kinetic energy, E, is in ergs when other items are in c.g.s. units. It can be noted that the total kinetic energy in the horizontal layer is a function only of the radius of maximum wind, R, and the pressure difference, $p_n - p_o$, and, unlike the cyclostrophic wind speed, is independent of the air density.

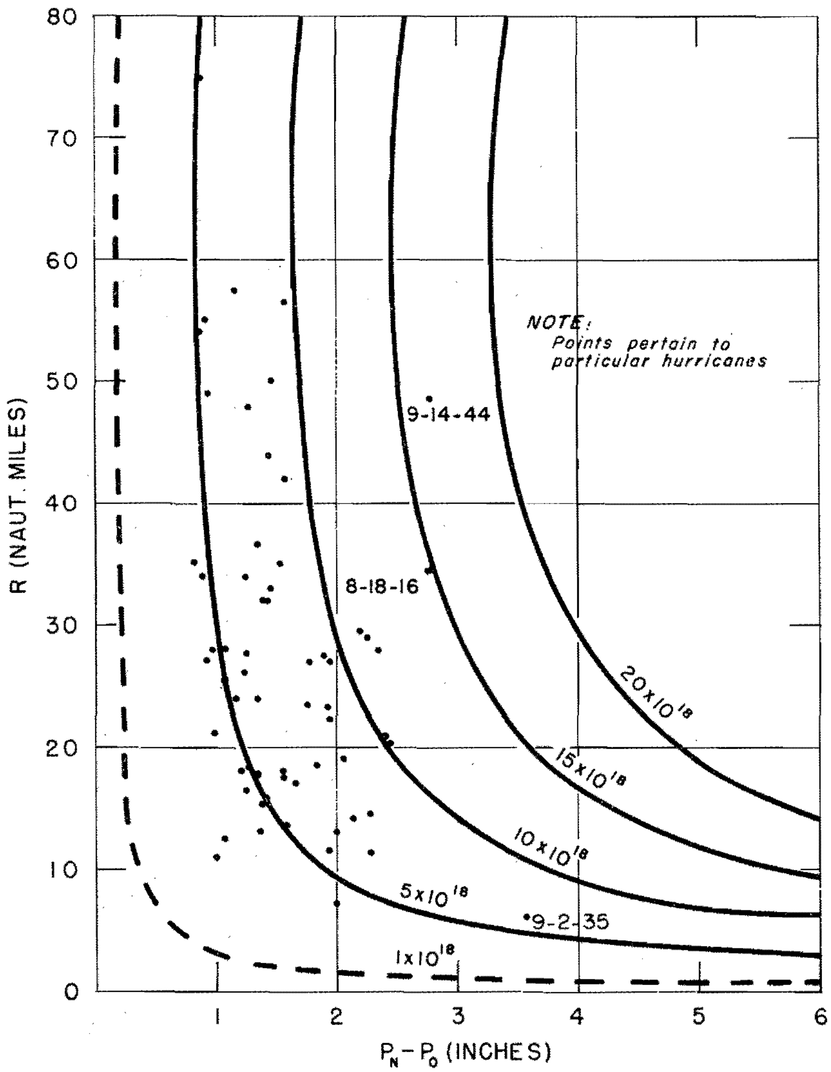
Radius of maximum wind vs. pressure difference

To investigate the relation of size to intensity the values of R from table 1 were plotted against the corresponding value of $p_n - p_o$ (p_o' was not used). R is the shape factor for the pressure profile and is an index of the lateral extent of a hurricane. The pressure difference, $p_n - p_o$, is an index of the maximum hurricane wind, as is shown by the expression for the maximum cyclostrophic speed,

$$v_{cx}^2 = \frac{p_n - p_o}{\rho e} \qquad (6)$$

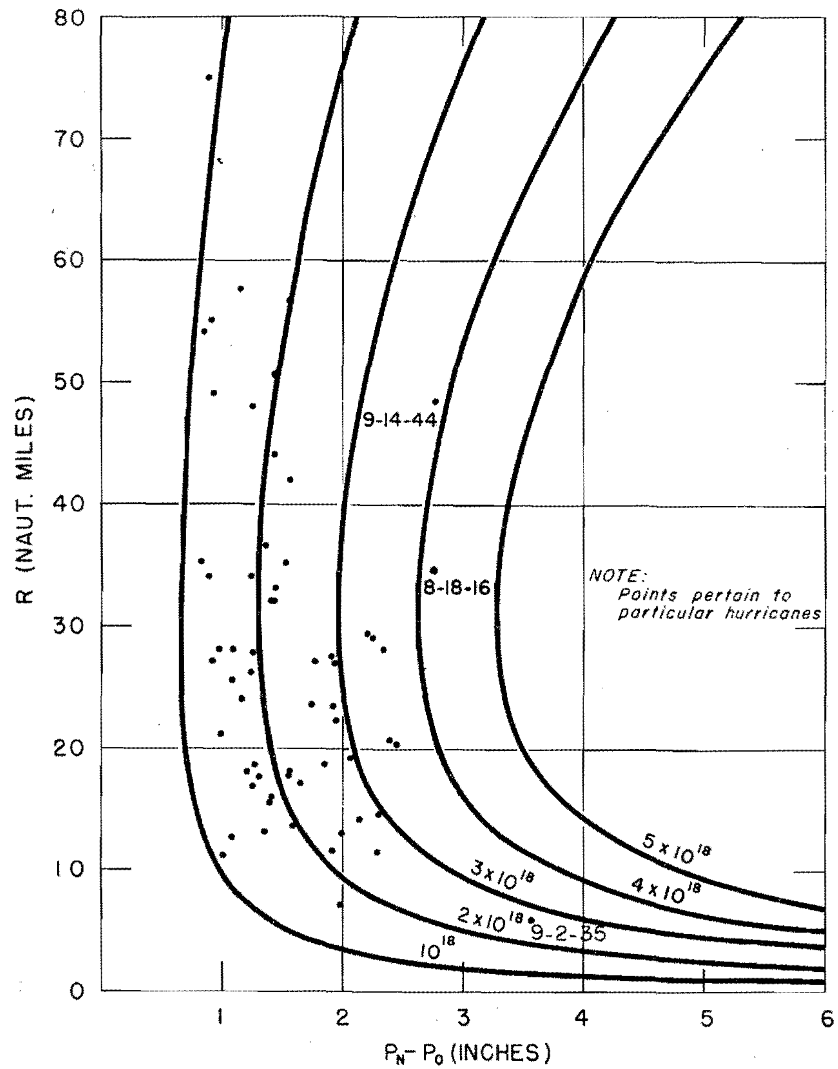
The plotted points are shown in figures 37 and 38 (the points are identical in the two figures). The curves in the figures, depicting the total kinetic energy of the cyclostrophic wind within a horizontal, circular layer one centimeter deep extending from the center to a radius, respectively, of 50 and 100 nautical miles, were computed from equation (8).

A tendency is clearly evident in figure 38 for the points to lie along a band of kinetic energy values. This is interpreted as evidence that a very large value of either R or $p_n - p_o$ would probably be associated with a small value of the other factor. If the points of figure 38 were to be stratified by curves enveloping various fractions of the data, it would be logical to construct the curves parallel to the kinetic energy lines. That there is a better grouping of the points along a kinetic band in figure 38 than in figure 37 is reasonable, as a radius of 100 nautical miles is a more inclusive and pertinent dimension of hurricanes than is 50 miles. The point for the September 1935 hurricane is labeled with the date and lies in the lower right-hand portion of figures 37 and 38. It is seen that



KINETIC ENERGY (ERGS) IN A CIRCULAR LAYER OF 100-NAUTICAL-MILE RADIUS, 1 CM DEEP, AS FUNCTION OF R AND $P_N - P_O$.

FIG. 38



KINETIC ENERGY (ERGS) IN A CIRCULAR LAYER OF 50-NAUTICAL-MILE RADIUS, 1 CM DEEP, AS A FUNCTION OF R AND $P_N - P_O$.

FIG. 37

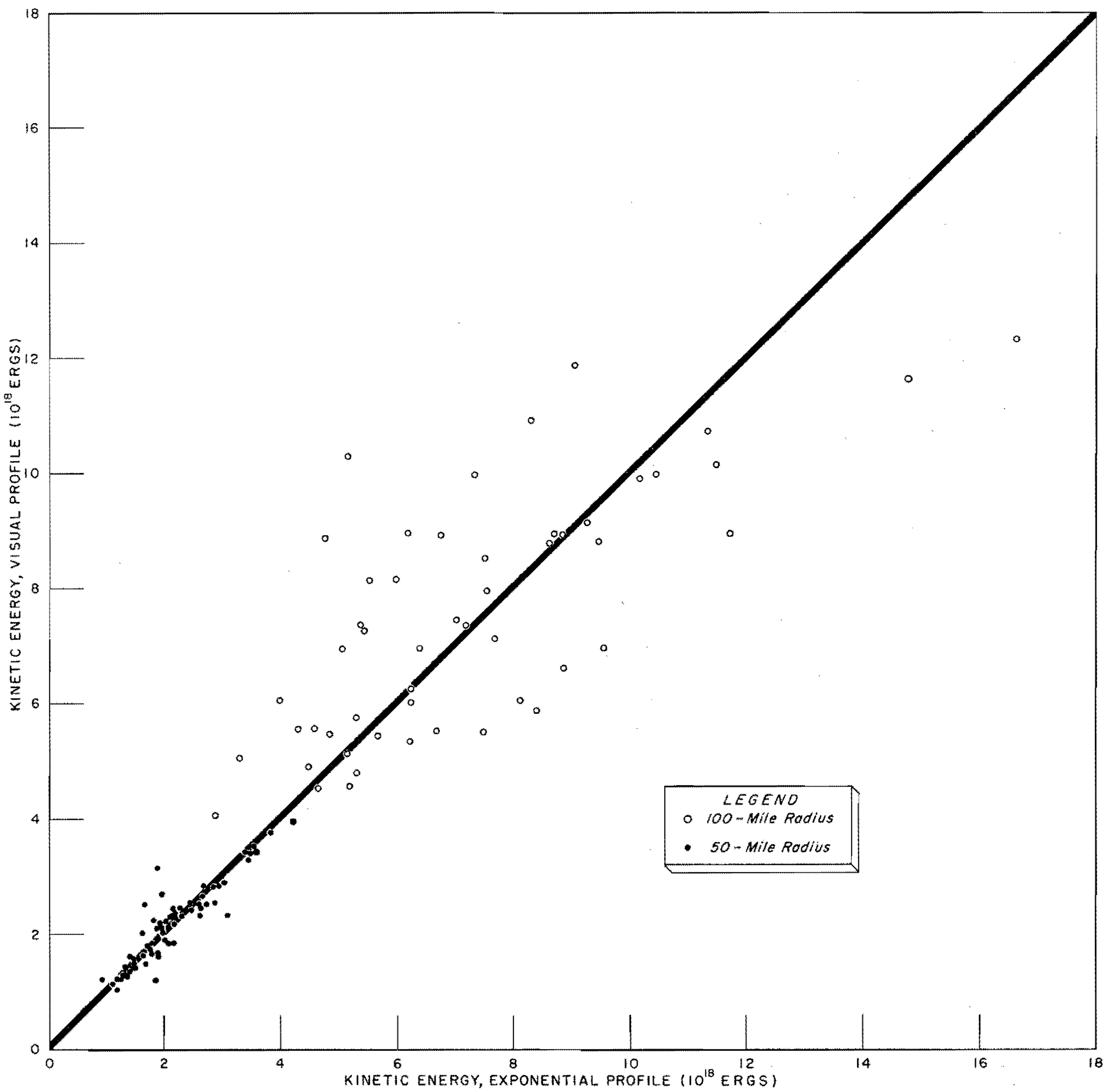
in this storm the kinetic energy integrated to a radius of 100 miles is only moderate in magnitude in comparison with the other hurricanes but has a somewhat higher relative position with the energy computed to but 50 miles.

