HYDROMETEOROLOGICAL REPORT NO. 31

Analysis and Synthesis of Hurricane Wind Patterns Over Lake Okeechobee, Florida

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HYDROMETEOROLOGICAL REPORTS

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No. 29. Seasonal variation of the standard project storm for areas of 200 and 1,000 square miles east of 105th meridian. 1953.*
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HYDROMETEOROLOGICAL REPORT NO. 31

ANALYSIS AND SYNTHESIS OF HURRICANE WIND PATTERNS OVER LAKE OKEECHOBEE, FLORIDA

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INTRODUCTION

The Hydrometeorological Section of the U. S. Weather Bureau undertook a comprehensive study of hurricane winds over Lake Okeechobee, Florida, for the Corps of Engineers, U. S. Army, in accordance with a memorandum dated April 16, 1948, and conferences held prior thereto. General instructions from the Corps of Engineers were:

> "It is desired that the Hydrometeorological Section studies provide sufficient information concerning surface wind velocities, duration and direction for use in scientific analysis of wind tides and waves in Lake Okeechobee. The specific detail and presentation of data necessary to obtain the general objective stated above must necessarily be determined as studies by the Hydrometeorological Section and this office progress."

This report describes the evolution of meteorological ideas and techniques, which will be combined with oceanographic techniques, to arrive at design values for the levees on the shores of Lake Okeechobee. In order to develop, evaluate, and test oceanographic formulas applicable to Lake Okeechobee, it was required that the Section reproduce, as closely as possible, sequences of winds over the Lake during storms for which wind-tide and wave data were available. To reconstruct wind-tide and wave data for historical storms over the Lake, prior to measurement of oceanographic (and meteorological)data, it was necessary to develop a general method for the derivation of winds from available observations. To evaluate the effects of slightly different paths of historical storms of magnitude comparable to those that have occurred over southern Florida, it was necessary to devise a method for transposition of hurricanes and for reconstructing the winds in the transposed locations. Finally, to evaluate storms of greater potential than any ever observed in southern Florida, it was necessary to develop a way of describing a hurricane by means of measureable parameters, to construct the wind field in such a hurricane, and then to subject the Lake Okeechobee area to the passage of such storms and describe the changing wind field over the Lake.

Weather Bureau Training Paper No. 1 entitled "Hurricane Notes," published in 1948, contains a comprehensive summary of hurricane characteristics and models suggested by various authors. In addition, appendix A of that publication is a comprehensive bibliography of the more important literature pertaining to tropical cyclones. Therefore, except in special instances, background references in this paper are kept to a minimum.

As is the case in most problems of applied meteorology, the final result is an analysis and presentation of the available data to conform with the requirements of the particular problem at hand. In the case of estimates of probable maximum precipitation, the Hydrometeorological Section has attempted to present the results in a degree of detail commensurate with hydrologic techniques of streamflow routing and structural design. In the development of the critical hurricane winds over Lake Okeechobee, the Section, through close cooperation with the Corps of Engineers, has attempted to develop the available meteorological data obtained within hurricanes in order to provide information on winds to which oceanographic techniques could be applied for the determination of resultant wind tides and waves.

The collection of hurricane data at Lake Okeechobee by the Corps of Engineers began in 1935 with the installation of three water-stage recorders. By 1936 five stations on the shore of the Lake were equipped with anemographs, barographs, and water-stage recorders. Other stations were added and maintained in continuous operation until 1949 when it was found profitable to install more stations but to operate only during the hurricane season. Figure 1 shows the location of engineer installations on Lake Okeechobee, and figure 2 the period of record for each of the gages in the Lake Okeechobee area.

ANALYSIS, RECONSTRUCTION, AND TRANSPOSITION OF HISTORICAL HURRICANES

During the period the water-stage recorders were in operation, determination and evaluation of oceanographic formulas required careful determination of the wind field over the Lake. Six hurricanes that influenced conditions over Lake Okeechobee were recorded during this time: October 1950, August 1949, October 1948, September 1948, September 1947, and September 1945.

From the viewpoint of analysis of hurricane winds, the occurrence of the tropical storm of August 26-27, 1949, over Lake Okeechobee, was a fortunate event. The storm was one of the most severe ever experienced in the Lake Okeechobee area, although, because of protective works and adequate warnings, it did not result in the damage or loss of life of the 1926 and 1928 hurricanes. Very high tides occurred at the southern and, later, northern portion of the Lake as the center of the storm passed northwestward over the northern portion. An unequalled set of observations near the center of a hurricane was yielded by recording wind instruments, at 10 stations, 7 on the shore of the Lake and 3 just set-up by the Corps of Engineers on pylons in the Lake.

Techniques employed in the analysis of the pressure and wind data in the 1949 hurricane are fully described in Hydrometeorological Report No. 26. In brief, a path of pressure symmetry was determined for the storm, based upon the assumptions that the pressure field was symmetrical about the storm center, at least out to about 100 miles, and that there was no appreciable filling of the storm center during its passage over the Lake Okeechobee area. The assumptions are reasonable although not strictly accurate, as shown on the half-hourly pressure charts in Report No. 26. Once the storm center was located, use of the "horn-card" technique* of I. M. Cline, made it possible to obtain profiles of wind speed vs. distance from the center, and deflection angle vs. distance from the center. These three items then -- path, wind-speed profile, and wind-direction field -- represent the basic description of the hurricane. As requested by the Corps of Engineers, the wind speeds and directions represent 10-minute averages. Furthermore, the wind-speed profile was developed only from the stations in the Lake and hence represents conditions over a uniform frictional surface.

*The "horn-card" technique utilizes observations of wind and pressure at a few stations at several successive observation times to give the equivalent of a map containing many stations at one particular time. An overlay of transparent paper is placed on a synoptic map, the position of the hurricane center is marked, the observations are plotted, and the direction of north is indicated. Then, the overlay is placed on each succeeding synoptic map in such a way that the centers of the hurricane coincide and the orientation remains constant. In each position the observations are transcribed from the synoptic map to the overlay. Thus, the successive observations at each station fall along a line parallel to the direction of movement of the storm. The net result is to combine all the observations into a composite map of the hurricane.

Analysis of the frictional effect on wind speed

From the observations taken during the storm of August 1949, it was possible to establish a wind field, representative of a uniform frictional surface--"over-water winds"--as defined by the three stations on the Lake. Approximate frictional effects due to the exposure of the remaining stations were obtained by relating the winds observed at the shore stations to the over-water winds. The percentage by which the over-water wind was multiplied to correct for exposure and site is presented in table 1, taken from Hydrometeorological Report No. 26.

Table 1

PERCENT OVER-WATER WIND

Station	Off Water	Off Land
Hurricane Gate No. 1	55	55
" " " 2	73	58
" " " 3	81	64
" " " 4	80	66
" " " 5	89	56
" " " 6	87	57
Port Mayaca	89	64

This empirical approach was deemed more practical than any theoretical approach. The influence of friction upon wind velocity has always been a major difficulty in any theoretical computation of winds near the ground surface. Numerous intangible factors, such as surface roughness and mixing length, become involved in any theoretical computation. Similarly, rapidly changing and almost non-measurable items, such as local wind shears, stability, and inherent instrumental inadequacies, encumber practical applications. Even the exposure of the instruments and their environmental influences cannot be resolved to a common base except in a qualitative way.

Analysis of the frictional effect on wind direction

The deflection angle of the wind across the isobars is given as a function of distance from the wind center by an empirical curve based on the 1949 data (figure 66 of Hydrometeorological Report No. 26.) This turning of the wind toward low pressure due to frictional effects at the earth's surface presented a somewhat more serious problem, since the effects of local exposures upon wind direction could not be evaluated easily. To circumvent the effects of variable exposures in a general way, the deviations of the observed winds from normals to the lines drawn from the center of the storm to the stations were plotted against distances from the storm center during the passage of the hurricane. Although there was a considerable scattering of points, the mean curve is considered a satisfactory representation of the deflection angle.

Reconstruction of storms during period of water-stage recorders (1945-1950)

In accordance with the techniques described earlier, wind-speed profiles, wind-direction spirals, and speed of movement were developed for the six storms. These data are shown in figures 3-8 and are the basic tools for construction of wind fields over the Lake area.

Except during the 1949 and 1950 storms, there were no direct observations of wind speed or direction over the Lake, and there was no over-water wind profile obtained from direct observation. The over-water wind profiles were obtained by adjusting observed shore-station winds by the reciprocals of the values given in table 1. The wind profiles shown in the figures represent an envelopment of the 10-minute-average over-water wind speeds obtained in this manner.

Reconstruction of winds

The method of constructing the winds over the Lake, once the path of the storm, wind-speed profile and deflection angle were determined, was reduced to a mechanical procedure by suitable conversion of the graphical data. As shown in figures 9 and 10, the deflection-angle-vs.-distance curve was converted to a spiral, on a scale corresponding to the scale of the work charts, and the wind-speed profiles were converted to a scale of wind speed instead of distance. The origin of each of these scales can be placed over the location of the hurricane center at a particular time and the undisturbed over-water wind field reproduced. Shore-station values for off-water and off-land winds were obtained from the over-water winds in all hurricanes in accordance with factors given in table 1. Isotachs were drawn to complete the pattern as shown in figure 11, a reproduction of a working chart for the storm of September 1947.

Another complete set of charts for each storm was constructed by the same procedure based on a mean 10-minute-average profile rather than an envelopment of the 10-minute speeds. These charts produced winds which could more readily be adapted to use in study of the oceanographic formulas for wind-tide and waves.

Reconstruction of storms prior to water-stage recorders

Only three Florida hurricanes prior to 1945 were of sufficient note to require analysis of the wind field. These were the storms of 1935, 1928, and 1926. The latter two were of especial interest because of the damage and loss of life in the Lake Okeechobee area, and the former because of its unusual severity and extremely low reported central pressure. Figures 12, 13, and 14 provide the description of these hurricanes. It should be pointed out that the wind-speed profile is not truly representative of 10-minute-average over-water wind speeds as was the case in figures 3-8. Lacking observations around the Lake, it was necessary to make maximum use of whatever data were available -- some 1-minute averages, some 5-minute averages, and some peak gusts reported at scattered stations. Barometric records were quite adequate to determine a reliable path of pressure symmetry so that the heterogeneous wind reports could be plotted on a reliable distance graph. Smoothing of the wind reports results in a wind profile little different from a 10-minute-average profile, except in the neighborhood of the peak values. Probable wind patterns over Lake Okeechobee were determined for the 1928 and 1926 storms similar to figure 11. This was not done for the 1935 since the Lake was beyond the influence of high winds.

Transposition of hurricanes

The Hydrometeorological Section has, since its inception, applied a technique of transposition of storm rainfall amounts within a region of meteorological homogeneity. This increases, in effect, the storm history of a particular locality. An analogous technique has been developed to estimate hurricane wind conditions over Lake Okeechobee, comparable in magnitude to the most severe experienced in southern Florida.

During the review of storm history in the Lake Okeechobee region, it was concluded that the most intense storms arrived from the southeastern quadrant. Those arriving from the southwestern quadrant were characterized by lower wind speeds, although they covered a much larger area. In general, storms from the southwest have already developed mature-stage characteristics after recurvature, with features transitional to an extra-tropical storm, including greater speed of movement. Furthermore, the greater land trajectory from the southwest would favor greater filling. In consideration of these facts, it was concluded that storms that were observed to have travelled from the southeastern quadrant would be allowed a change in path ranging between east and south for transposition purposes. Those storms that were observed to have travelled from the southwestern quadrant were allowed a range between south and west. Although tropical storms have occasionally approached the Lake Okeechobee area from more northerly directions, they have been decadent and filled quickly upon crossing land, with wind velocities considerably less vigorous than those in storms approaching from the southern semicircle. Because there was very little curvature in most of the observed storm paths, and to avoid the unreasonable effects of looping at one particular place, it was decided to consider the paths of the storms as straight lines when transposed.

Guided by these limits on changes in storm path and the definition of wind field for individual storms, major tropical storms experienced in southern and central Florida were passed over the critical levee areas in such fashion that, at the time of maximum wind speed, the direction of the wind would be parallel, or as nearly parallel as possible, to the critical fetches (figure 15) designated by the Corps of Engineers. For each of the storms the rate of forward movement was kept the same as that observed during the actual storm occurrence. The wind speeds and wind directions over the Lake were determined by the same procedure as outlined earlier.

Thus, for each of the nine storms there were prepared five sets of charts, each set representing 10-minute-average wind speeds and directions at hourly intervals for a period from six hours before to six hours after the passage of the hurricane center over Lake Okeechobee. The resulting sets of charts represent conditions that would have occurred over Lake Okeechobee had any of the storms experienced in southern Florida taken a path across the Lake in a critical direction.

SYNTHESIS OF HURRICANE WINDS OVER LAKE OKEECHOBEE

The described techniques and analyses, as applied to observed storms in Florida, provide a suitable answer to the first two phases of the project -- reproduction of observed winds and reproduction of these that could be expected had observed hurricanes taken a critical path across Lake Okeechobee. There remains the problem of evaluating the characteristics and resultant wind fields over Lake Okeechobee, of hurricanes of intensity greater than those ever experienced in Florida.

Importance of the pressure profile

The wind velocities measured by instruments are not strictly comparable from one station to another, or even at the same station under varying conditions of direction of flow and character of atmospheric stability. Observations of winds at Lake Okeechobee during passage of hurricanes provide the necessary basic data for comparison between a theoretically-determined wind and observed winds and for the reduction of computed winds from a synthesized hurricane to anticipated winds over Lake Okeechobee. The existence of compartively numerous pressure observations and the fundemental relationships between pressure gradients and theoretical winds indicated the desirability of an accurate definition of the pressure profile of any hurricane by means of a mathematical expression as the best approach to the evaluation of winds over Lake Okeechobee during passage of a synthesized hurricane.