Simpson[20] has published a description of a reconnaisance flight into a mature typhoon in the western Pacific in August 1951. A sea-level pressure of 26.43 inches was recorded at the center (p_n - p_o about 3.50 inches). The radius of maximum winds is not known but, from the description of other phenomena, was probably in excess of 20 nautical miles. The energy in that typhoon, as computed from figure 38, turns out to be greater than that for any of the hurricanes surveyed in the present study, all of which were of Atlantic origin. While there is probably more frequent opportunity for such a storm to develop in the vast expanses of the Pacific than in the Atlantic, the possibility cannot be excluded that a "Cape Verde" hurricane--the type that crosses the entire Atlantic before reaching the United States--could be of equal magnitude.

Comparison of kinetic energy values from visually-drawn and exponential profiles

The kinetic energy values of figures 37 and 38 depend to a great extent on the slope of the outer portion of the radial exponential pressure profiles from which the parameters R and p_n - p_o are derived, because the outer portion sweeps the largest area in integrating around a circle. However, since the exponential profiles were fitted to the innermost 40 miles of the corresponding visually-constructed profiles, the outer portion of the exponential profiles is the least accurate portion. The validity of the interpretation of figure 38 was therefore tested by comparing the kinetic energy values there with more accurate energy values computed directly from the visually-drawn profiles. The energy values from the visually-drawn pressure profiles, though more reliable, cannot readily be substituted in figures 37 and 38, as there is no logical basis for assigning values of the coordinates R and p_n - p_o. Kinetic energy values derived by the two methods--both to 50 and 100 miles--are compared in figure 39. Many of the visually-drawn pressure profiles did not extend inward to the center of the hurricane. In these instances the exponential pressure profile was substituted for the visually-drawn profile over the missing portion. The energy from this substituted portion was a small fraction of each total.

Figure 39 is in reality a test of the goodness of fit of the exponential pressure profile to the visually-drawn profile but is presented in terms of energy values for convenience for present purposes. The points in figure 39 lie sufficiently close to the 45° line to substantiate the general reliability of energy values in figures 37 and 38. In fact, the range of values of energy from the visually-drawn profiles, as a scrutiny of figure 39 will reveal, is smaller than that for the exponential profile values. This adds weight to the interpretation that the energy values in figure 38 lie along a restricted band.



COMPARISON OF HURRICANE KINETIC ENERGY VALUES COMPUTED FROM VISUALLY FITTED AND EXPONENTIAL PRESSURE PROFILES

FIG. 39

The two points which have the highest energy values in figures 37 and 38, and which stand apart from the body of the data, were subjected to particular examination. They pertain to the storms of September 14, 1944, off Cape Hatteras, and August 18, 1916, on the Texas coast. Both were great hurricanes. The 1916 storm is included in Mitchell's list, quoted by Tannehill[4], of the 16 hurricanes during the half-century preceding 1928 that "can be classed as 'great' both as to intensity and diameter." Of the 1944 storm Tannehill says, "It was one of the most violent hurricanes of history, in fact there is no definite proof of a more violent hurricane in the records." In both storms, however, the exponential pressure profile departed from the visually-drawn profile in the direction that exaggerates the kinetic energy as computed from the exponential profile. The energy to 100 miles for the September 1944 storm, computed from the visually-drawn profile, is 12.3×10^{18} ergs (16.7×10^{18} ergs in figure 38) and is the highest value for any storm by this method. The value for the 1916 storm is slightly smaller. There is, then, justification for undercutting the two highest points in constructing an enveloping curve for figure 38.

Kinetic energy distribution for specific problems

The fifteen highest kinetic-energy values of the cyclostrophic wind, computed from the visually-drawn pressure profile, are listed in table 12 to facilitate comparison of the relative force of the various hurricanes. The actual kinetic energy in a particular hurricane of interest may be ascertained more accurately from a wind profile in which the diminution of the ratio of actual wind to cyclostrophic or gradient wind with distance from the hurricane center is taken into account, as described in chapters III and IV.

The plotted points of figures 37 and 38 provide a convenient basis for obtaining a first approximation of the frequency in the 50 years of U. S. hurricanes of different values of the total kinetic energy over any specified area, for example, an area equivalent to Lake Okeechobee. If a relationship, either analytical or graphical, can be developed for the kinetic energy over an area of interest or along a line of fetch, the appropriate set of kinetic energy lines can be substituted for the curves of figures 37 and 38.

Conclusion and interpretation

The work presented in chapters V and VI supports the inverse relationship between hurricane size and hurricane intensity that has been suspected by various authors. The relationship applies both at different times in the life of a single hurricane and between different hurricanes. That such a relationship should exist is logical. We may speculate that the hurricane, which feeds on atmospheric convective instability not greatly in excess of the usual at the season, can produce phenomenally high winds when its energy is concentrated in a small area. On the other hand, if the hurricane is very large, the inflow of fresh unstable air required to release the energy

Table 12

KINETIC ENERGY OF THE CYCLOSTROPHIC WIND

U. S. Hurricanes 1900-1949
(Energy computed from visually-fitted pressure profiles)

	Energy 10^{18} ergs per cm. deep	Within 50 nautical miles: Date	Near
1.	4.26	August 18, 1916	Santa Gertrudis, Tex.
2.	3.79	September 14, 1944	Hatteras, N. C.
3.	3.54	October 20, 1926	Key West, Fla.
4.	3.49	September 5, 1933	Brownsville, Tex.
5.	3.46	September 16, 1928	West Palm Beach, Fla.
6.	3.41	*September 18, 1926	Miami, Fla.
7.	3.19	August 11, 1940	Savannah, Ga.
8.	3.10	September 29, 1915	New Orleans, La.
9.	2.94	September 17, 1947	Hillsboro, Fla.
10.	2.85	August 25, 1949	West Palm Beach, Fla.
11.	2.84	September 2, 1935	Long Key, Fla.
12.	2.82	September 28, 1929	Long Key, Fla.
13.	2.70	September 16, 1945	Homestead, Fla.
14.	2.70	September 7, 1900	Galveston, Tex.
15.	2.58	*September 20, 1926	Perdido Beach, Ala.
		Within 100 nautical miles	
1.	12.34	*September 14, 1944	Hatteras, N. C.
2.	11.86	September 16, 1933	Hatteras, N. C.
3.	11.64	August 18, 1916	Santa Gertrudis, Tex.
4.	10.90	September 21, 1938	Hartford, Conn.
5.	10.71	September 5, 1933	Brownsville, Tex.
6.	10.29	*September 14, 1944	Point Judith, R. I.
7.	10.16	September 29, 1915	New Orleans, La.
8.	9.98	October 20, 1926	Key West, Fla.
9.	9.97	September 28, 1917	Pensacola, Fla.
10.	9.90	September 18, 1926	Miami, Fla.
11.	9.14	August 25, 1924	Hatteras, N. C.
12.	8.97	August 30, 1942	Seadrift, Tex.
13.	8.96	September 16, 1928	West Palm Beach, Fla.
14.	8.94	July 5, 1916	Mobile, Ala.
15.	8.93	October 19, 1944	Sarasota, Fla.

*Same hurricane

necessary to establish very high winds over a great area would soon exhaust the available supply of fresh unstable air within the range of the storm, and the hurricane would then weaken before it had attained an extreme intensity. Another aspect was presented in chapter III, namely, that inflowing air parcels in the hurricane are accelerated by the pressure gradient as they move toward lower pressure, v increasing while r decreases in the term v^2/r of the cyclostrophic wind equation, until cyclostrophic balance is obtained or exceeded. The distance from the center at which the maximum winds occur, symbolized by R in the present study, is very close to the distance at which the cyclostrophic balance is reached. An increase in the pressure gradient, of which $p_n - p_o$ of figures 37 and 38 is an index, will drive the air inward to a larger v and smaller r before cyclostrophic balance is obtained, thus decreasing R. A decreasing pressure gradient will have the opposite effect.

SUMMARY

The principal contributions of the study are:

1. A method for reconstructing the track and the pressure and wind fields of a hurricane on a systematic basis from sparse data. (Chapter I.)

2. Estimation of the central pressures of virtually all hurricanes reaching the United States during a fifty-year period. (Figure 12, chapter II.) It was shown that a hurricane pressure near the United States on the order of the record, 26.35 inches, is an exceedingly rare event.

3. A detailed procedure for reducing gradient winds to anemometer-level winds at Lake Okeechobee. (Chapter III, summary at end of chapter.)

4. An estimate of the frequency of occurrence of hurricane winds at the coast based on all parts of all significant hurricanes in the area considered over 50 years. (Figure 33, chapter IV.)

5. The finding, validated by data, that free-air winds in a hurricane range along a storm radius from sub-gradient speed at the periphery to super-gradient speed at the radius of maximum wind. (Chapters III and IV.)

6. Evaluation of the average filling characteristics of hurricanes moving inland. The filling in the normal transit time of a hurricane from the Atlantic Ocean to Lake Okeechobee is, on the average, quite small and in every case is concentrated near the storm center. (Figure 34, chapter V.)

7. Confirmation, from an empirical investigation of storm energies, of an inverse relationship between hurricane intensity and lateral extent. (Chapter VI.)

8. The presentation of gust factors observed in a hurricane. (Table 7, chapter IV.)

ACKNOWLEDGMENTS

Previous work on hurricanes by the Hydrometeorological Section, which is published in part in Hydrometeorological Report Nos. 26 and 31, formed the basis from which much of the present Report evolved. Most of the previous work was directed by Alexander L. Shands and Robert W. Schloemer, project leaders in succession, and Robert D. Fletcher, the former Chief of the Section. The present study was carried out by Vance A. Myers under the guidance of Charles S. Gilman, Chief of Section. Other members of the Section providing professional and computational assistance were James F. Appleby, A. E. Brown, Annie Laurie Criss, James L. Keister, John T. Lindgren, Margaret E. Linehan and Harlan H. Vinnedge. The report was edited by Lillian K. Rubin and the copy prepared by Marian I. Hammer and Betty L. Fox. Drafting was by Carroll W. Gardner, Nemesio O. Calub, Joseph E. Fimiani and Ishmael A. Santiago.

REFERENCES

1. HYDROMETEOROLOGICAL SECTION, U. S. Weather Bureau, "Analysis of Winds over Lake Okeechobee During the Tropical Storm of August 26-27, 1949", Hydrometeorological Report No. 26, 1951.