Previous formulas describing pressure and wind profiles

Numerous investigators have fitted formulas to observed pressures and winds of the outer portions of tropical storms. Others have postulated theoretical hurricane models. Deppermann* has suggested the existence of a Rankine vortex where the product of wind speed and distance is constant in the outer portions of the hurricane ($vr = K$), and wind speed divided by distance is constant near the center ($v/r = K$). He describes the intervening portion of the wind profile as a ring of violent convection. Although the inner and outer winds, not near the radius of maximum wind, appear to approximate these descriptions, this project is vitally concerned with the character of the winds within 100 miles of the center and, in particular, in the immediate vicinity of the radius of maximum wind. Some proposed formulas describing a hurricane, when applied to wind computations, are either grossly in error near the center of the storm or present a discontinuity of gradient at the radius of maximum wind, which hardly

*See model in "Hurricane Notes".

seems reasonable in a natural phenomenon. Rather, it seems there should be a transition zone with reciprocal action operating between the forces controlling the inner and outer portions of the storm. The aim of this phase of the study was to obtain a suitable universal pressure profile and, by accepted formulas, compute theoretical winds which could then be modified for exposures at Lake Okeechobee during passage of the synthesized hurricane along selected paths.

The empirical approach

The Section has attempted to arrive at a formula, not by hypothesizing balances of forces and accelerations, followed by rigorous mathematical development, but by considering pressure profiles in actual storms and attempting to arrive at a reasonable description of the storm pressure profile through use of parametric equations and logical selection of the required parameters.

At this point the question may arise as to why, since the winds are to be computed from pressure gradient ($v^2 = \frac{1}{\rho} r \frac{dp}{dr}$), individual pressure gradients are not compared directly to observed winds. There were three reasons. First, experimentation with measurement of pressure gradient indicated that measurement of the slope of the tangent to a curve such as a barograph trace is subject to wide individual error. Second, the pressure gradients would have to be smoothed during the analysis procedure before they could be used, and the process of smoothing can be carried out much more elegantly by the simple expedient of fitting a formula to the pressure profile. Third, it was decided to concentrate upon the best possible reproduction of the pressure profile, rather than the wind profile, so that separate empirical investigations of frictional effects could be carried forward by means of comparisons of observed and computed winds. It would be very difficult, if not impossible, to assess theoretically the errors introduced by the assumption of cyclostrophic wind conditions. Having analyzed the storm of August 1949, the Section has been able to obtain empirical reduction factors to modify a computed wind profile for exposure and site of the stations around Lake Okeechobee. Thus, from the standpoint of ultimate maximization or synthesis of hurricane winds, the concentration on the reproduction of the pressure profile allows opportunity for study of deviations from cyclostrophic conditions.

Since the pressure profiles of hurricanes indicate a systematic increase of pressure from the center outward, it was generally agreed that total pressure deficit of the storm (the difference between the pressure outside the storm and that in the storm center) must be a parameter when pressure and distance from the center are considered variables. Therefore, the general form of the equation adopted and tested was $\frac{p - p_o}{p_n - p_o} = f(r)$, where p is the pressure at distance r from the center, p_o the central pressure, and p_n the normal or asymptotic pressure at the outer periphery of the hurricane.

From examination of pressure and wind profiles, certain other general characteristics of the pressure profile can be specified qualitatively. Most important of these are that the pressure gradient must approach zero near the storm center and at the periphery and that the computed winds must be a maximum at some distance from the center, which will be referred to as the radius of maximum winds, R.

Ten general formulas fitting the requirements were listed and examined. These formulas are given in table 2. This is not an exhaustive list, but it does encompass the possibilities capable of treatment in a reasonable time.

Table 2

PRESSURE-PROFILE FORMULAS

$$\frac{p - p_o}{p_n - p_o} = 1 - e^{-nr^i}$$

$$\frac{p - p_o}{p_n - p_o} = e^{-\frac{n}{r^i}}$$

$$\frac{p - p_o}{p_n - p_o} = \frac{1}{1 + \frac{1}{nr^i}}$$

$$\frac{p - p_o}{p_n - p_o} = \frac{1}{\left(1 + \frac{1}{nr}\right)^j}$$

$$\frac{p - p_o}{p_n - p_o} = \frac{1}{\left(1 + \frac{1}{nr^i}\right)^j}$$

$$\frac{p - p_o}{p_n - p_o} = \frac{2}{\pi} \arctan \frac{1}{nr^i}$$

$$\frac{p - p_o}{p_n - p_o} = \frac{2}{\pi} \operatorname{arccot} \frac{1}{nr^i}$$

$$\frac{p - p_o}{p_n - p_o} = \frac{2}{\pi} \operatorname{arcsec} (1 + nr^i)$$

$$\frac{p - p_o}{p_n - p_o} = \frac{2}{\pi} \operatorname{arccsc} \left(1 + \frac{1}{nr^i}\right)$$

$$\frac{p - p_o}{p_n - p_o} = \tanh nr^i$$

n, i, and j are undefined parameters

Any of these formulas, with appropriate values of the parameters, appear to produce a reasonable fit to observed pressure data. Consequently, the procedure was followed of allowing the data to determine the formula to be used.

The limited storm sample hindered detailed statistical treatment of the data. However, it was possible to investigate, in a qualitative way, such parameters as latitude, direction of storm movement, month of occurrence, radius of maximum wind, and total storm diameter.

Although the total pressure deficit in the center of a storm, $p_n - p_o$, is important, even more important for our problem is the character of the distribution of gradients or the shape of the pressure profile. The distribution of gradients is of utmost importance when wind speeds are computed by means of the cyclostrophic formula, $v^2 = \frac{1}{\rho} r \frac{dp}{dr}$. It is apparent that in order to locate the maximum wind correctly (near the maximum pressure gradient), it should be given considerable attention in the general equation.

Table 3 lists the principal characteristics of the nine storms studied. The asymptotic pressure, p_n, was taken as that pressure which approximated the position at which the curvature of the isobars on a synoptic map changed from cyclonic to anticyclonic. R was taken as the distance at which the maximum wind speed occurred on the profile of the 10-minute-average wind speed for each of the storms, and p_o was estimated as closely as possible from the available synoptic data. Improvement in the reliability and accuracy of these measurements is a continuing goal of the project.

An example of the initial step in selecting the general formula is shown in figure 16 where $\frac{p - p_o}{p_n - p_o}$ is plotted against distance for the storm of October 17-18, 1950. A similar chart was drawn for each of the storms listed in table 3. Figure 17 shows the respective curves for all of the storms.

Table 3

TROPICAL STORM PARAMETERS

Date	p_n (mb)	p_o (mb)	p_n-p_o (mb)	R (miles)
1950 October	1009	960	49	12
1949 August	1015	955	60	22
1948 October	1008	977	31	31
1948 September	1010	962	48	18
1947 September	1010	940	70	22
1945 September	1012	946	66	14
1935 September	1010	892	118	16
1928 September	1006	929	77	26
1926 September	1005	935	70	17

The general shape of the pressure profiles and the formulas listed in table 2 indicated the desirability of using semi-log paper in order to highlight the significant remaining parameters. Figure 18 represents the same data as shown in figure 17 except that $\frac{p - p_o}{p_n - p_o}$ is plotted on a log scale. It is seen that the curves suggest a family of rectangular hyperbolas which have the general formula of xy = k. Locating the origin at $\frac{p - p_o}{p_n - p_o} = 1$ and substituting directly, we obtain $r \ln \frac{p_n - p_o}{p - p_o} = k$, where y = distance from center of hurricane (r) and $x = \ln \frac{p_n - p_o}{p - p_o}$.

As indicated earlier, location of the radius of maximum winds is a vital requirement for determination of the wind distribution over Lake Okeechobee during passage of a synthesized hurricane. Therefore, it again appeared logical to investigate the relationships inherent in the expression $k = k_1R^i$. At this stage of the development, the restricted storm sample became a severe limitation, and quantitative evaluation of k_1 and i was not considered feasible without more data. Qualitative examination of the data indicates these values are not sufficiently different from unity to introduce appreciable error in computation of wind. Insertion of R for k in the above equation and taking antilogarithms results in the equation

$$\frac{p - p_o}{p_n - p_o} = e^{-R/r}$$

which corresponds to the second equation given in table 2.

The Section is aware of potential improvements in the formula that could result from analysis of a greater sampling of hurricanes. Particularily, as indicated before, there is probably a constant multiplier of R and an exponent of R. Errors in the general equation could result from neglect of the total area of the storm (which would improve fit in the peripheral area), latitude (which would probably improve the fit in all portions), and the relationship between these variables. Influence of these and other variables is an essential part of the continuing study of hurricanes. It is believed that the selected formula is a reasonable representation of the pressure profile of a hurricane out to a distance of about 100 miles.

<u>Conversion of friction-free winds to 10-minute averages</u>

The preceding paragraphs have outlined a method of approach to the synthesis of hurricane winds over Lake Okeechobee. Differentiation of the basic equation

$$\frac{p - p_o}{p_n - p_o} = e^{-R/r}$$

with respect to r results in

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

which, when substituted in the cyclostrophic wind equation,

$$(v^2 = \frac{1}{\rho} r \frac{dp}{dr})$$

provides the basis for computation of friction-free instantaneous wind speeds of a synthesized hurricane by insertion of appropriate values for the parameters.

The assignment of the project indicated that a breakdown of winds to 10-minute averages at hourly intervals would be about the greatest refinement capable of assimilation for oceanographic studies. Therefore, a conversion from instantaneous friction-free winds to 10-minute averages at anemometer level over Lake Okeechobee would be required. In the course of analysis of the winds in the Florida Keys storm of 1935, Patrick J. Harney suggested that the peak gusts recorded may correspond to the speed of the gradient-level winds, which are friction free. Following this suggestion the Section attempted to relate peak gusts as recorded on anemographs during ten-minute intervals to the 10-minute-average wind speeds for identical intervals at the individual stations. The results indicated a frictional reduction factor of 30 to 40%, but there remained too much scatter for the relationship to be called good. Not until the 10-minute-average speeds at the individual stations were adjusted to a common base -- the over-water wind -- did the relationship become useful. The adjustment was made by use of the reciprocals of the factors in table 1. The regression line establishing the relationship between the 10-minute-average over-water wind speed and the peak gusts is $Y = 9.5 + .77x$, where Y is the 10-minute-average over-water wind. The correlation coefficient is 0.866. Assuming, then, that the wind profile developed by selected parameters can be used as peak gusts, the speed-distance profile of 10-minute-average over-water winds can be obtained. It should be emphasized that the wind speeds derived here represent 10-minute-averages for the Okeechobee area.

Wind direction

In all of the hurricanes studied, there appeared to be a rather constant average deflection angle in the outer portion of the storm. (This angle decreased very rapidly near the region of maximum wind, approaching zero and even becoming negative in one case.)

The most critical condition of wind direction would probably result from constant direction along a critical fetch. This is obtained by combining a constant wind-deflection angle with a straight-line path that crosses the Lake. In the hurricanes studied, an average deflection angle of about 35° was most common, so this was chosen as the angle of deflection in the model hurricane.

Critical path and speed of movement

The Corps of Engineers, in the letter of assignment, specified the five critical fetches (figure 15) along which the cumulative effects of wind on wave were to be related to hurricane wind structure, duration, and direction. The path of the synthesized hurricane for each fetch was, therefore, oriented in such fashion as to keep the winds parallel to the critical fetch. The one restriction placed on the path direction was that the hurricane should approach from the southern semicircle. The resulting paths are shown in figure 19.

The slower the forward progress of a synthesized hurricane, the longer the persistence of winds of highest speed over the Lake. In fact, the extreme condition would result from a stationary hurricane with the levee under consideration at the radius of maximum winds. However, from the practical viewpoint of design, such a situation is not reasonable. Analysis of the speed of forward movement of hurricanes indicates an average speed of 10 miles per hour prior to and during recurvature but a much greater speed thereafter. The most intense hurricanes in the vicinity of Lake Okeechobee have occurred prior to or during recurvature. Therefore, 10 miles per hour was chosen as a reasonable speed of forward progress for synthesized hurricanes.

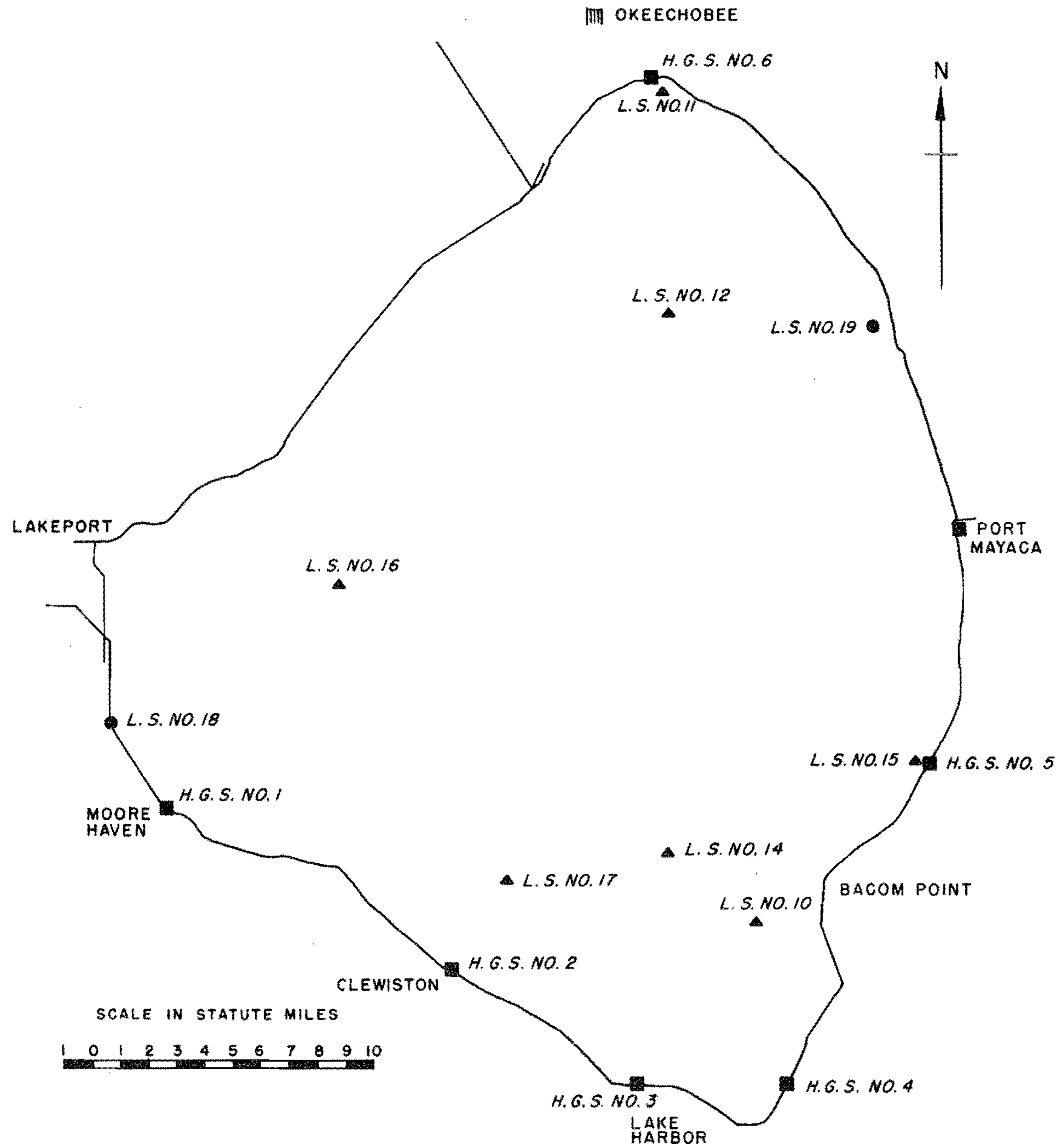
As an example of the results of the methodology used to evolve the pattern of winds over Lake Okeechobee, the maps shown in figures 20a to 20i represent the expected 10-minute-average winds over Lake Okeechobee from a hurricane with a central pressure of 931 mbs, normal pressure of 1013 mb, radius of maximum wind of 20 miles, and forward speed of movement of 10 miles per hour along a path from 145°. Many similar charts for other paths and other combinations of variables have been prepared to meet the requirements for Lake Okeechobee levee design.

Acknowledgments

The early, investigative phase of the project was under the direction of A. L. Shands, then Assistant Chief of the Hydrometeorological Section; later, the author was project leader. Other members of the Section contributing to the report were R. D. Fletcher, then Chief of Section, C. S. Gilman, D. R. Harris, N. E. Manos, E. F. Grabowski, R. E. Johnson, J. T. Walser, J. C. Coffin, J. S. Smith, M. L. Waggoner, J. T. Stebbins, L. C. Reant, J. L. Keister and P. J. Davis. The final editing was accomplished by Mrs. L. K. Rubin, the drafting by C. Gardner, C. S. Gladden and J. E. Fimiani, and the typing by Miss B. L. Fox and Miss M. I. Hammer.

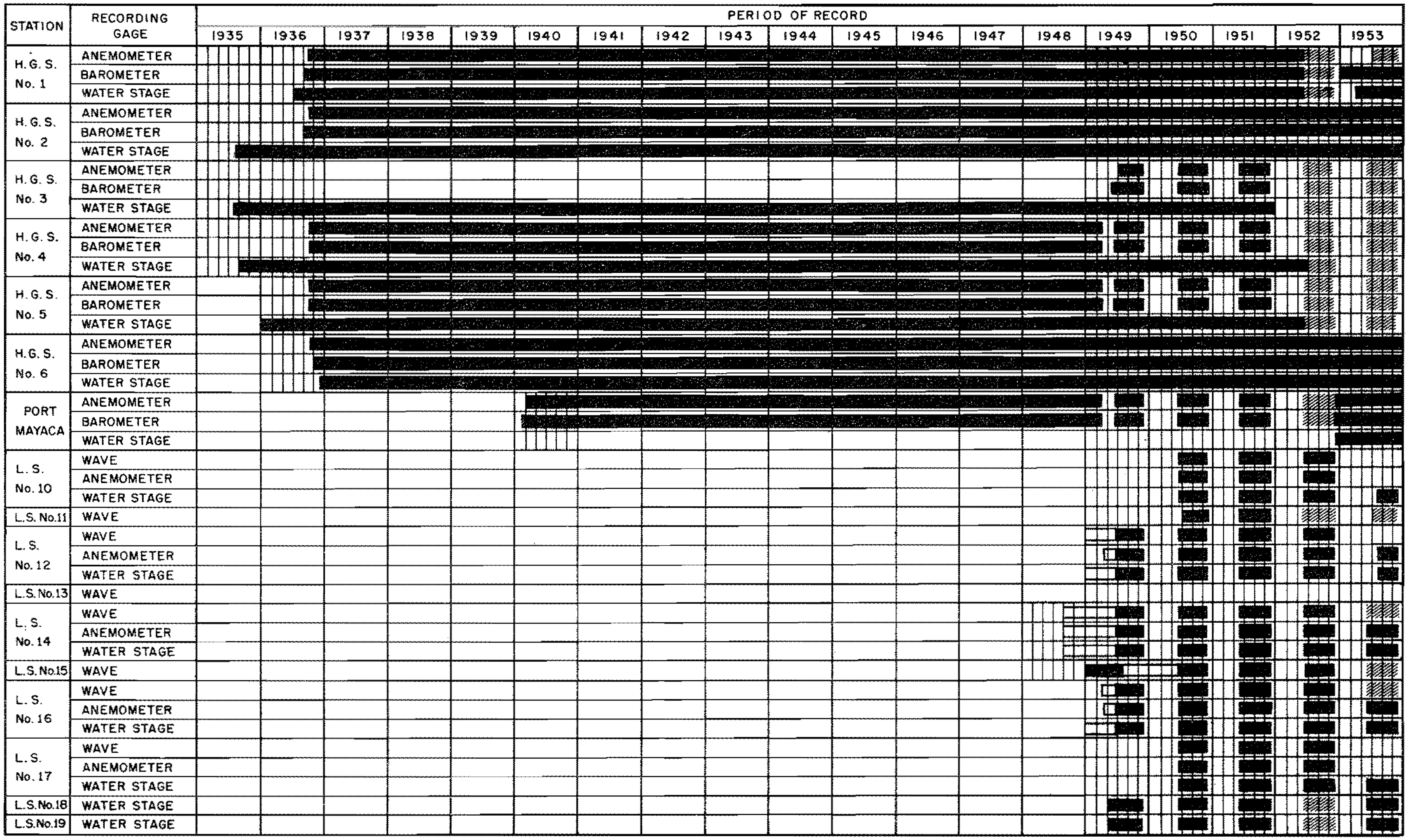
Particular thanks are due Dr. I. M. Cline, who kindly made available to the Section the originals of the drawings appearing in his book, "Tropical Cyclones". During the early part of the work on the project, these data suggested techniques and guides which were in part adapted to the present study.

Most of the progress made in this study is due to the close cooperation of the Corps of Engineers, U. S. Army, and in particular to their foresight in the establishment of a network of observing stations around, and on, Lake Okeechobee. These stations provided a wealth of observations unequalled in areas visited by tropical storms.



INSTALLATIONS ON LAKE OKEECHOBEE

FIG. 1



— LEGEND —

CONTINUOUS OPERATION

STAND-BY OPERATION

INTERMITTENT OPERATION OR MALFUNCTION OF GAGE

— NOTES:

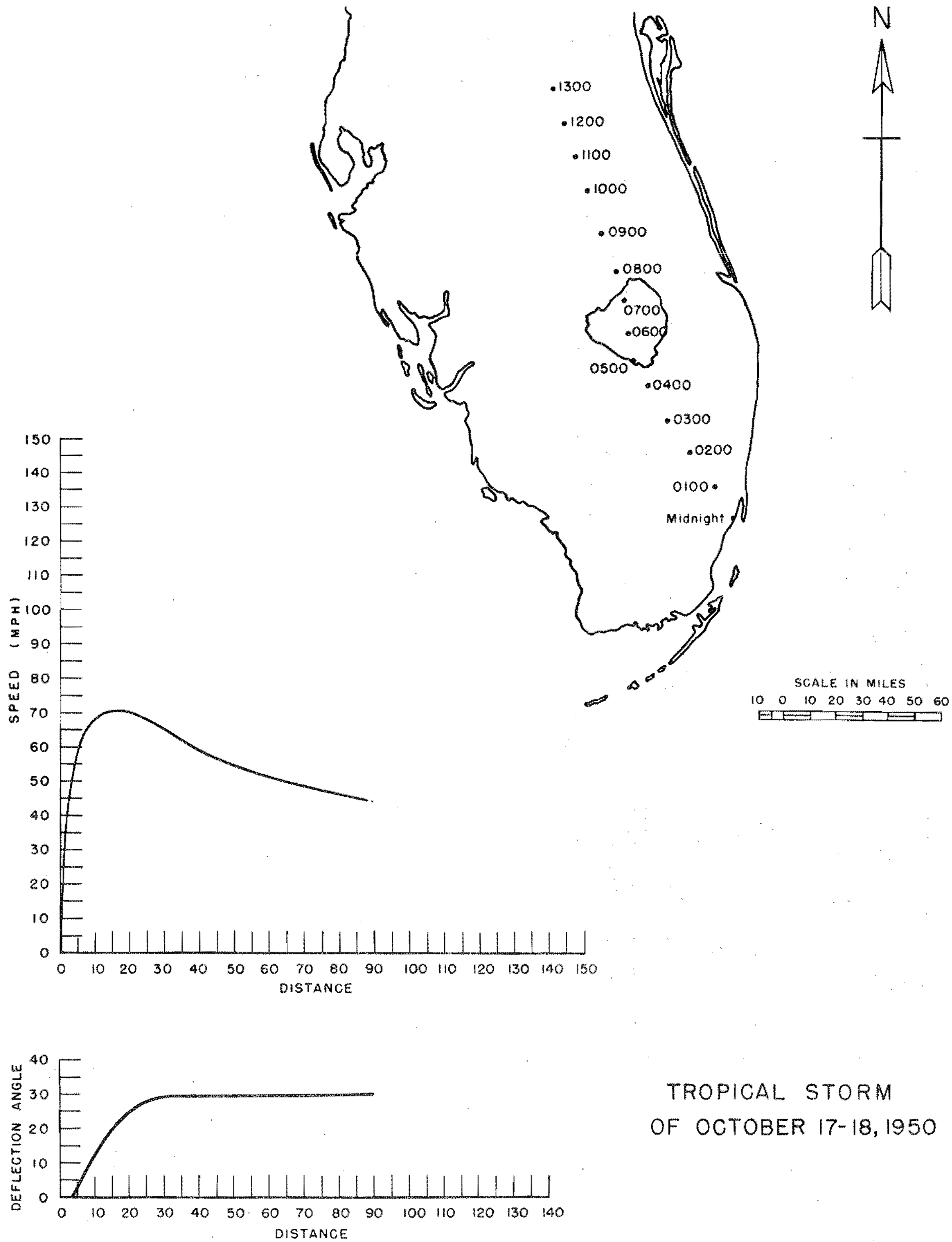
Other gages in operation but not applicable to waves and wind-tide program, are not included in this tabulation.

Since 1949 major gaging program operation has been limited to hurricane season, June 15 — November 15.

Stand-by operation means gage is ready for immediate activation upon receipt of hurricane alert.

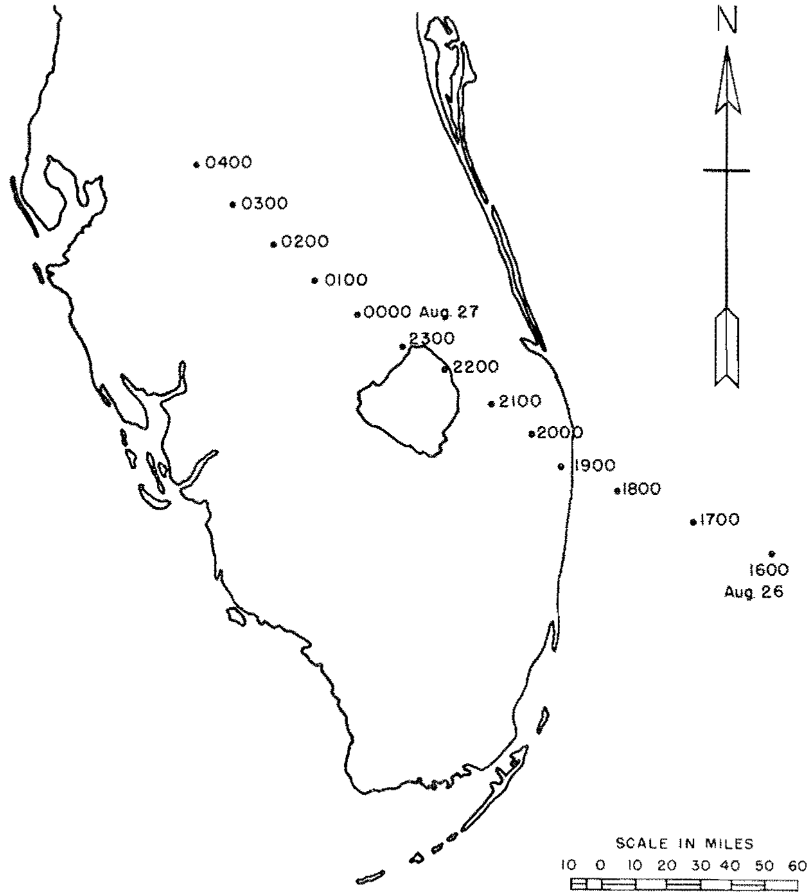
FIGURE 2. PERIOD OF RECORD FOR INSTALLATIONS ON LAKE OKEECHOBEE, FLORIDA

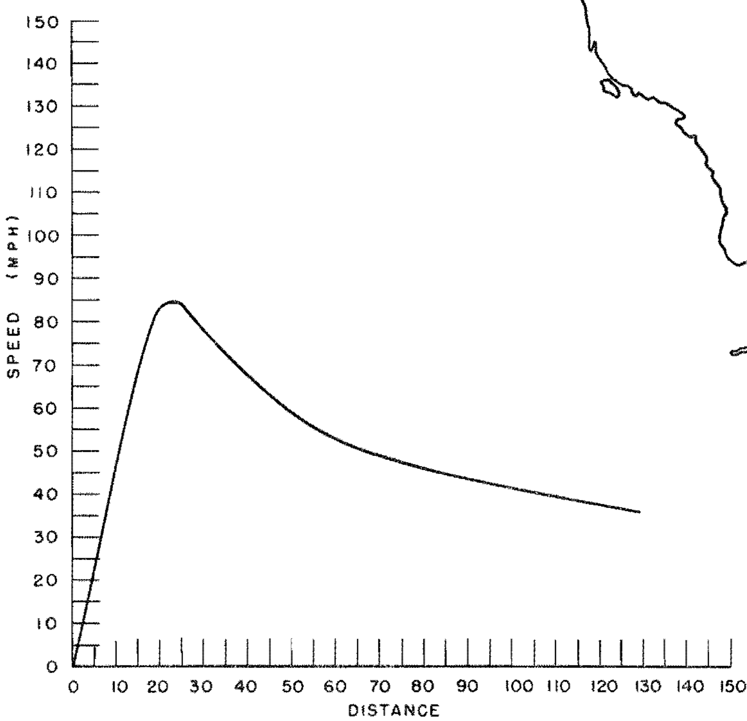
(Data furnished by Corps of Engineers)