2. HYDROMETEOROLOGICAL SECTION, U. S. Weather Bureau, "Analysis and Synthesis of Hurricane Winds over Lake Okeechobee, Florida", Hydrometeorological Report No. 31, 1954.

3. GENTRY, ROBERT C., "Wind Velocities During Hurricanes", Proceedings, Amer. Soc. of Civil Eng., vol. 79, Separate No. 218, July 1953.

4. TANNEHILL, I. R., "Hurricanes", 7th Edition, 1950.

5. CLINE, I. M., "Tropical Cyclones", 1926.

6. HURD, WILLIS E., "The Calm Center, or Eye, of the Tropical Cyclone", Pilot Charts of the Indian Ocean, U. S. Hydrographic Office, September 1950.

7. DEPPERMANN, C. E., "Is there a Ring of Violent Upward Convection in Hurricanes and Typhoons?", Bull. Amer. Meteor. Soc., vol. 27, No. 1, January 1946.

8. YEH, T. C., "The Motion of Tropical Storms under the Influence of a Superimposed Southerly Current", J. Meteor., vol. 7, No. 2, April 1950.

9. DUNN, G. E., "Tropical Cyclones", Compendium of Meteorology, Amer. Meteor. Soc., 1951.

10. SNEDECOR, G. W., "Statistical Methods", 4th ed., 1946, p. 218.

11. GRAY, R. W., revised by GRADY NORTON, "Florida Hurricanes", U. S. Weather Bureau, 1936.

12. SHERLOCK, R. H., "Variation of Wind Velocity and Gusts with Height", Proceedings, Amer. Soc. of Civil Eng., vol. 78, Separate No. 126, April 1952.

13. McCORMICK, R. A., "Discussion of Variations of Wind Velocity and Gusts with Height", Proceedings, Amer. Soc. of Civil Eng., vol. 79, Separate No. D-126, March 1953.

14. MATTICE, W. A., "A Comparison Between Wind Velocities as Recorded by the Dines and Robinson Anemometers", Monthly Weather Review, vol. 66, No. 8, August 1938.

15. HUSS, P. O., "Relation Between Gusts and Average Winds for Housing Load Determination", University of Akron, June 1946.

16. HARNEY, P. J., "Computed Wind Velocities in the Florida Keys Hurricane of September 2, 1935", (mimeographed manuscript, circa 1938).

17. McDONALD, W. F., "Low Barometer Readings in West Indian Disturbances of 1932 and 1933", Monthly Weather Review, vol. 61, No. 9, September 1933.

18. DEPPERMANN, C. E., "Some Characteristics of Philippine Typhoons", Phillipine Weather Bureau, 1939.

19. SIMPSON, R. H., "A Note on the Movement and Structure of the Florida Hurricane of October 1946", Monthly Weather Review, vol. 75, No. 4, April 1947.

20. SIMPSON, R. H., "Exploring Eye of Typhoon 'Marge', 1951", Bull. Amer. Meteor. Soc., vol. 33, No. 7, September 1952.

21. SMITHSONIAN INSTITUTION, "Smithsonian Meteorological Tables", 6th ed., Smithsonian Miscellaneous Collections, vol. 114, 1951.

APPENDIX A

LAKE OKEECHOBEE WIND INSTRUMENT EXPOSURES

	Height of anemometer feet - m.s.l.
Moore Haven (H.G.S. No. 1)	58
Clewiston (H.G.S. No. 2)	55
Lake Harbor (H.G.S. No. 3)	56.5
Belle Glade (H.G.S. No. 4)	55
Canal Point (H.G.S. No. 5)	55
Port Mayaca	56
Okeechobee (H.G.S. No. 6)	55
Lake Station No. 10	46.5
Lake Station No. 12	46.5
Lake Station No. 14	48.5
Lake Station No. 16	47.5
Lake Station No. 17	45.5

The seven shore installations are on top of the levee. The crown elevation of the levee is, in general, 32.5 feet m.s.l. The elevation of the land near the levee is 16 feet m.s.l., plus or minus two or three feet, at all stations. The water level varies. The mean water level for the Lake immediately prior to the August 26, 1949 hurricane was 13.9 feet m.s.l. Extreme heights during the storm were 6 feet m.s.l. at the upwind shore and 24 feet m.s.l. at the downwind shore.

APPENDIX B

APPROXIMATION OF THE GRADIENT WIND SPEED

Standard tables of gradient wind speed are not convenient for evaluating the gradient wind in hurricanes because tabular values of the radius of curvature do not go low enough. For example, in the Smithsonian Meteorological Tables, 6th edition[21], the smallest radius in the gradient wind table is 100 miles. Direct computation of speeds by substitution in the gradient wind equation requires the solution of a quadratic equation. This is undesirable for a large number of computations. Therefore, throughout the present study the gradient wind speed, v_g, was computed by an approximate method, which consisted in first computing the cyclostrophic wind speed, v_c, from pressure profile parameters by use of equation (4) on page 3, then obtaining the gradient speed by subtracting a correction.

An expression for the correction, $v_c - v_g$, will be derived. Standard formulas for the cyclostrophic wind and gradient wind speeds are:

$$\frac{v_c^2}{r} = \frac{1}{\rho}\frac{dp}{dr} \tag{3}$$

and

$$\frac{v_g^2}{r} + fv_g = \frac{1}{\rho}\frac{dp}{dr} \tag{5}$$

where f is the coriolis parameter, dp/dr the pressure gradient, and ρ the air density. Equating the left-hand members of the above equations we obtain

$$\frac{v_g^2}{r} + fv_g = \frac{v_c^2}{r} \tag{9}$$

which may be solved for the desired correction factor, $v_c - v_g$:

$$v_c^2 - v_g^2 = rfv_g$$

$$(v_c + v_g)(v_c - v_g) = rfv_g$$

$$v_c - v_g = \frac{rfv_g}{v_c + v_g} \tag{10}$$

Over the range of hurricane speeds of interest the difference between the quantities v_c and v_g is small compared with the quantities themselves. The approximation is made in the right-hand member of equation (10) that $v_c = v_g$. This yields the required expression for $v_c - v_g$:

$$v_c - v_g = r(f/2) \tag{11}$$

where the elements are expressed in any consistent set of units. In this study the speeds are always expressed in miles per hour. The radius, r, is sometimes expressed in statute miles, but more often in nautical miles. In the latter instance the expression takes the form

$$v_c - v_g = 1.15(f/2)r \tag{12}$$

where f is in units of hours^{-1}. In computing the difference between the cyclostrophic and gradient winds from equations (11) and (12) approximate values of f/2 or 1.15 (f/2) were taken from the table below.

Table 13

APPROXIMATE VALUES OF f/2 AND 1.15 f/2
(Exact values are given in parentheses)

Latitude	f/2 (hours^{-1})	1.15f/2 (hours^{-1})
25°	1/9 (.111)	1/8 (.128)
30°	1/8 (.132)	1/7 (.152)
35°	1/7 (.150)	1/6 (.173)
40°	1/6 (.169)	1/5 (.194)

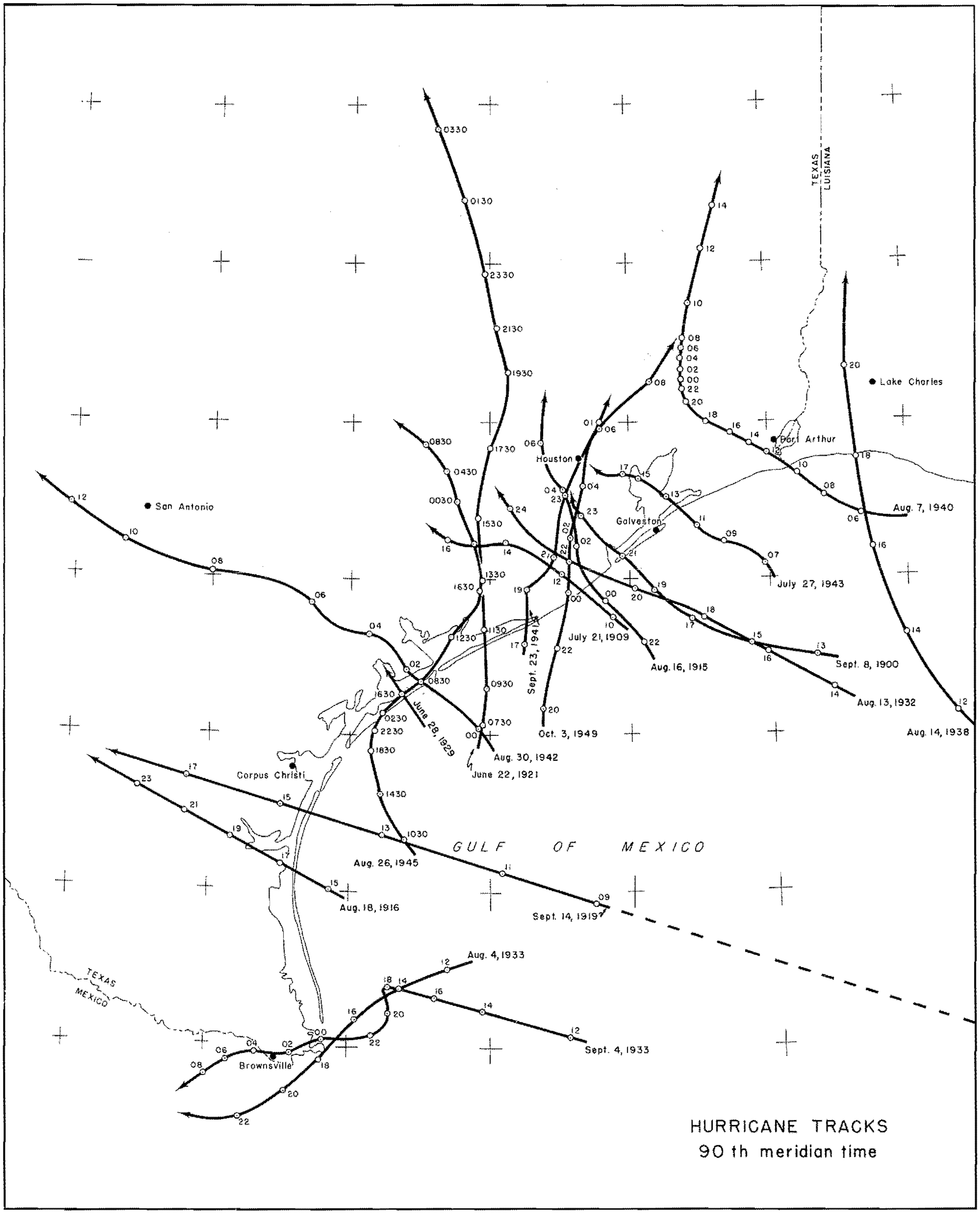
The difference between the approximate gradient wind as computed from equation (11) or (12) and the exact gradient wind that would be obtained from equation (5) is negligible. To take an extreme case as an example, if the cyclostrophic wind speed is 100 mph at a radius of 100 miles, at 25°N, the exact gradient wind speed is 89.5 mph. The approximate speed by the procedure described is 88.9 mph.