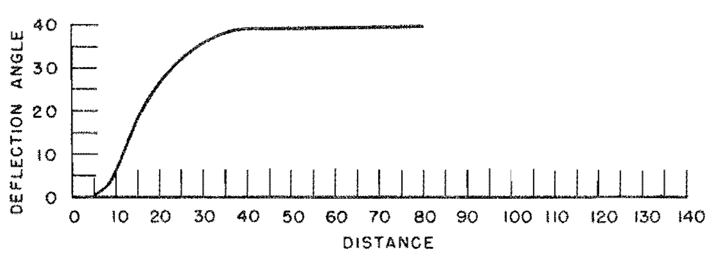


TROPICAL STORM
OF OCTOBER 17-18, 1950

FIG. 3

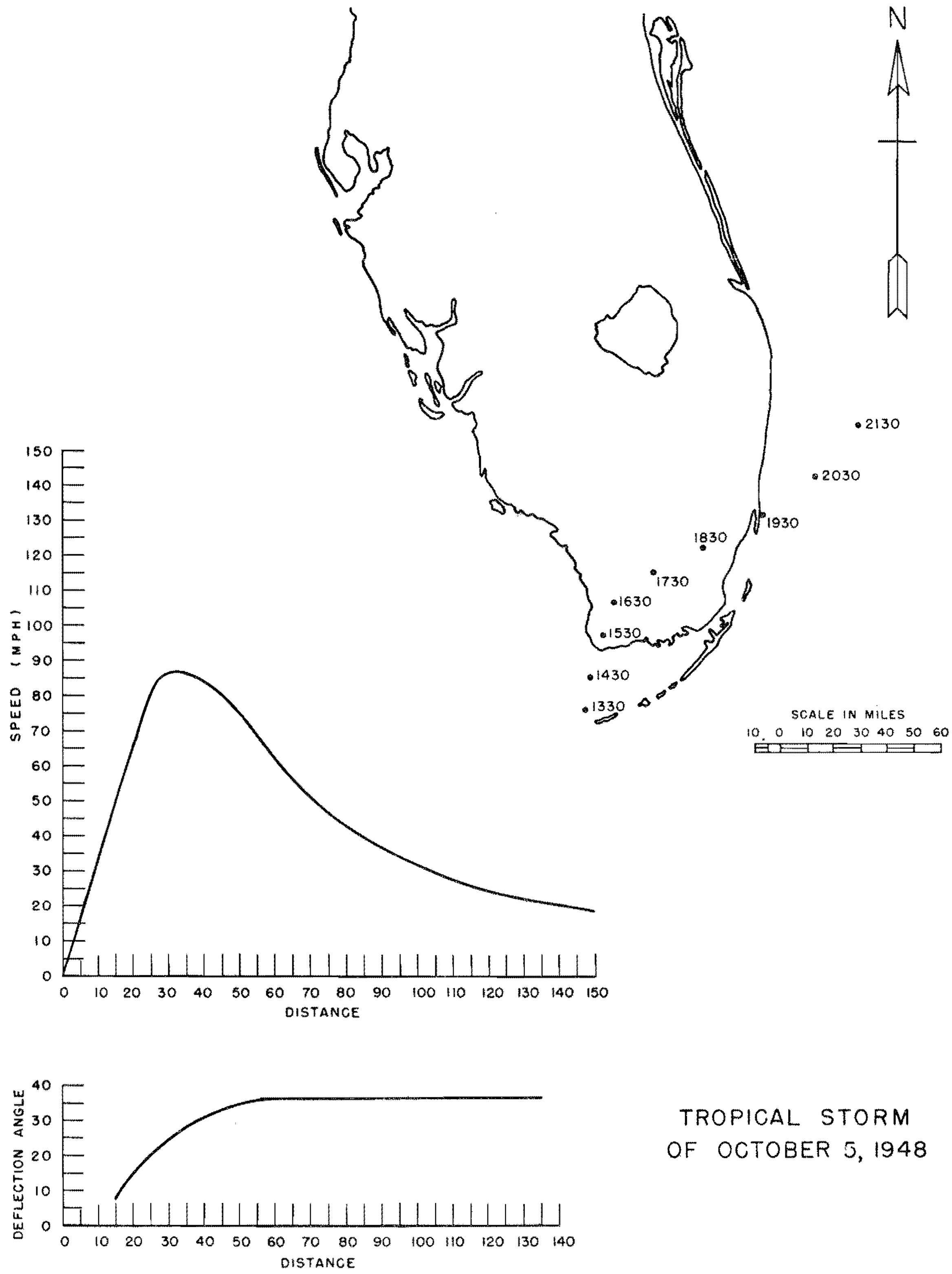






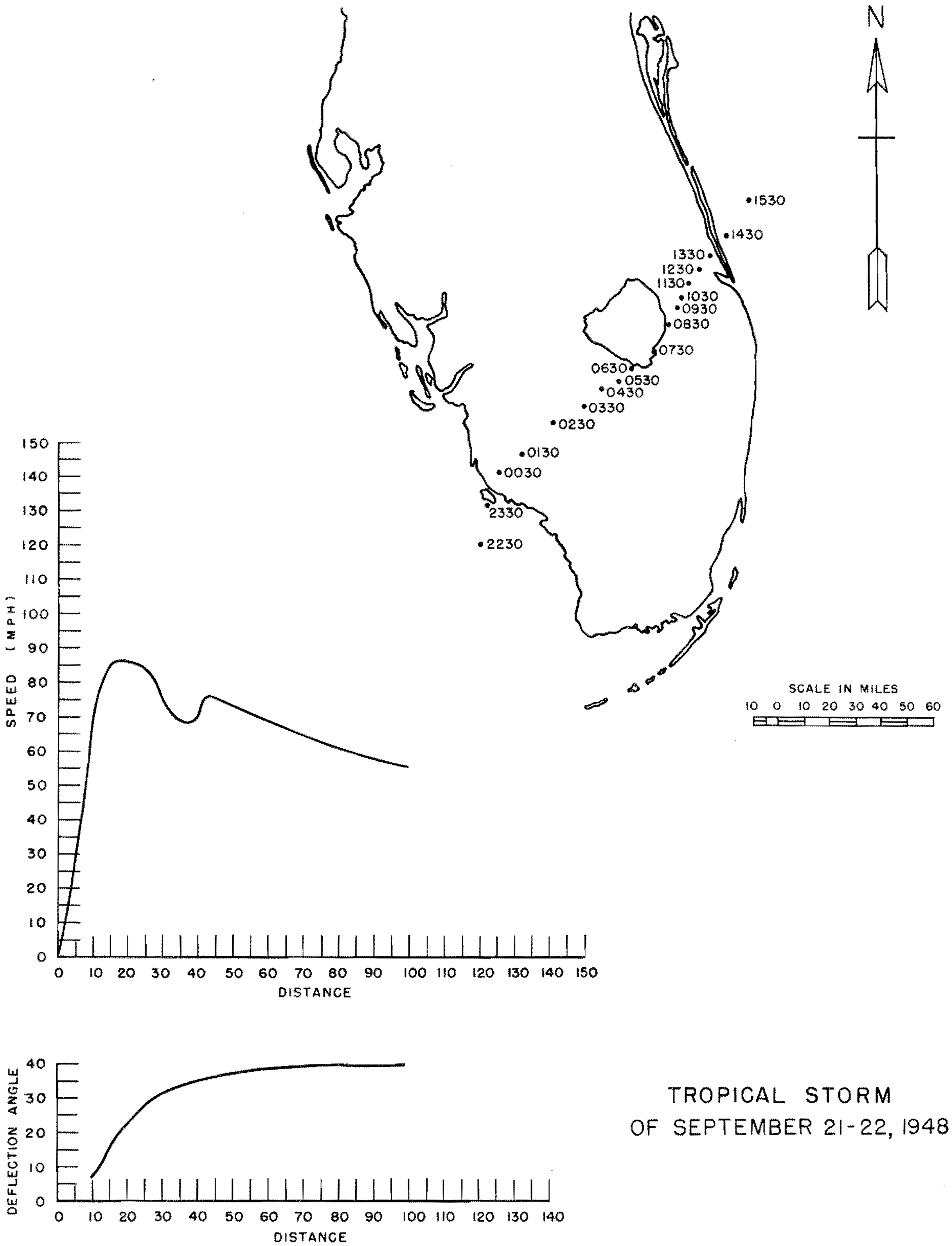
TROPICAL STORM
OF AUGUST 26-27, 1949

FIG. 4



TROPICAL STORM OF OCTOBER 5, 1948

FIG. 5


N
•1530
•1430
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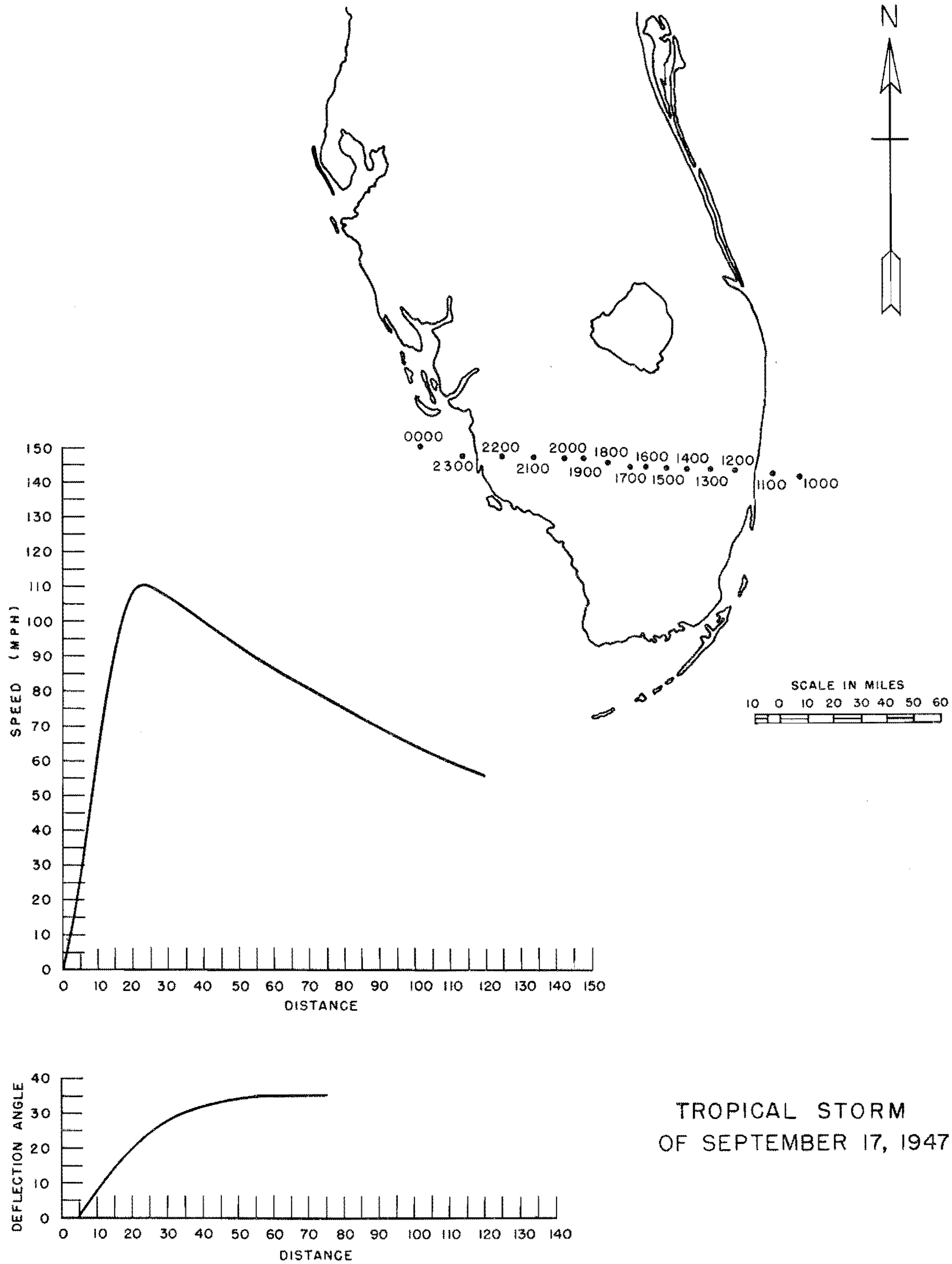
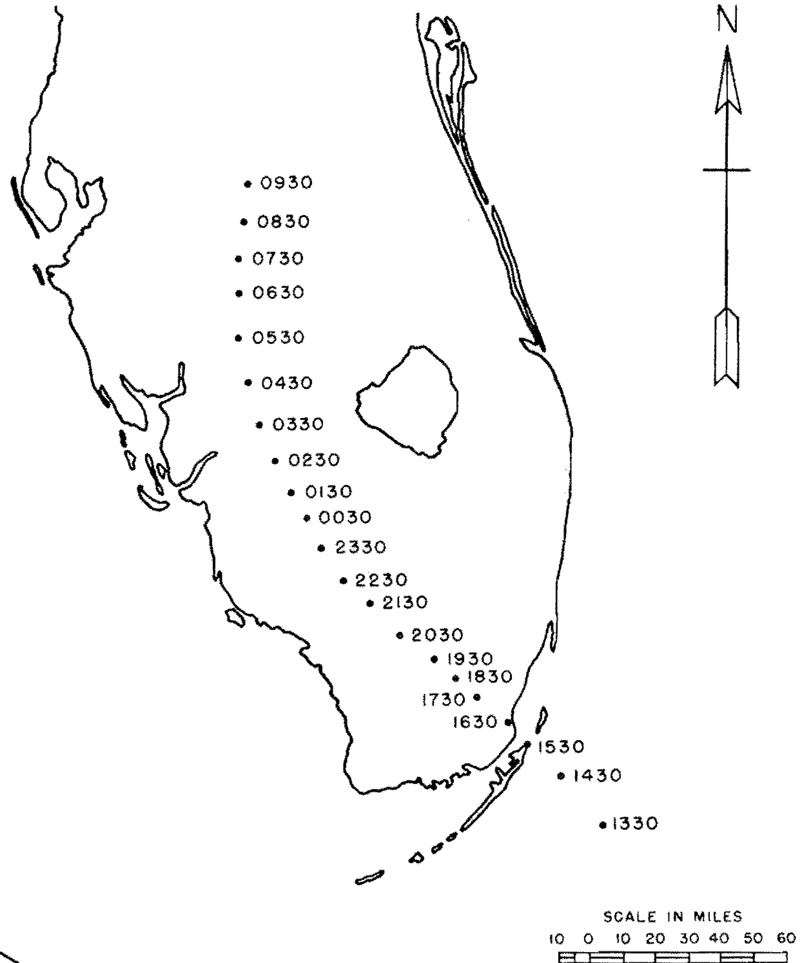
1230•
1130•
•1030
•0930
•0830
•0730
0630•
•0530
•0430
•0330
•0230
•0130
•0030
2330
•2230
SCALE IN MILES
10 0 10 20 30 40 50 60
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
SPEED (MPH)
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
DISTANCE
40
30
20
10
0
DEFLECTION ANGLE
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
DISTANCE
TROPICAL STORM
OF SEPTEMBER 21-22, 1948