APPENDIX C

HURRICANE TRACKS 1900-1949

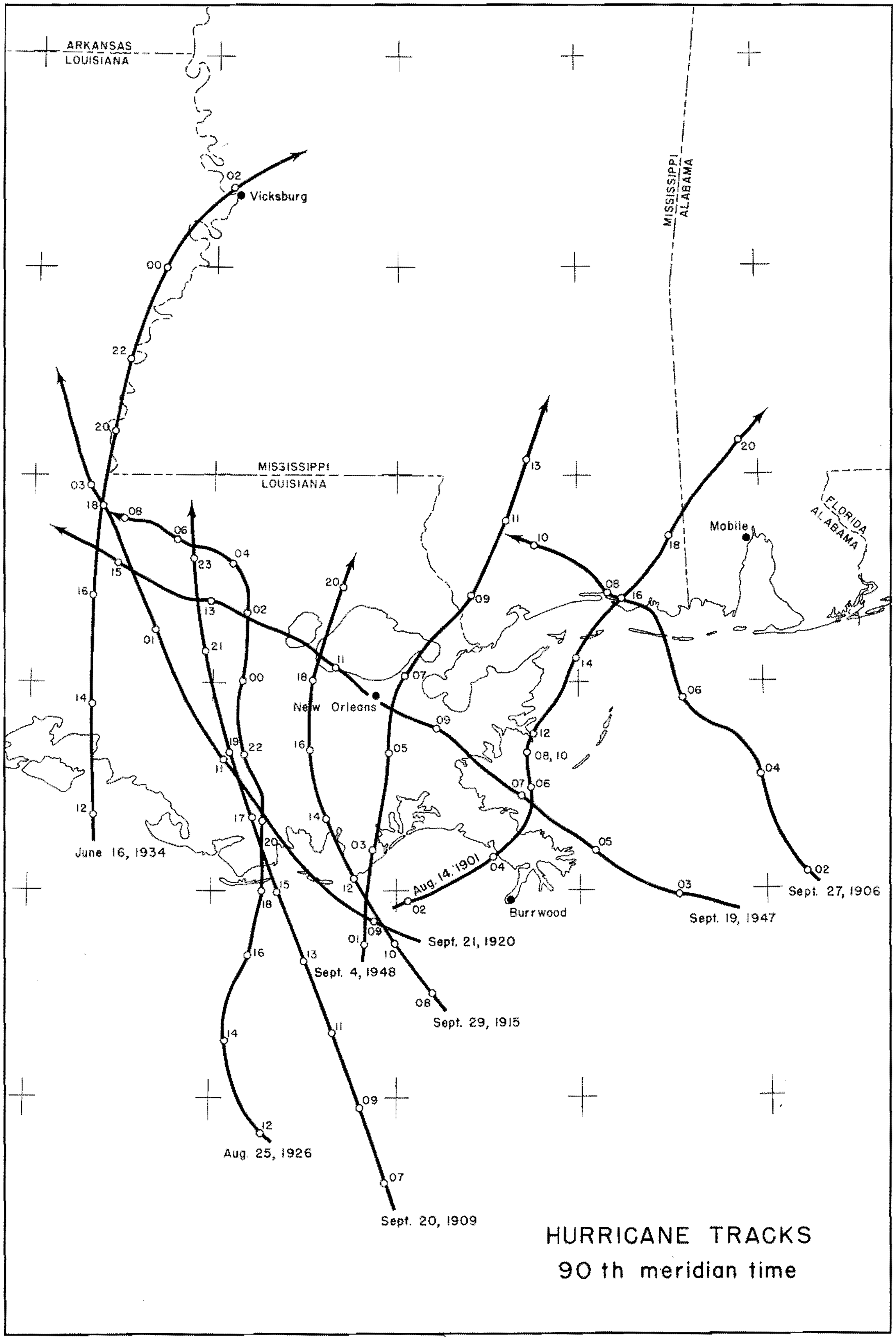
Tracks (figure 40-48) computed by the procedures of chapter I are shown for all the hurricanes listed in table 1 and also for a few other hurricanes, for which complete tracks were determined but which were excluded from table 1 for not meeting the pressure criteria.

Bi-hourly positions of storm centers are marked on the tracks. Dates pertain to the portion of the track immediately adjacent to the date. Dashes indicate that another portion of the track of the same hurricane appears in another figure.



TEXAS
LUISIANA
Lake Charles
Port Arthur
Houston
Galveston
San Antonio
Corpus Christi
Brownsville
TEXAS
MEXICO
GULF OF MEXICO
Aug. 7, 1940
July 27, 1943
Sept. 8, 1900
Aug. 13, 1932
Aug. 14, 1938
Aug. 16, 1915
July 21, 1909
Sept. 23, 1941
Oct. 3, 1949
Aug. 30, 1942
June 22, 1921
June 28, 1929
Aug. 26, 1945
Aug. 18, 1916
Sept. 14, 1919
Aug. 4, 1933
Sept. 4, 1933
HURRICANE TRACKS
90 th meridian time

FIG. 40



HURRICANE TRACKS
90 th meridian time

FIG. 41

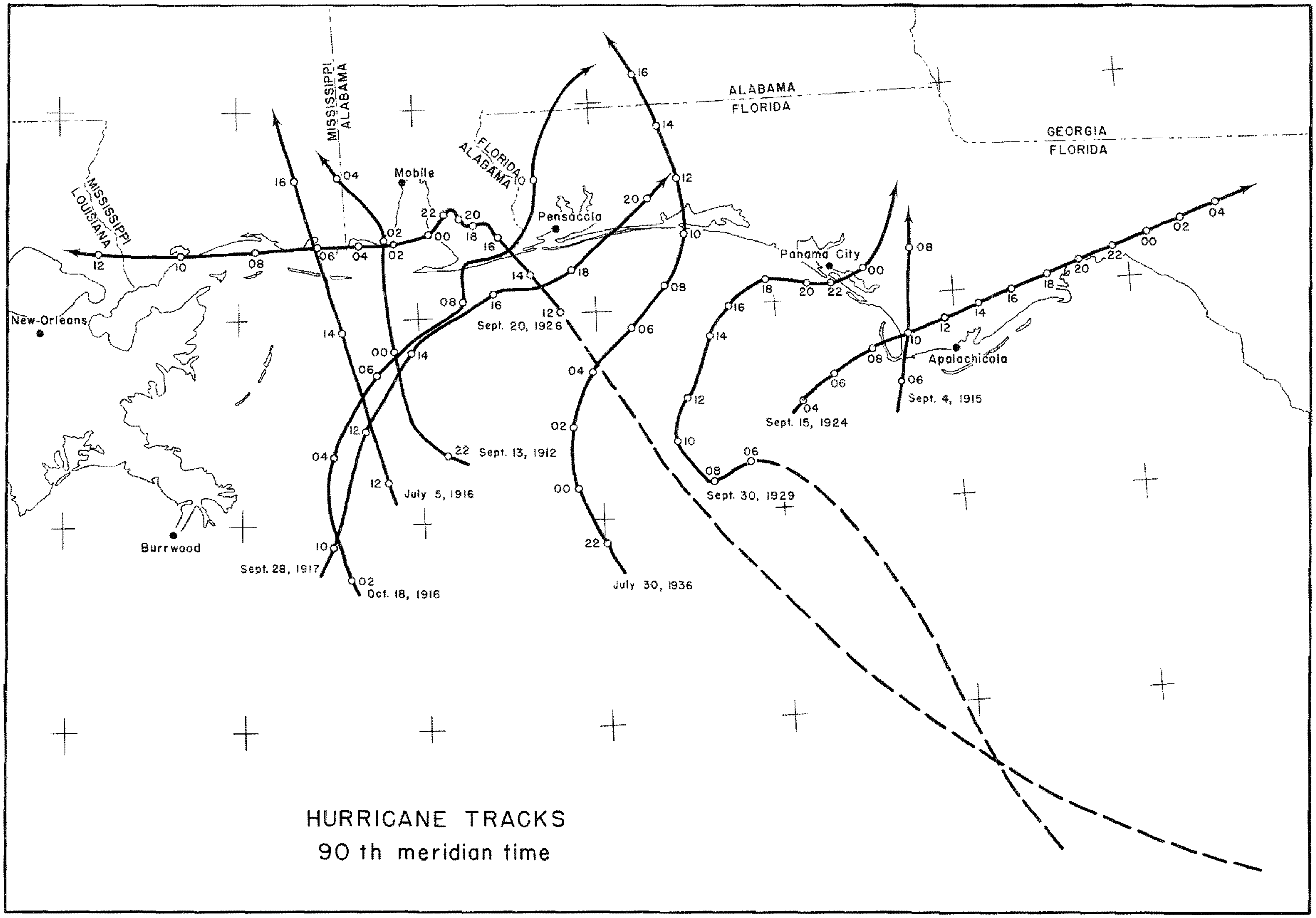

ALABAMA
FLORIDA
GEORGIA
FLORIDA
MISSISSIPPI
ALABAMA
FLORIDA
ALABAMA
MISSISSIPPI
LOUISIANA
Mobile
Pensacola
Panama City
Apalachicola
New-Orleans
Burrwood
Sept. 20, 1926
Sept. 13, 1912
July 5, 1916
Sept. 28, 1917
Oct. 18, 1916
July 30, 1936
Sept. 30, 1929
Sept. 15, 1924
Sept. 4, 1915
HURRICANE TRACKS
90 th meridian time

FIG. 42

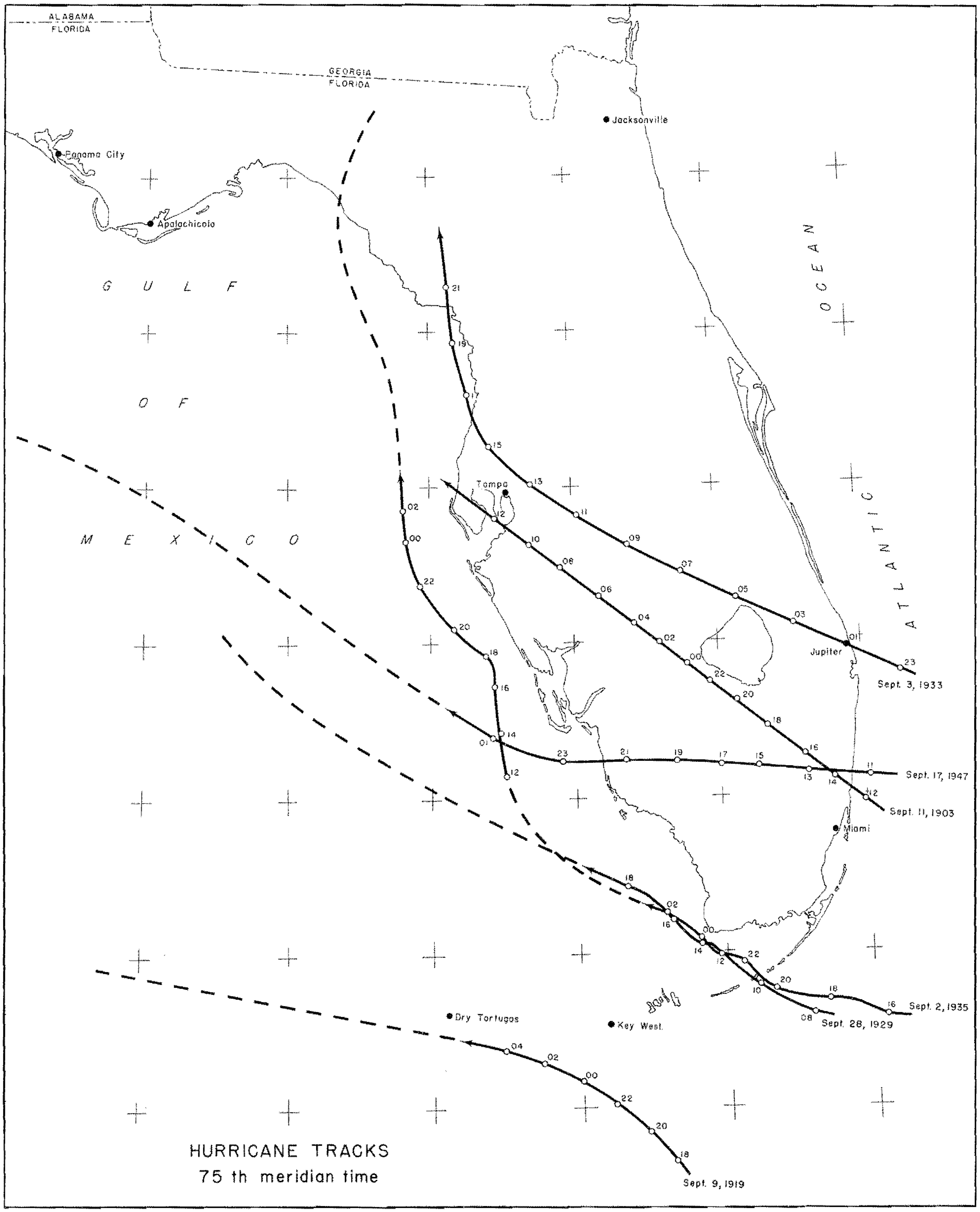
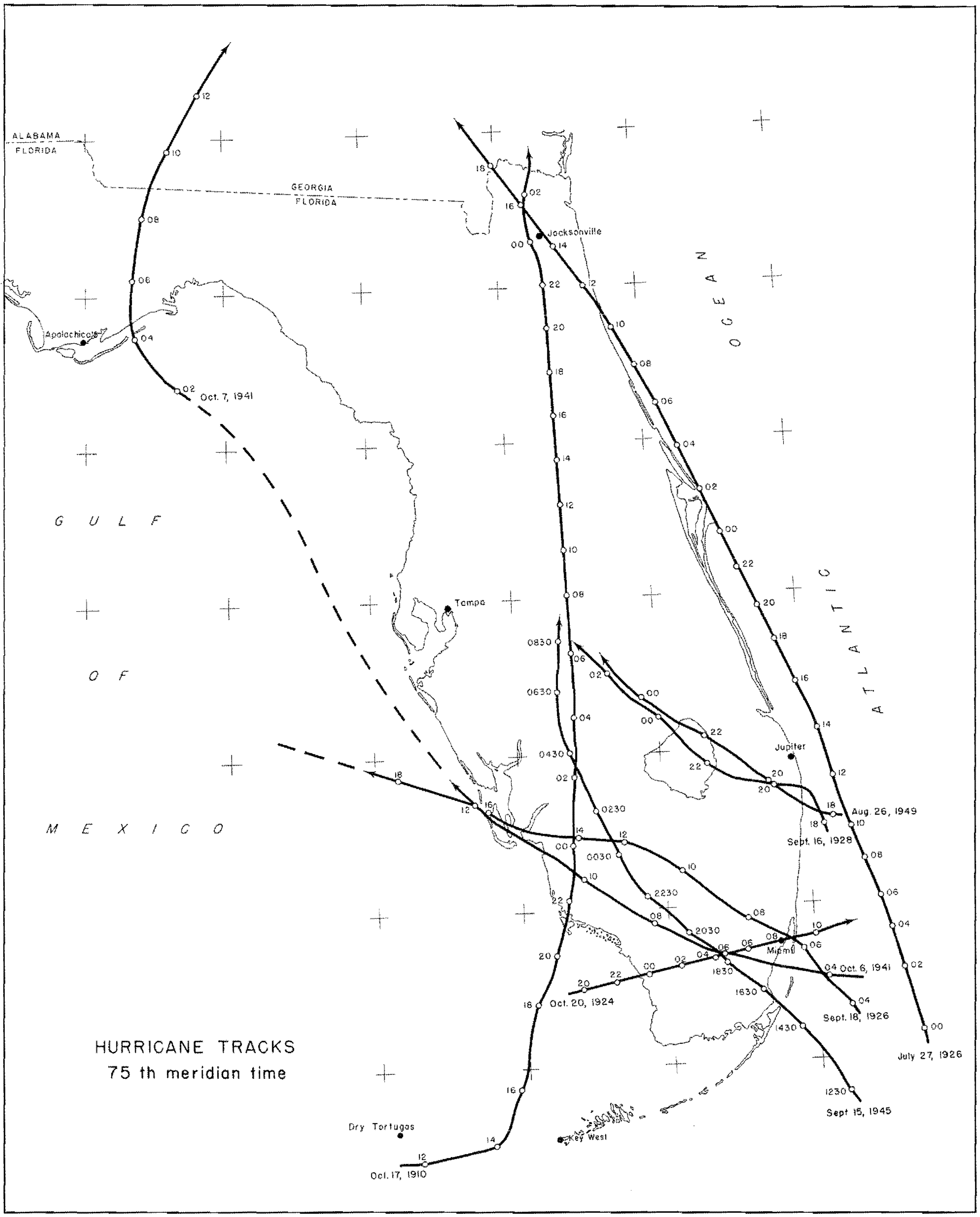

ALABAMA
FLORIDA
GEORGIA
FLORIDA
Jacksonville
Panama City
Apalachicola
G U L F
O F
M E X I C O
ATLANTIC
OCEAN
Tampa
Jupiter
Miami
Dry Tortugas
Key West
Sept. 3, 1933
Sept. 17, 1947
Sept. 11, 1903
Sept. 2, 1935
Sept. 28, 1929
Sept. 9, 1919
HURRICANE TRACKS
75 th meridian time

FIG. 43



ALABAMA
FLORIDA
GEORGIA
FLORIDA
Jacksonville
Apalachicola
Tampa
Jupiter
Miami
Key West
Dry Tortugas
GULF OF MEXICO
ATLANTIC OCEAN
Oct. 7, 1941
Aug. 26, 1949
Sept. 16, 1928
Oct. 6, 1941
Sept. 18, 1926
July 27, 1926
Sept 15, 1945
Oct. 20, 1924
Oct. 17, 1910
HURRICANE TRACKS
75 th meridian time

FIG. 44

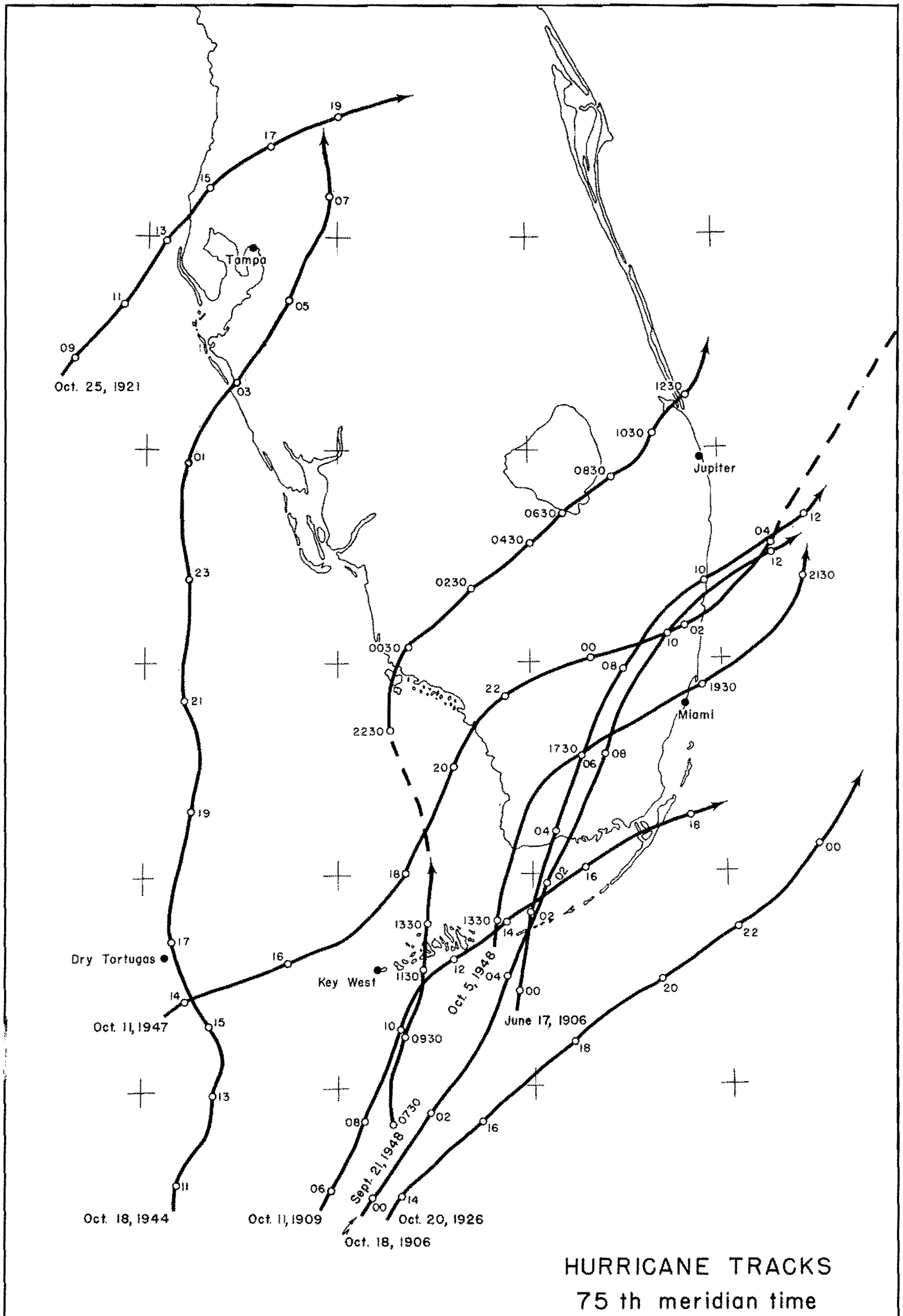

Tampa
Jupiter
Miami
Dry Tortugas
Key West
Oct. 25, 1921
Oct. 18, 1944
Oct. 11, 1947
Oct. 11, 1909
Oct. 18, 1906
Oct. 20, 1926
Sept. 21, 1948
Oct. 5, 1948
June 17, 1906
HURRICANE TRACKS
75 th meridian time