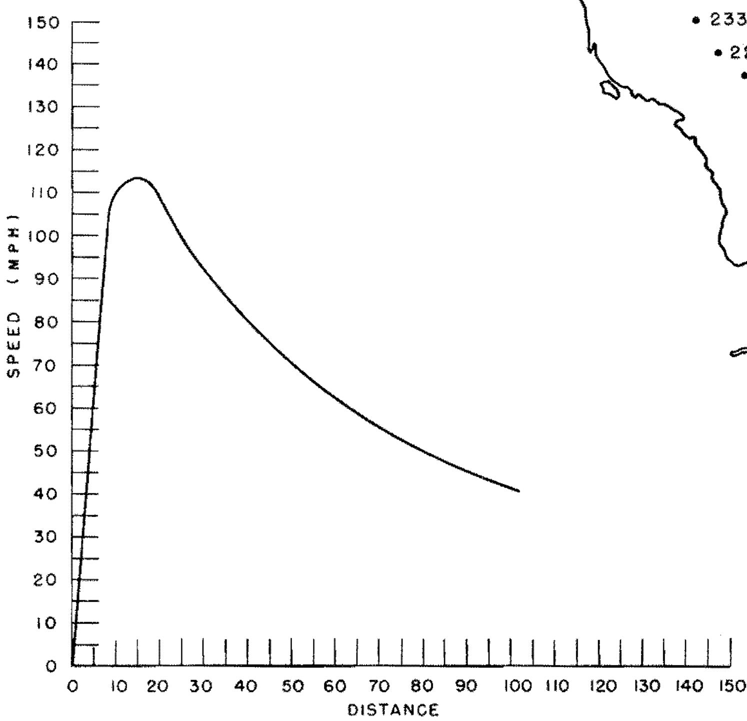
FIG. 6

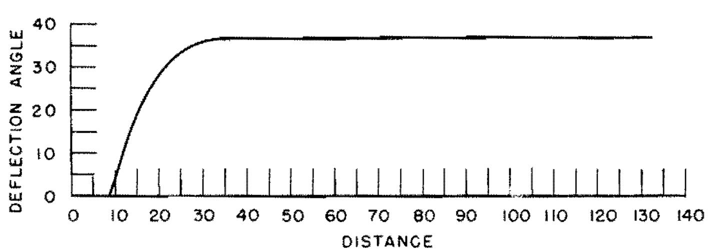


TROPICAL STORM
OF SEPTEMBER 17, 1947

FIG. 7

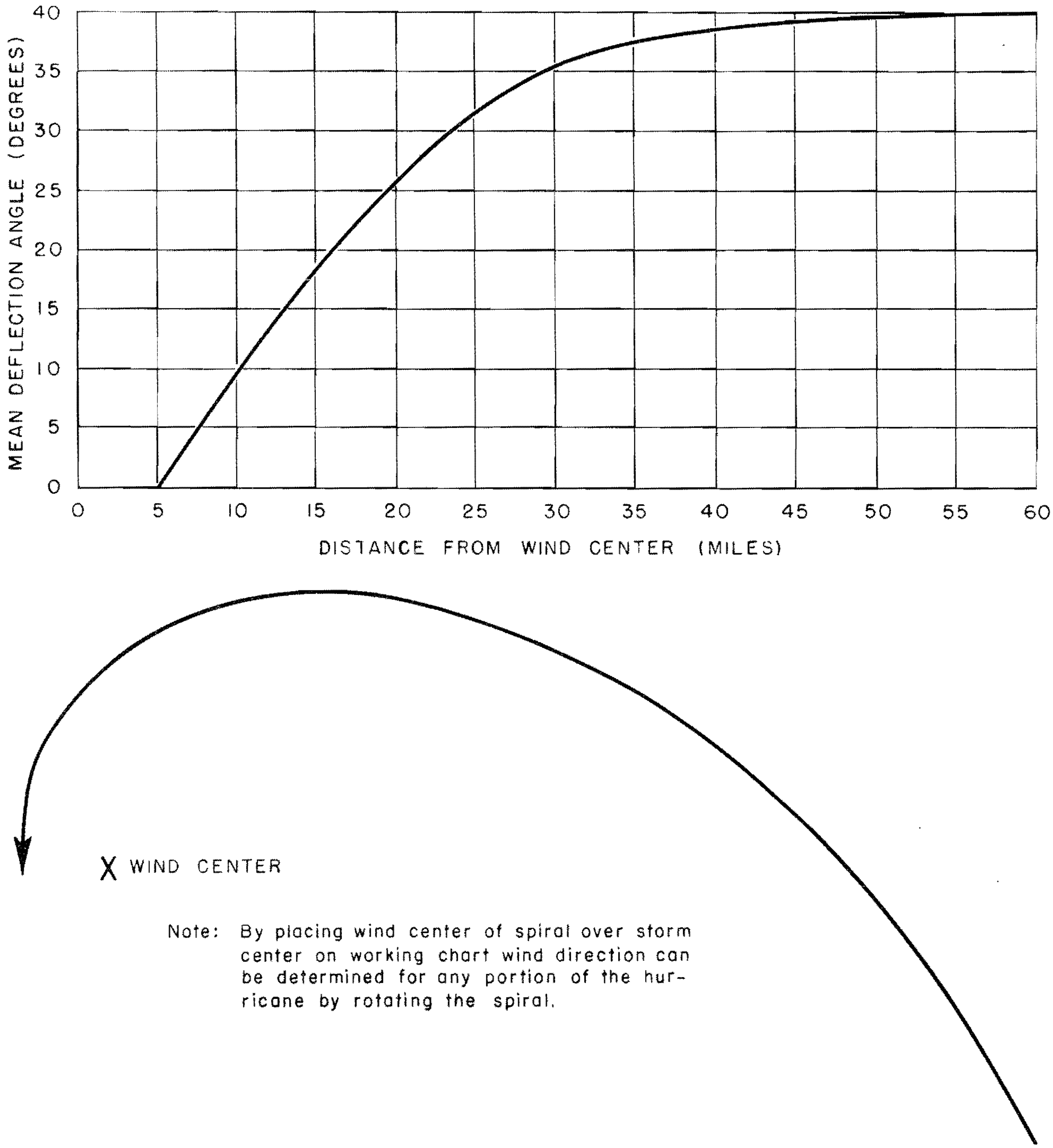






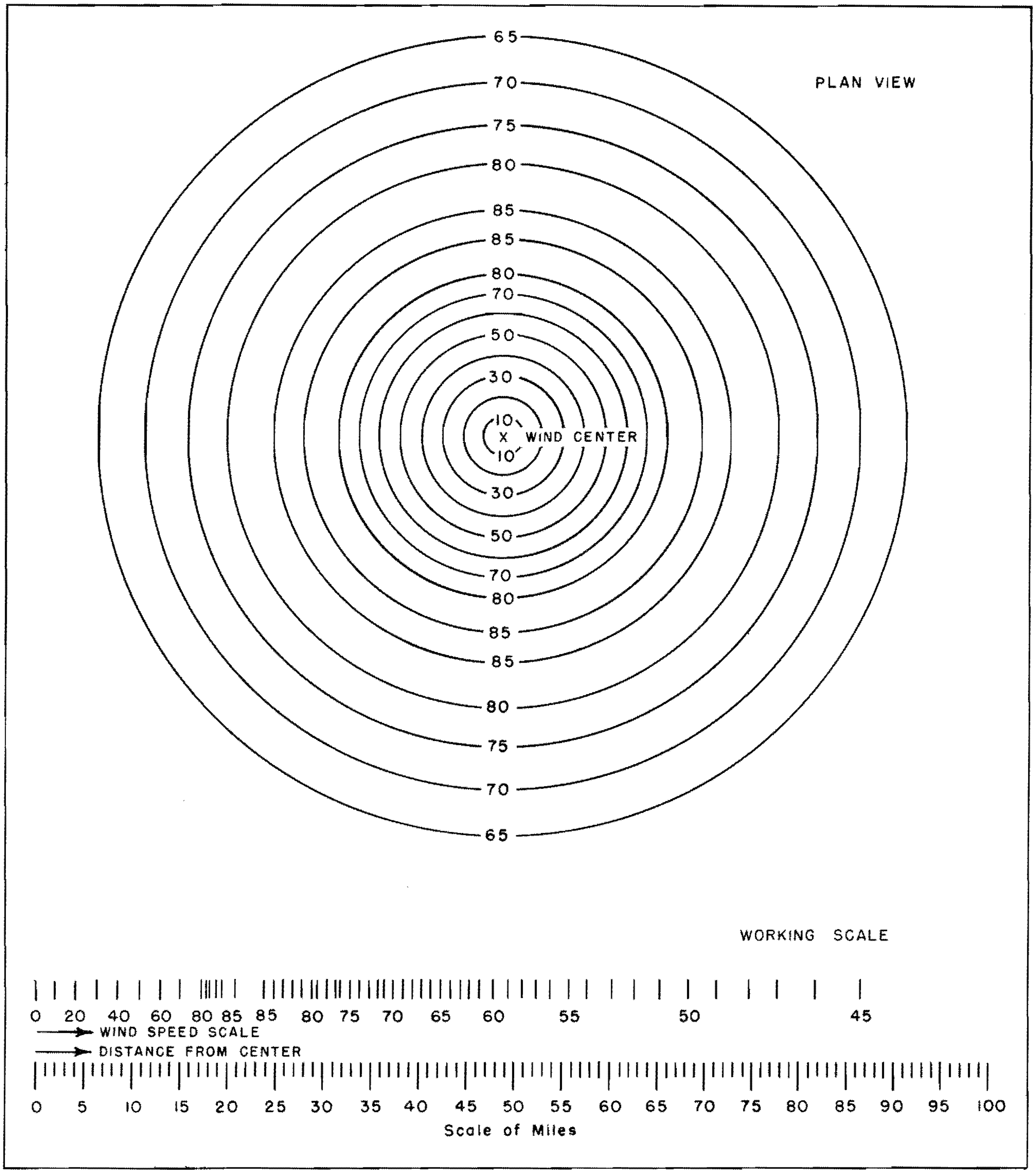
TROPICAL STORM
OF SEPTEMBER 15-16, 1945

FIG. 8

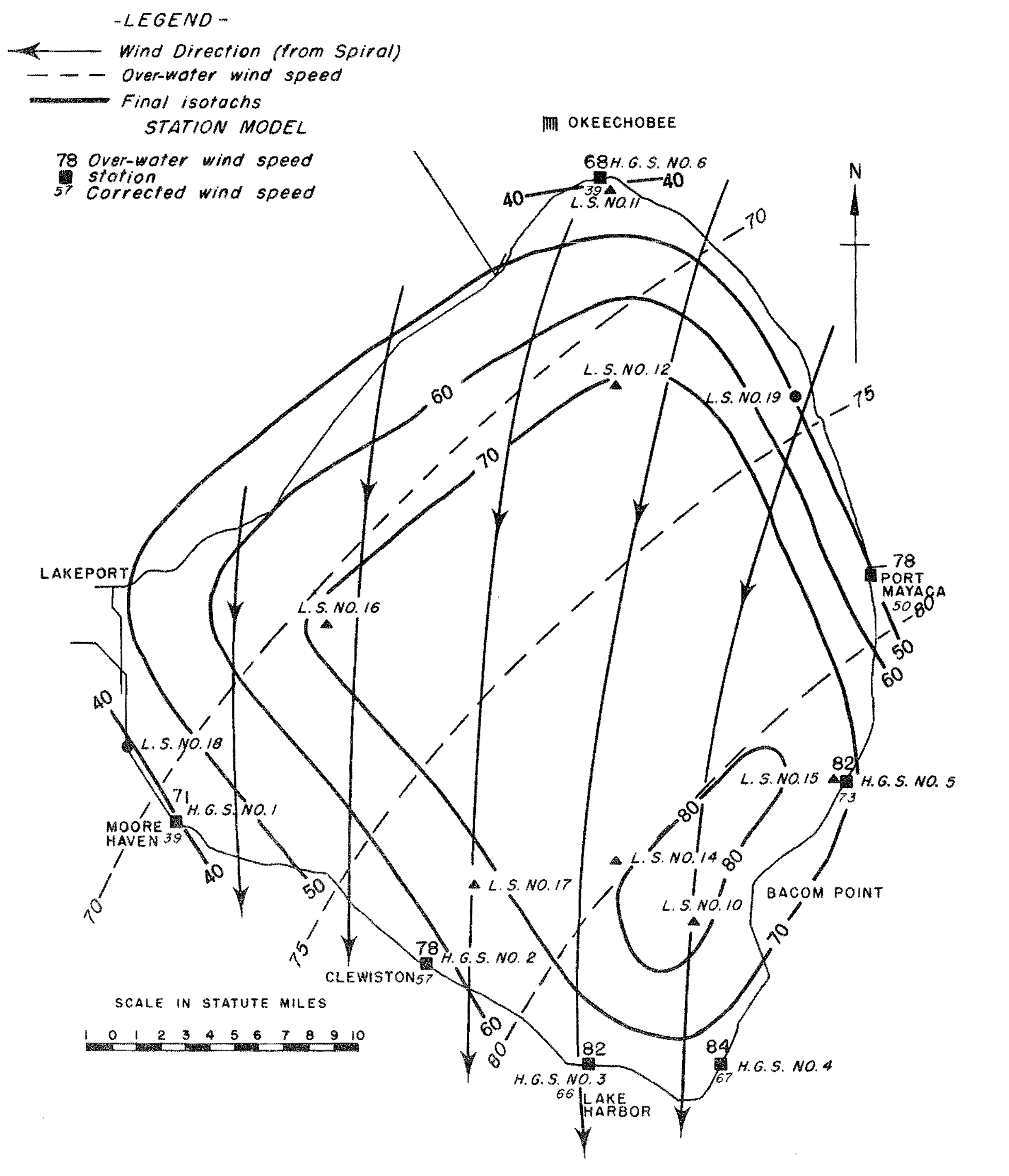


WIND-DIRECTION FIELD
HURRICANE OF AUGUST 26-27, 1949

FIG. 9

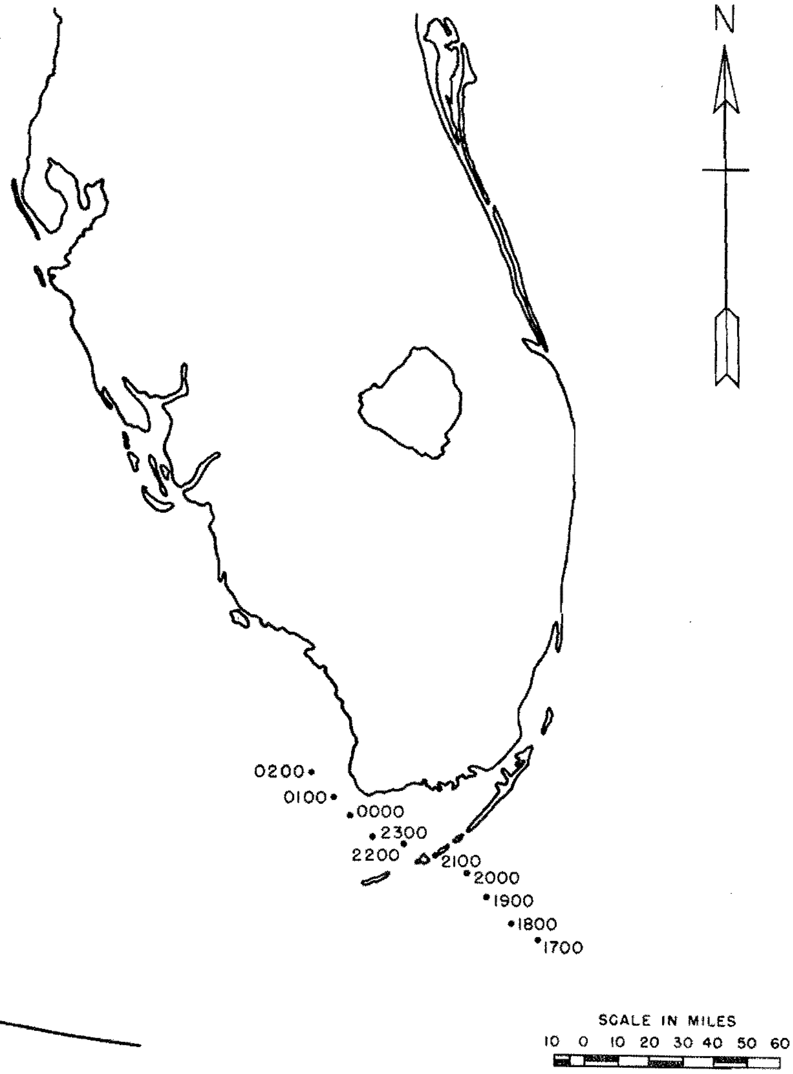


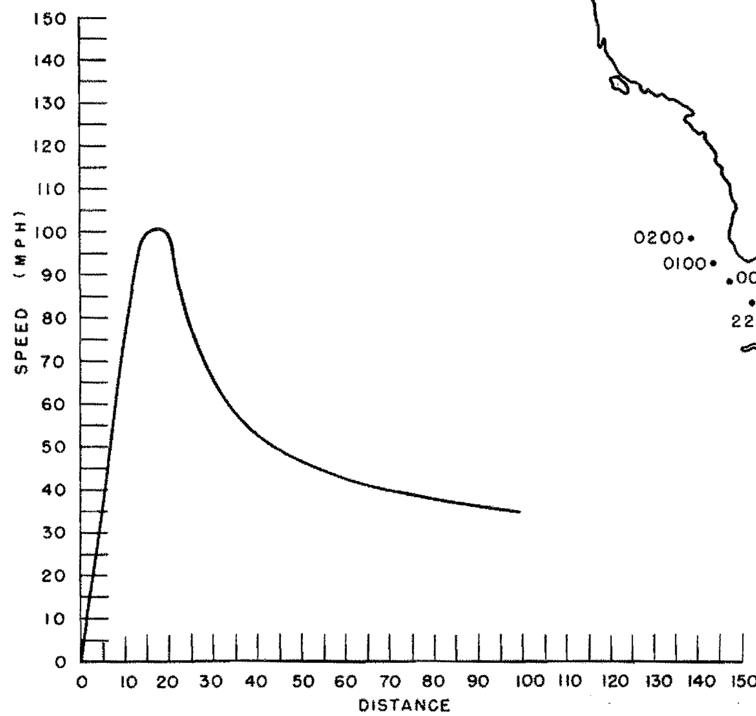
WIND-SPEED DISTRIBUTION
(10-MINUTE AVERAGE)
HURRICANE OF AUGUST 26-27, 1949
FIG. 10

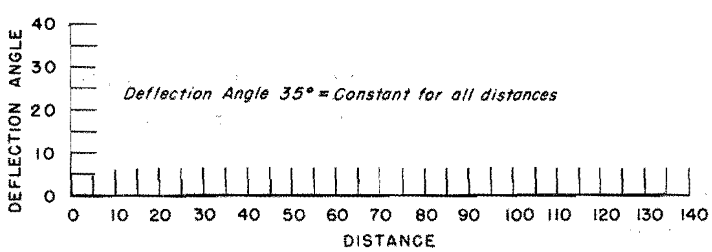


RECONSTRUCTION OF WIND FIELD OVER LAKE OKEECHOBEE
WORKING CHART FOR 11 A.M., SEPTEMBER 17, 1947

FIG. 11







TROPICAL STORM
OF SEPTEMBER 2-3, 1935

FIG. 12

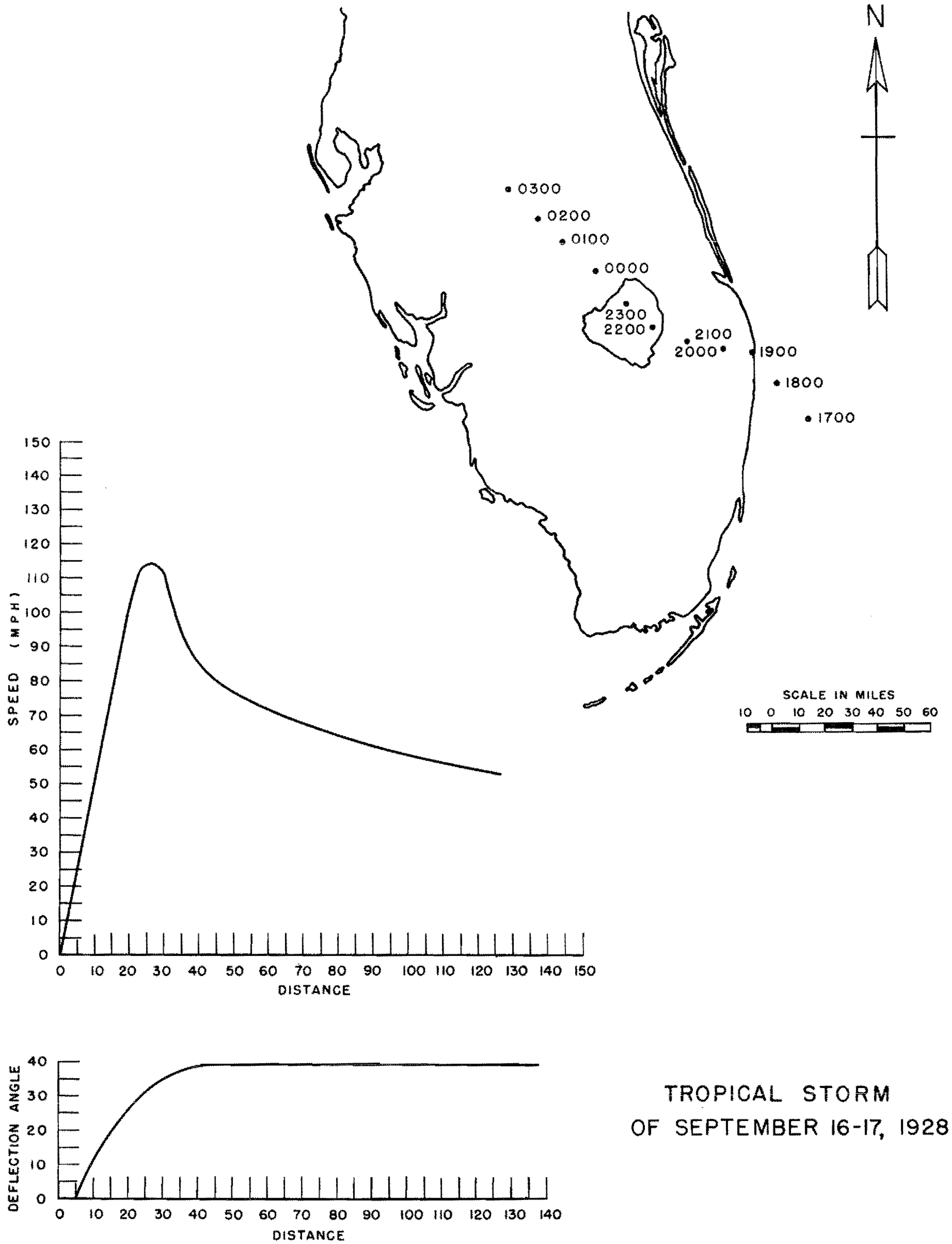
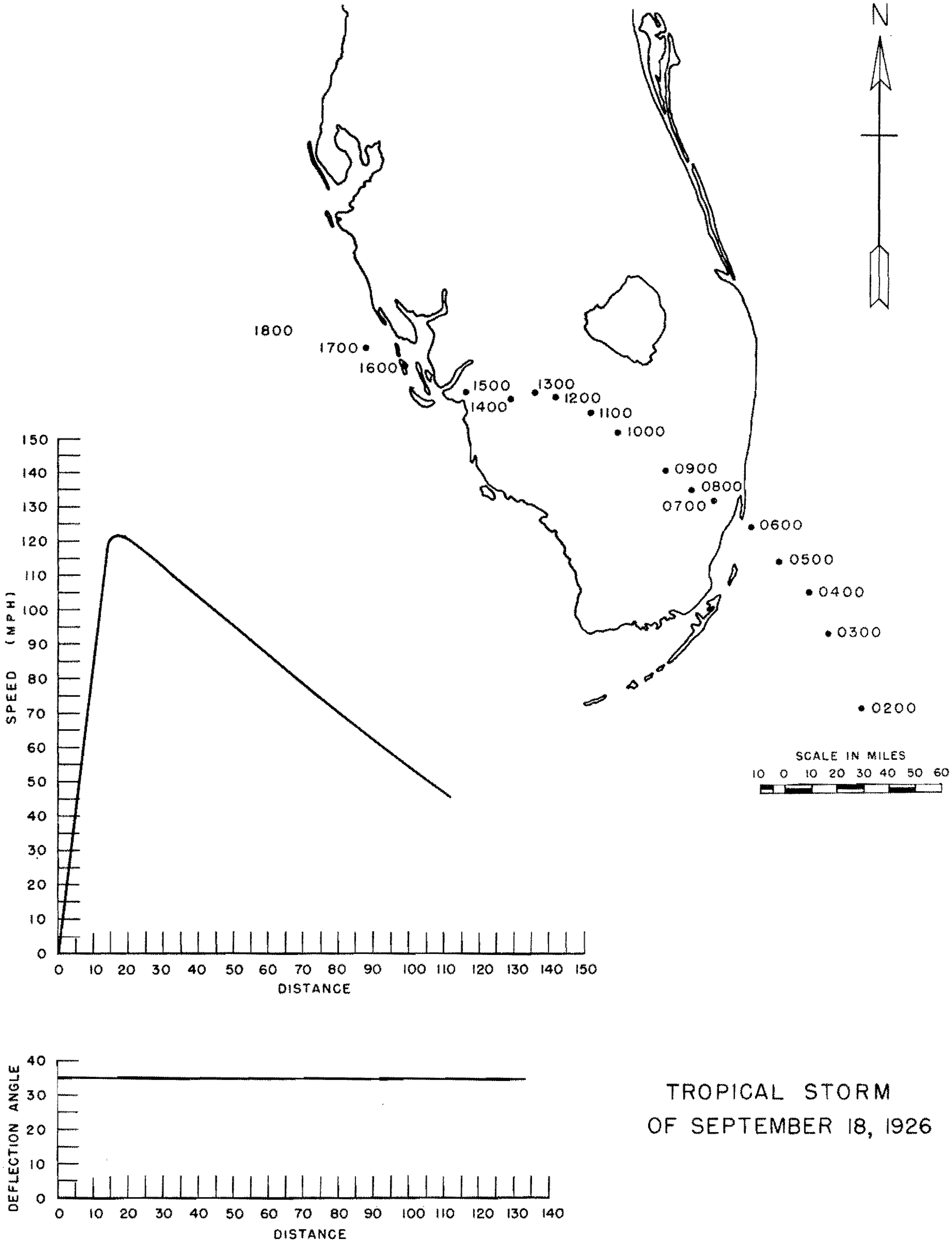
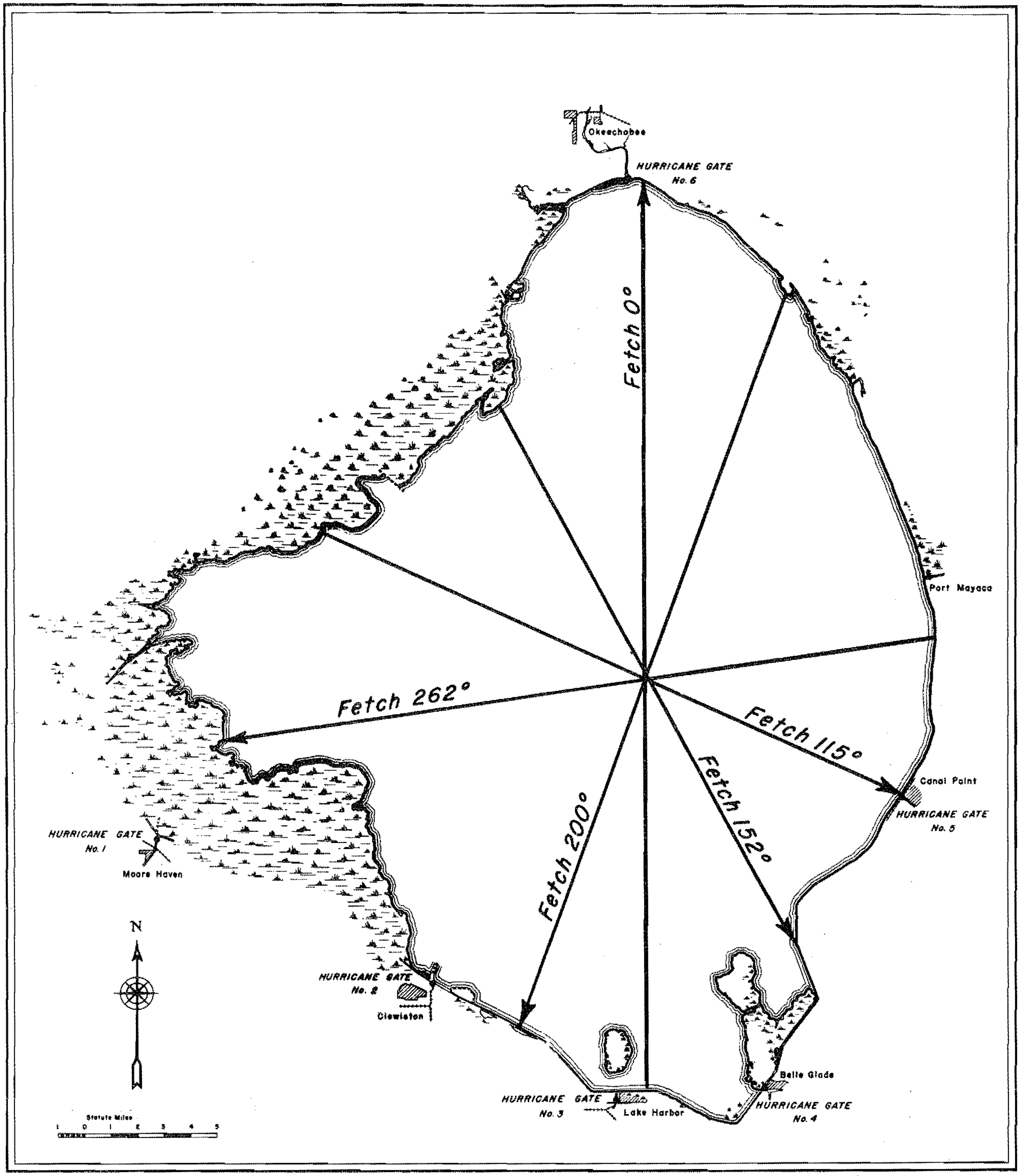