FIG. 45

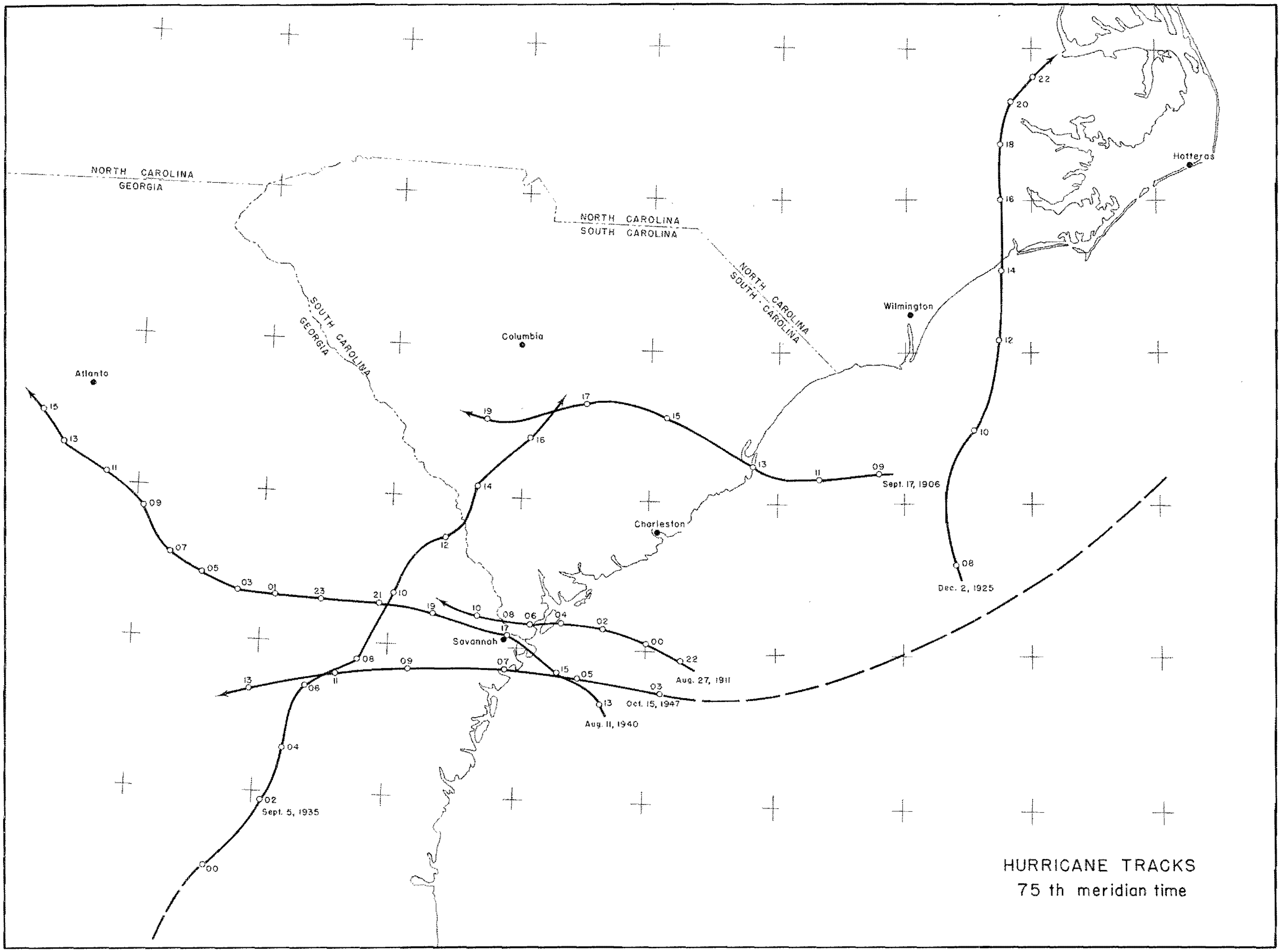
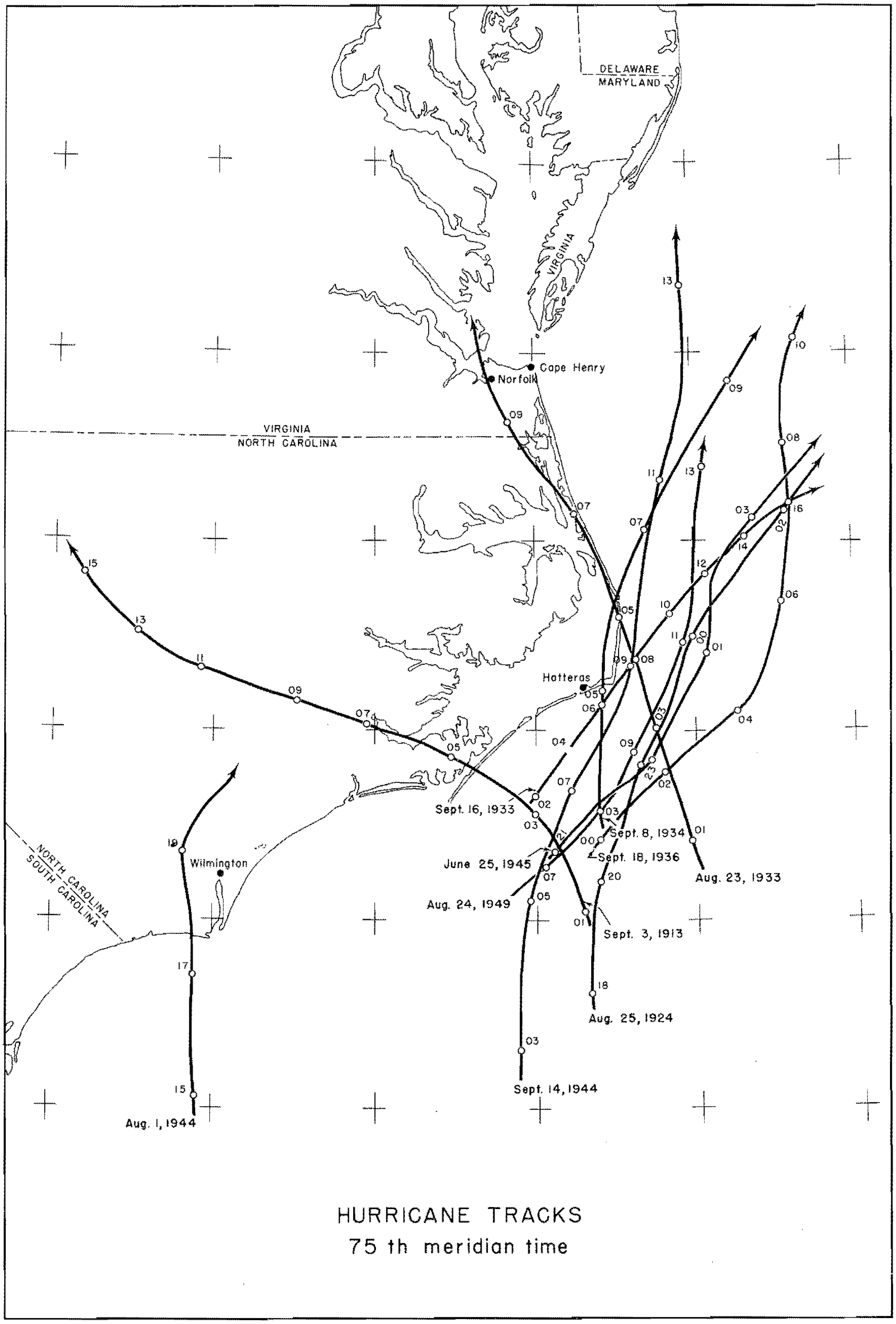
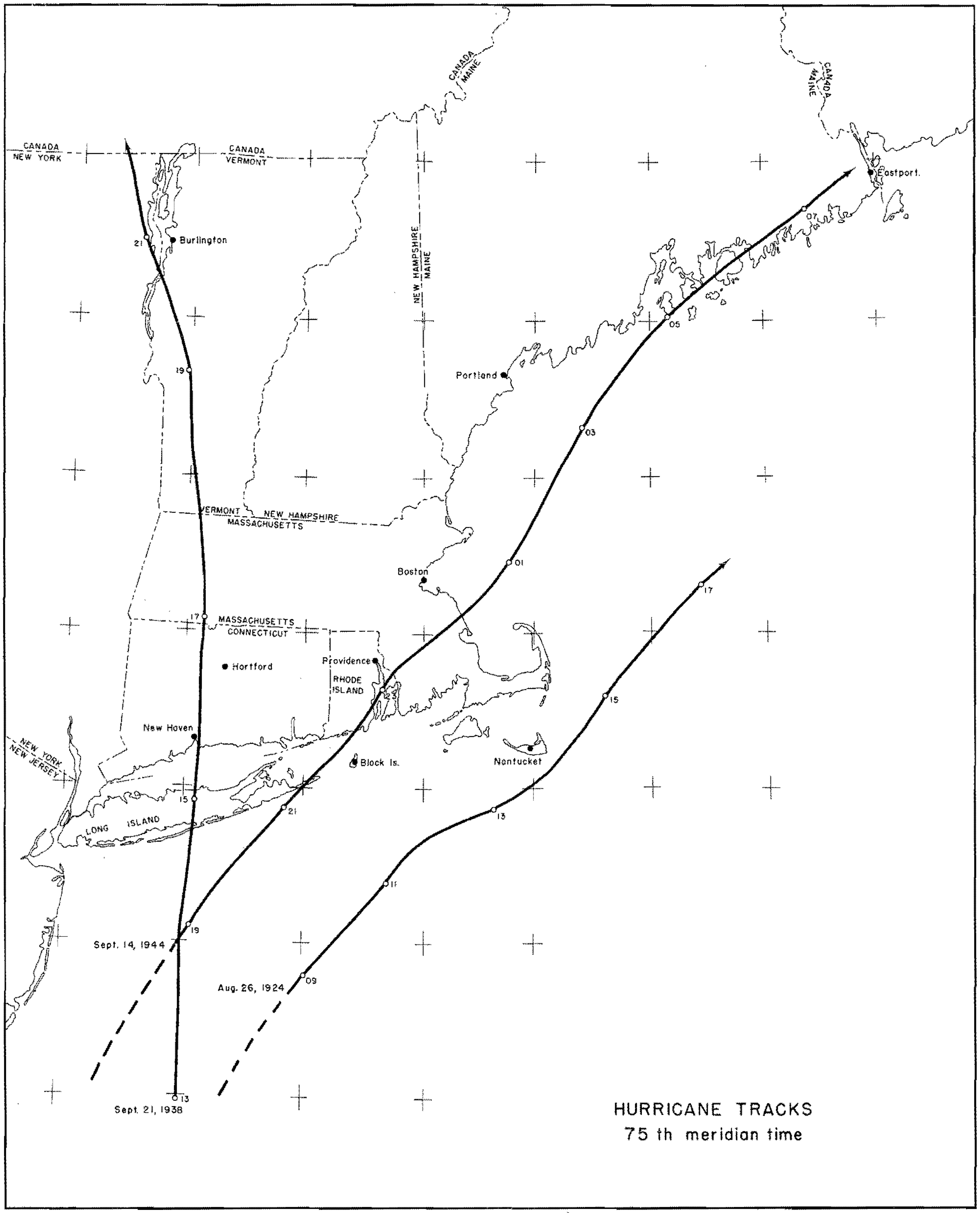