N
0300
0200
0100
0000
2300
2200
2100
2000
1900
1800
1700
SCALE IN MILES
10 0 10 20 30 40 50 60
SPEED (M P H)
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
DISTANCE
DEFLECTION ANGLE
0 10 20 30 40
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
DISTANCE
TROPICAL STORM
OF SEPTEMBER 16-17, 1928

FIG. 13



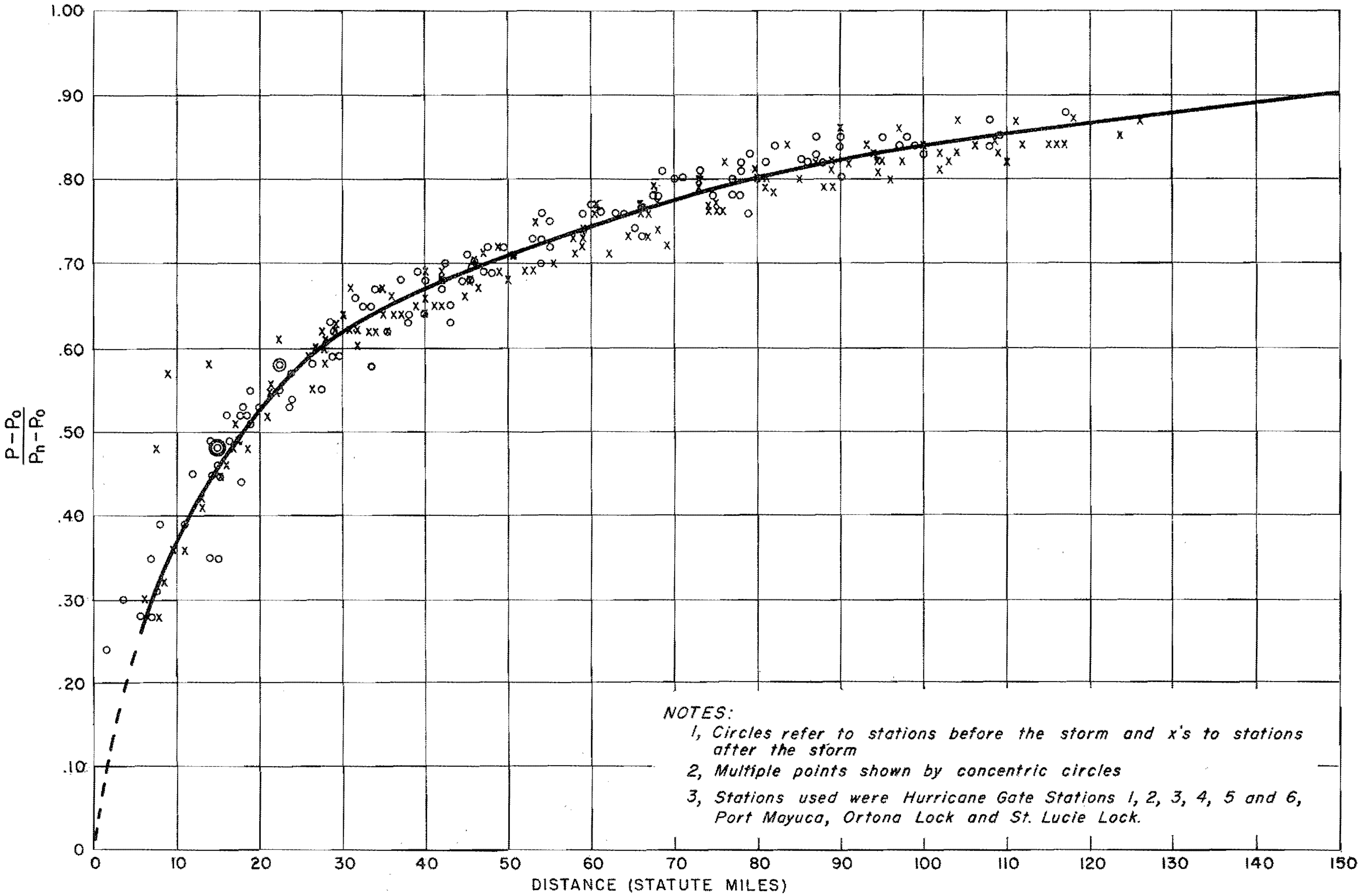
TROPICAL STORM
OF SEPTEMBER 18, 1926

FIG. 14



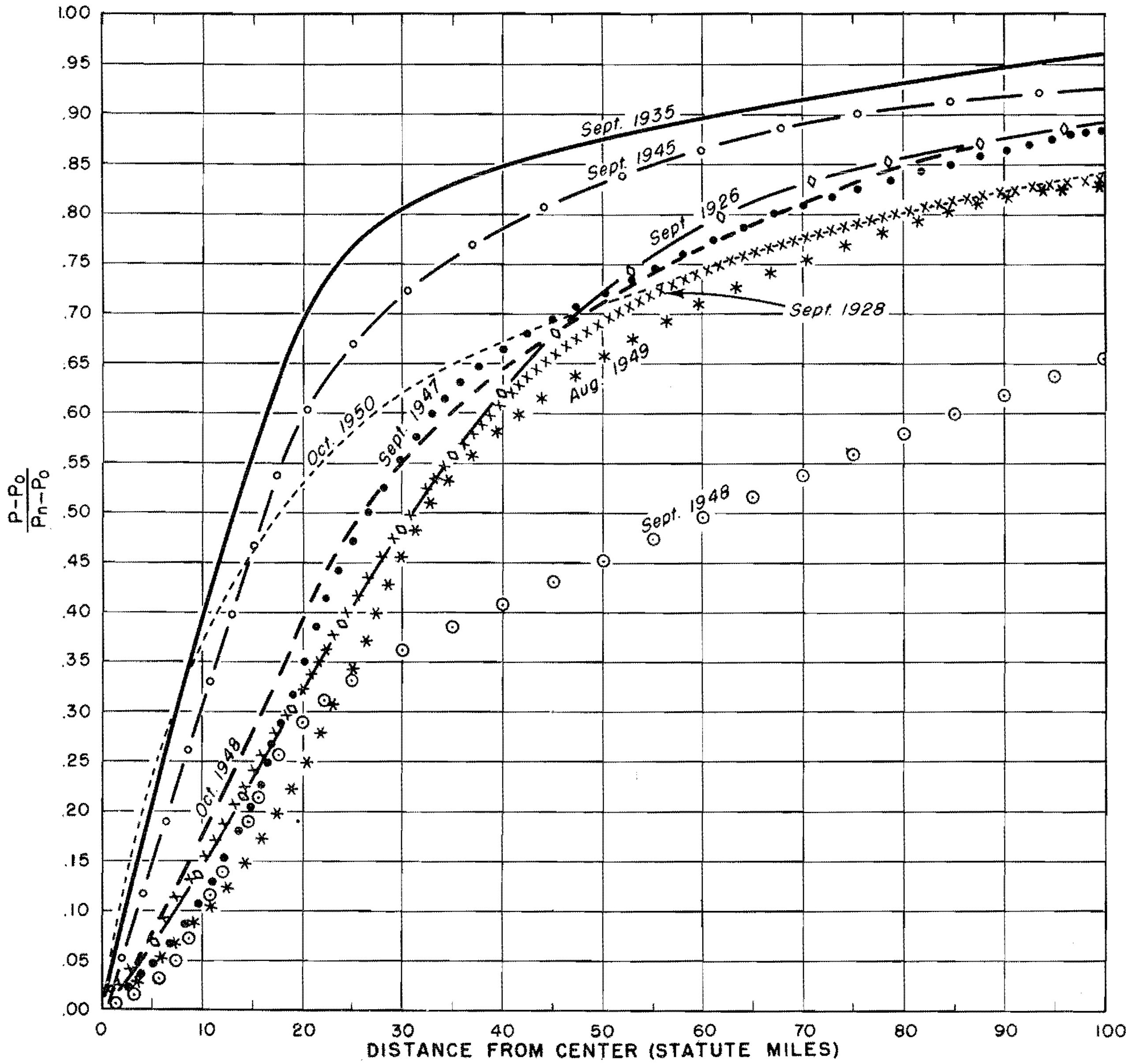
CRITICAL FETCH LINES

FIG. 15



PARAMETRIC PRESSURE PROFILE, STORM OF OCTOBER 17-18, 1950