HURRICANE TRACKS
75 th meridian time
NORTH CAROLINA
GEORGIA
NORTH CAROLINA
SOUTH CAROLINA
SOUTH CAROLINA
GEORGIA
Atlanta
Columbia
Wilmington
Hatteras
Charleston
Savannah
Sept. 17, 1906
Dec. 2, 1925
Aug. 27, 1911
Oct. 15, 1947
Aug. 11, 1940
Sept. 5, 1935

FIG. 46



DELAWARE
MARYLAND
VIRGINIA
Cape Henry
Norfolk
VIRGINIA
NORTH CAROLINA
Hatteras
Wilmington
NORTH CAROLINA
SOUTH CAROLINA
Sept. 16, 1933
Sept. 8, 1934
Sept. 18, 1936
June 25, 1945
Aug. 24, 1949
Sept. 3, 1913
Aug. 23, 1933
Aug. 25, 1924
Sept. 14, 1944
Aug. 1, 1944
HURRICANE TRACKS
75 th meridian time

FIG. 47



HURRICANE TRACKS
75 th meridian time
CANADA
NEW YORK
CANADA
VERMONT
CANADA
MAINE
Burlington
NEW HAMPSHIRE
MAINE
Portland
Eastport.
VERMONT
NEW HAMPSHIRE
MASSACHUSETTS
Boston
MASSACHUSETTS
CONNECTICUT
Hartford
Providence
RHODE ISLAND
New Haven
NEW YORK
NEW JERSEY
Block Is.
Nantucket
LONG ISLAND
Sept. 14, 1944
Aug. 26, 1924
Sept. 21, 1938

FIG. 48

APPENDIX D

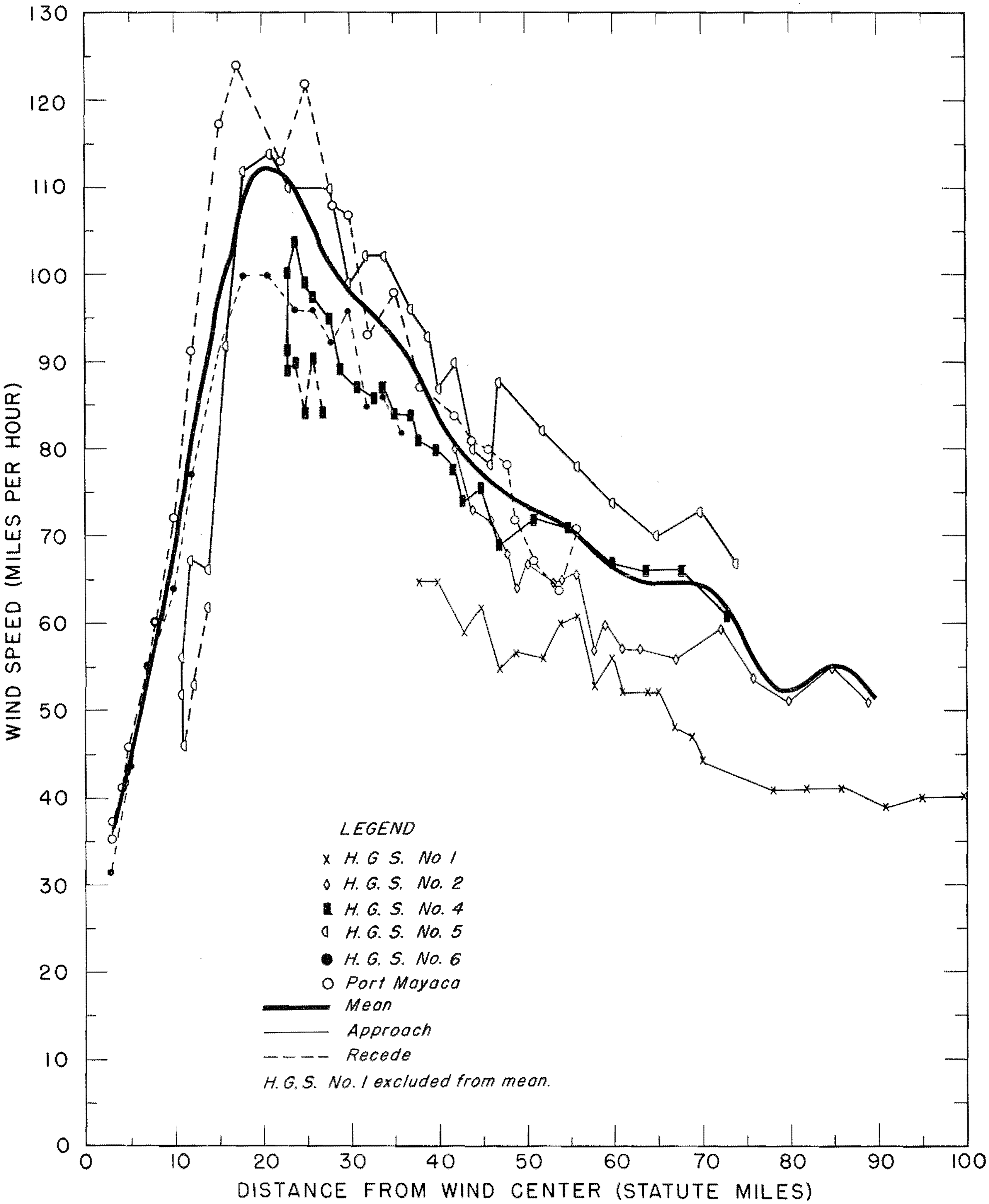
WIND PROFILES FOR HURRICANE OF AUGUST 26-27, 1949

Figures 49-53 depict the individual station wind-speed profiles in the August 26-27, 1949 hurricane at Lake Okeechobee in the five categories of wind speed named on page 37.

The wind-speed values pertain to successive ten-minute intervals and are connected by straight lines in the figures. The mean profiles are drawn, with slight smoothing, to means of the ordinates of the station profiles taken at five-mile intervals, except at the peak. The peak station values were averaged both horizontally and vertically to obtain the peak of the mean profile.

Moore Haven off-water winds were omitted from the means because of greater friction than at other stations.

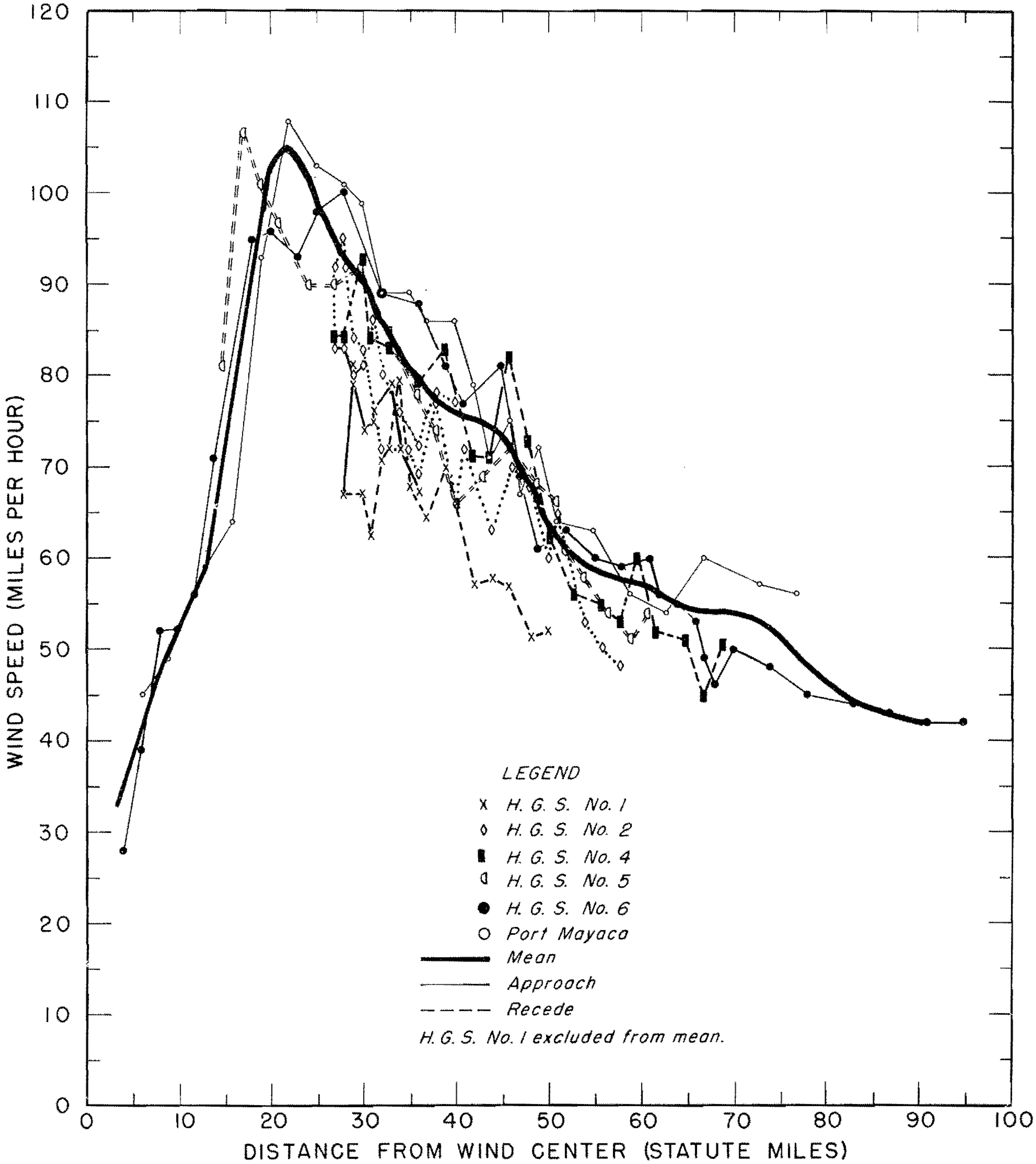
The five mean profiles are shown together in figure 21.



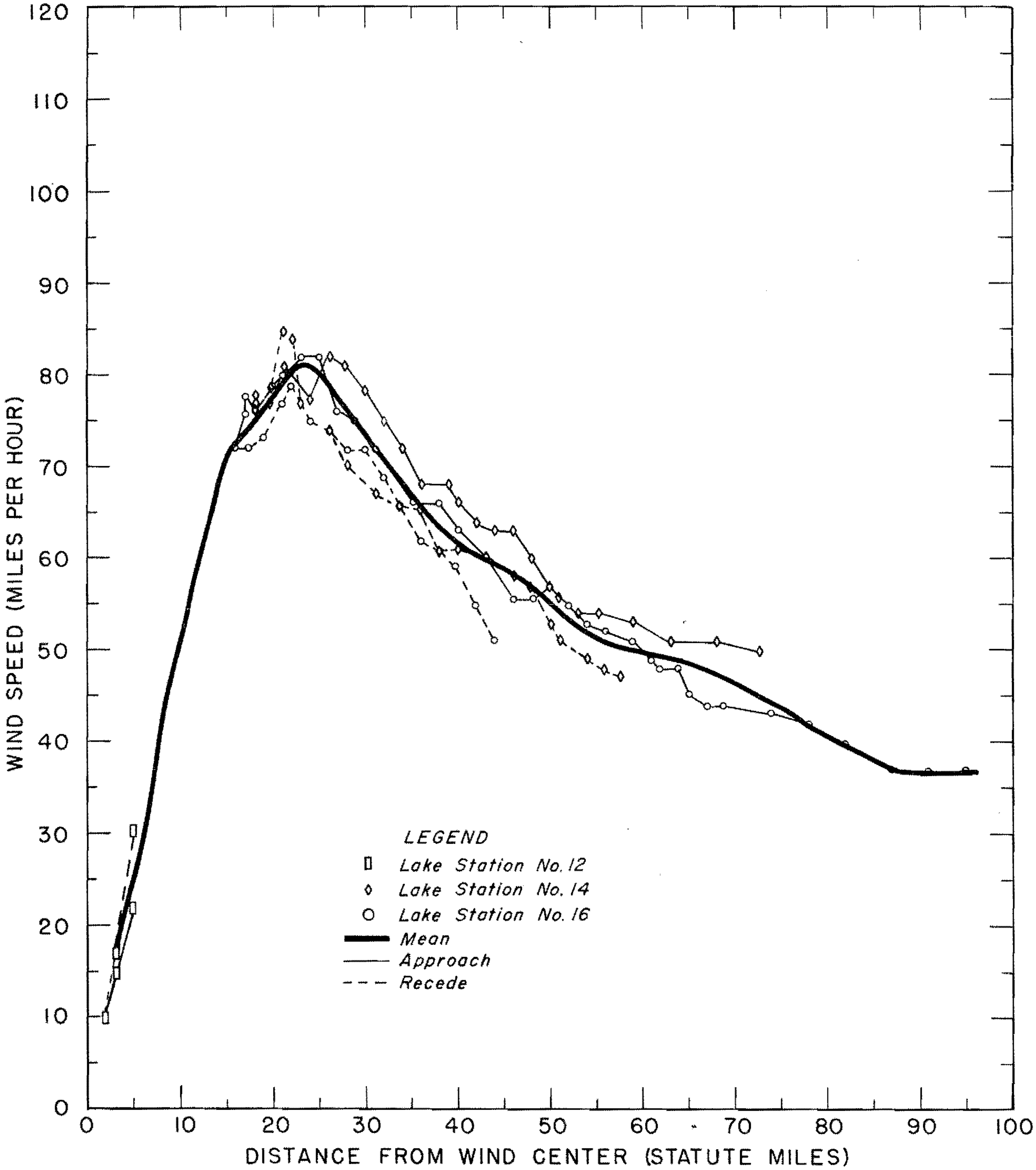
10-MINUTE PEAK GUSTS OFF-WATER WINDS (V_{pw})

AUGUST 26-27, 1949

FIG. 49



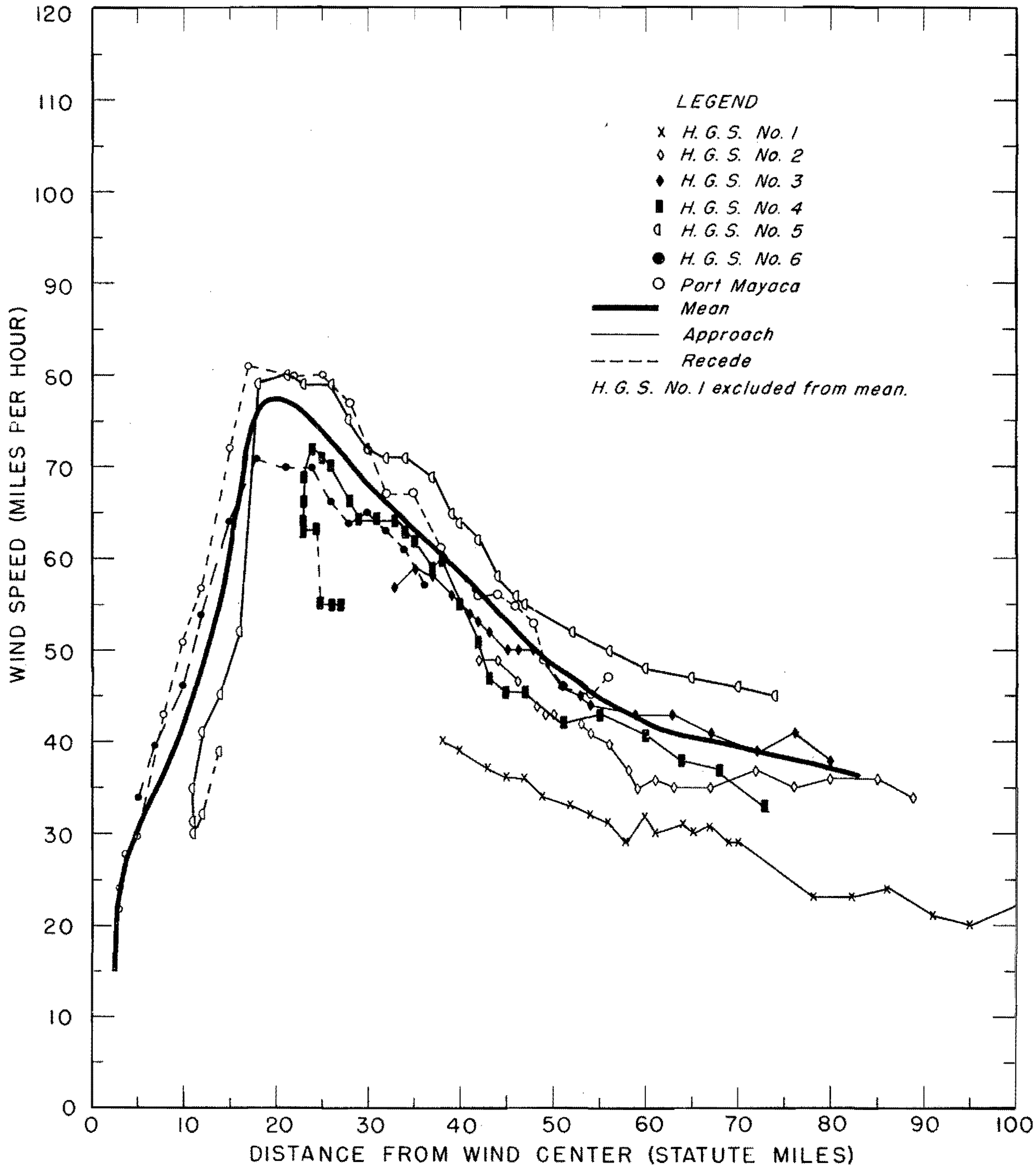
10-MINUTE PEAK GUSTS OFF-LAND WINDS (V_{pl})
AUGUST 26-27, 1949
FIG. 50



10-MINUTE-AVERAGE OVER-WATER WINDS (Vo)

AUGUST 26-27, 1949

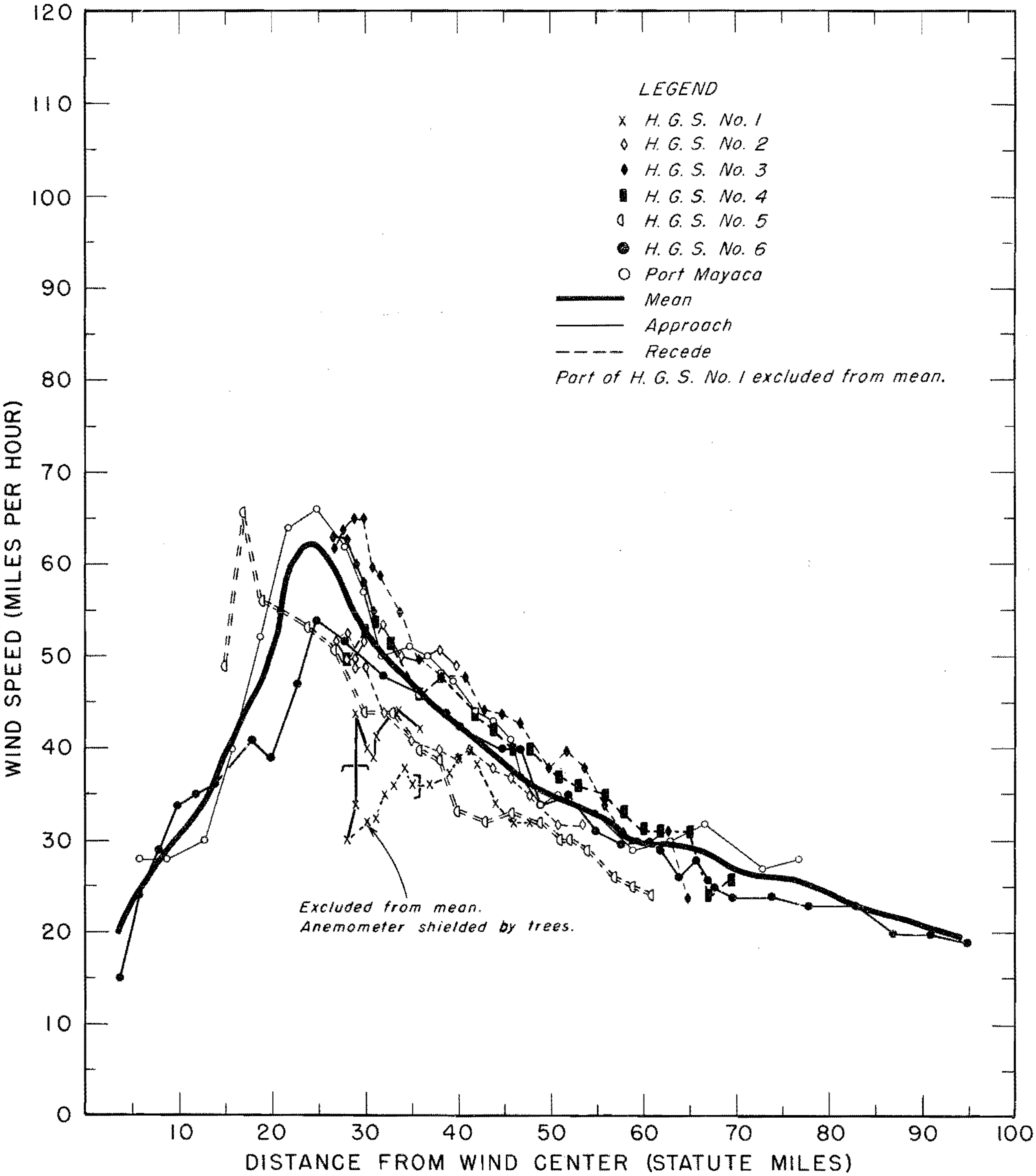
FIG. 51



10-MINUTE-AVERAGE OFF-WATER WINDS (V_w)

AUGUST 26-27, 1949

FIG. 52



10-MINUTE-AVERAGE OFF-LAND WINDS (V_l)

AUGUST 26-27, 1949

FIG. 53

☆U. S. GOVERNMENT PRINTING OFFICE : 1954 O - 296936