FIG. 16



PARAMETRIC PRESSURE PROFILES OF FLORIDA HURRICANES

FIG. 17

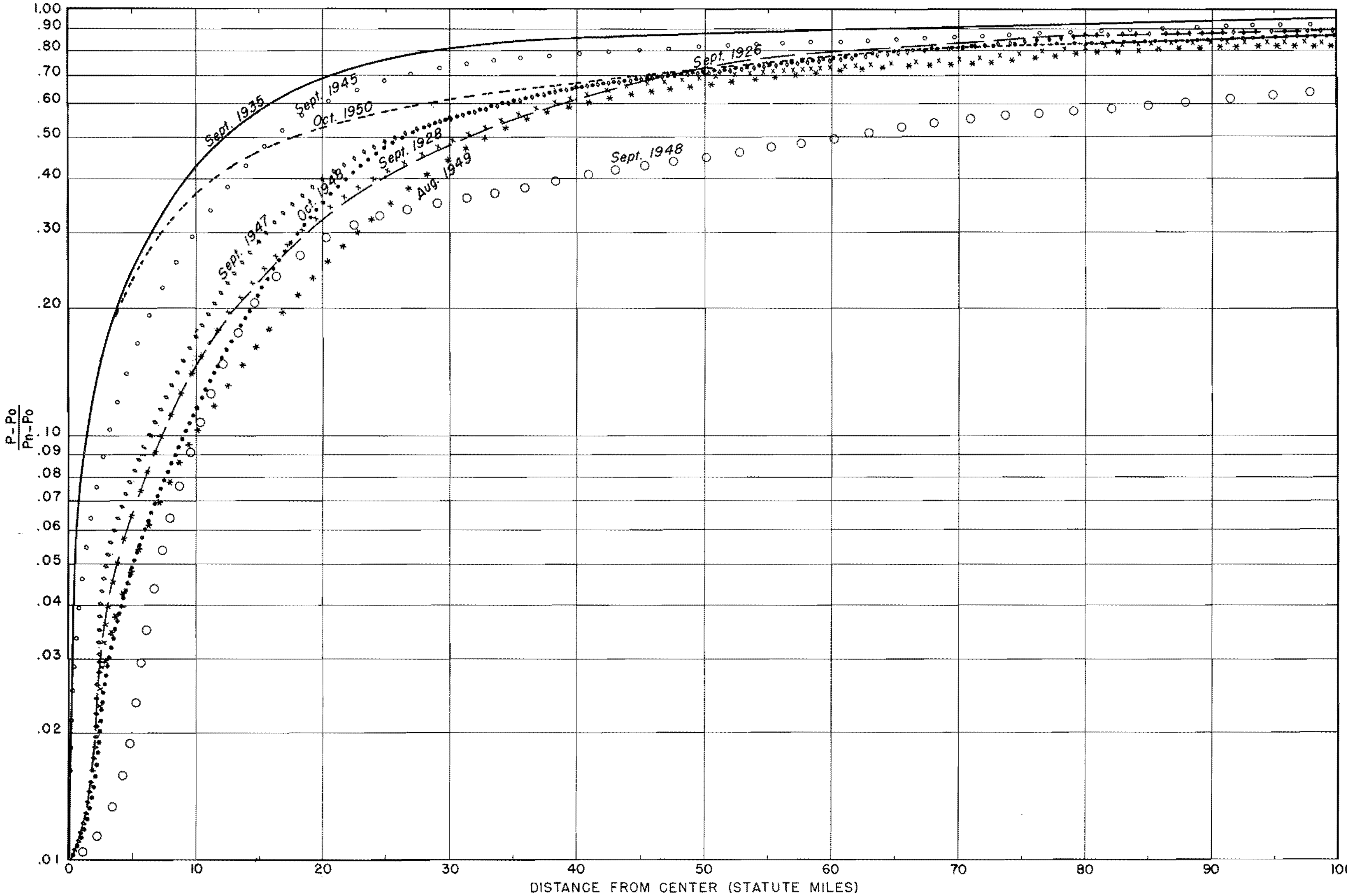
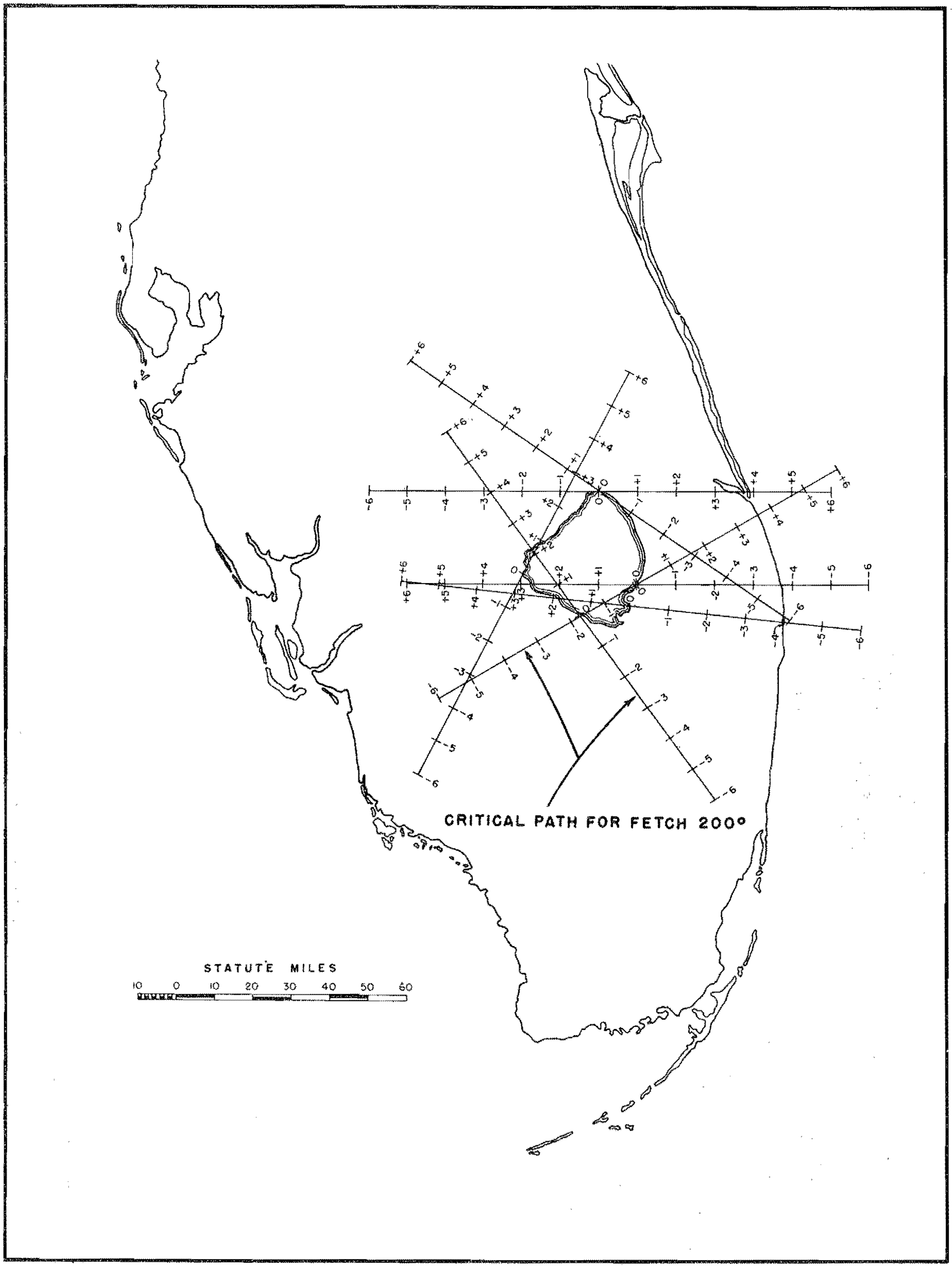
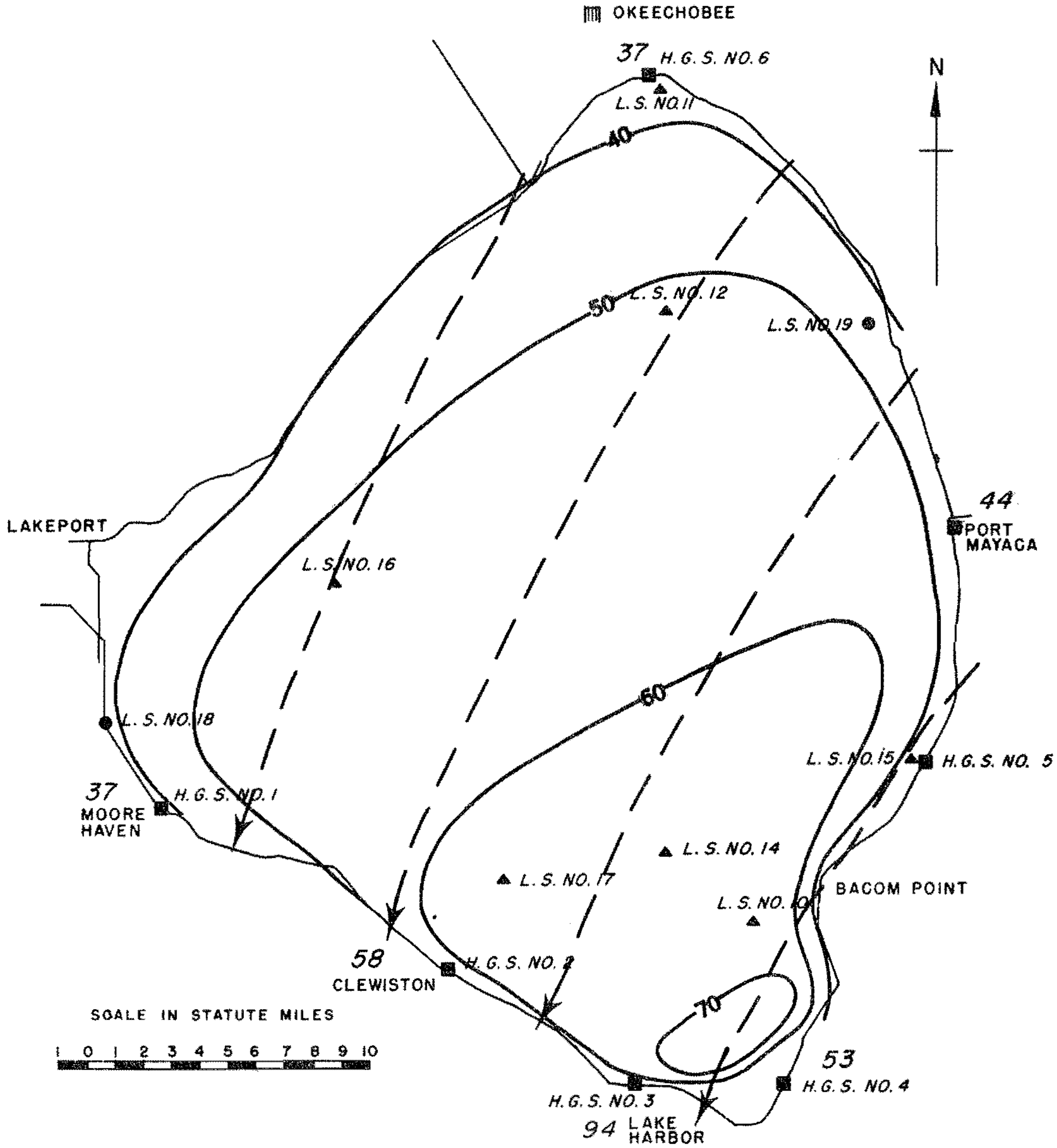


Fig. 18 PARAMETRIC PRESSURE PROFILES OF FLORIDA HURRICANES



CRITICAL PATHS FOR SYNTHESIZED HURRICANES

FIG. 19

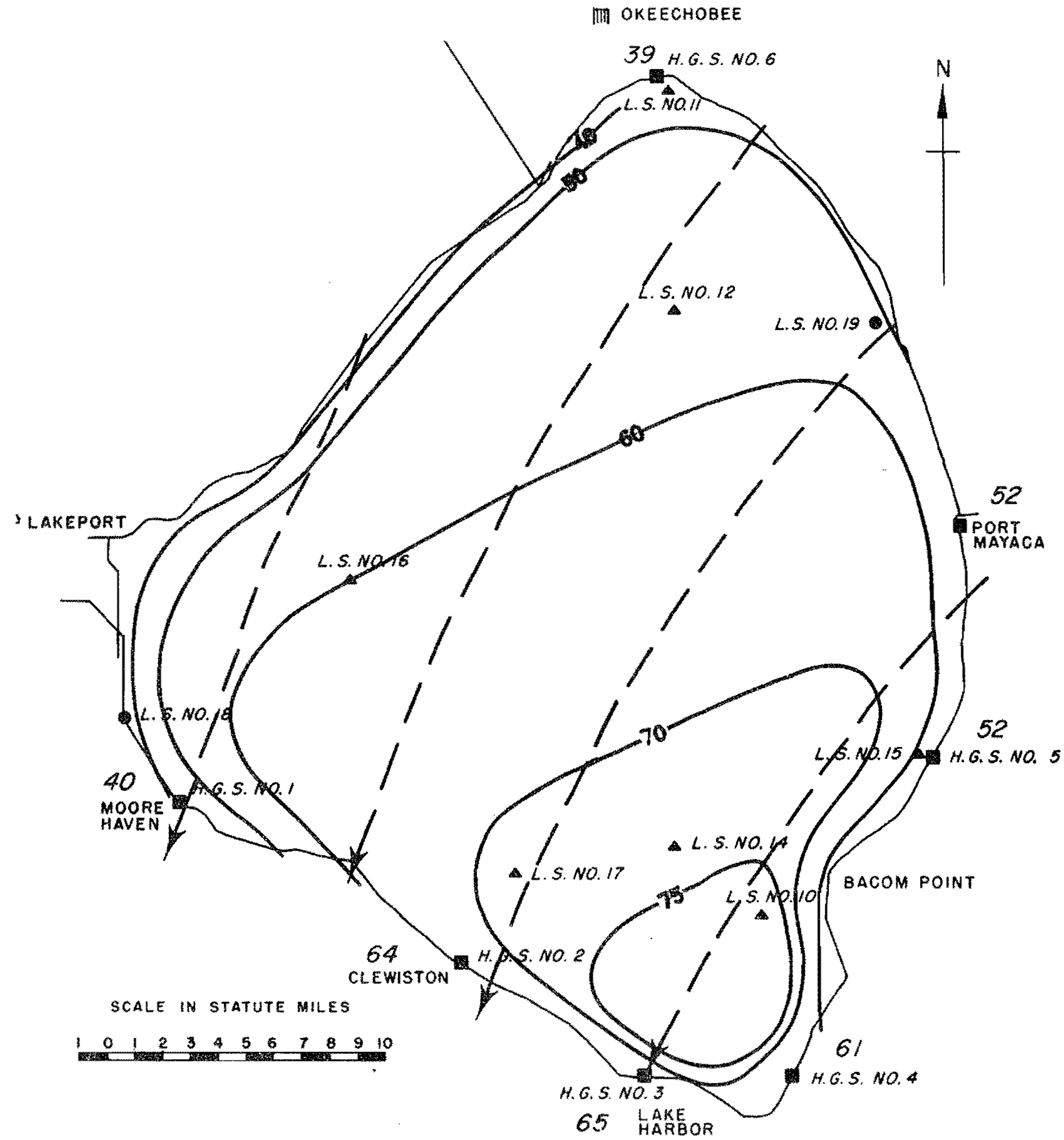


SYNTHESIZED HURRICANE WINDS OVER LAKE OKEECHOBEE

Time: -6 Hours

Speed 10 m.p.h., Path from 145°, P_0 = 931 mbs., P_n = 1015 mb., R=20 miles

FIG. 20 (a)

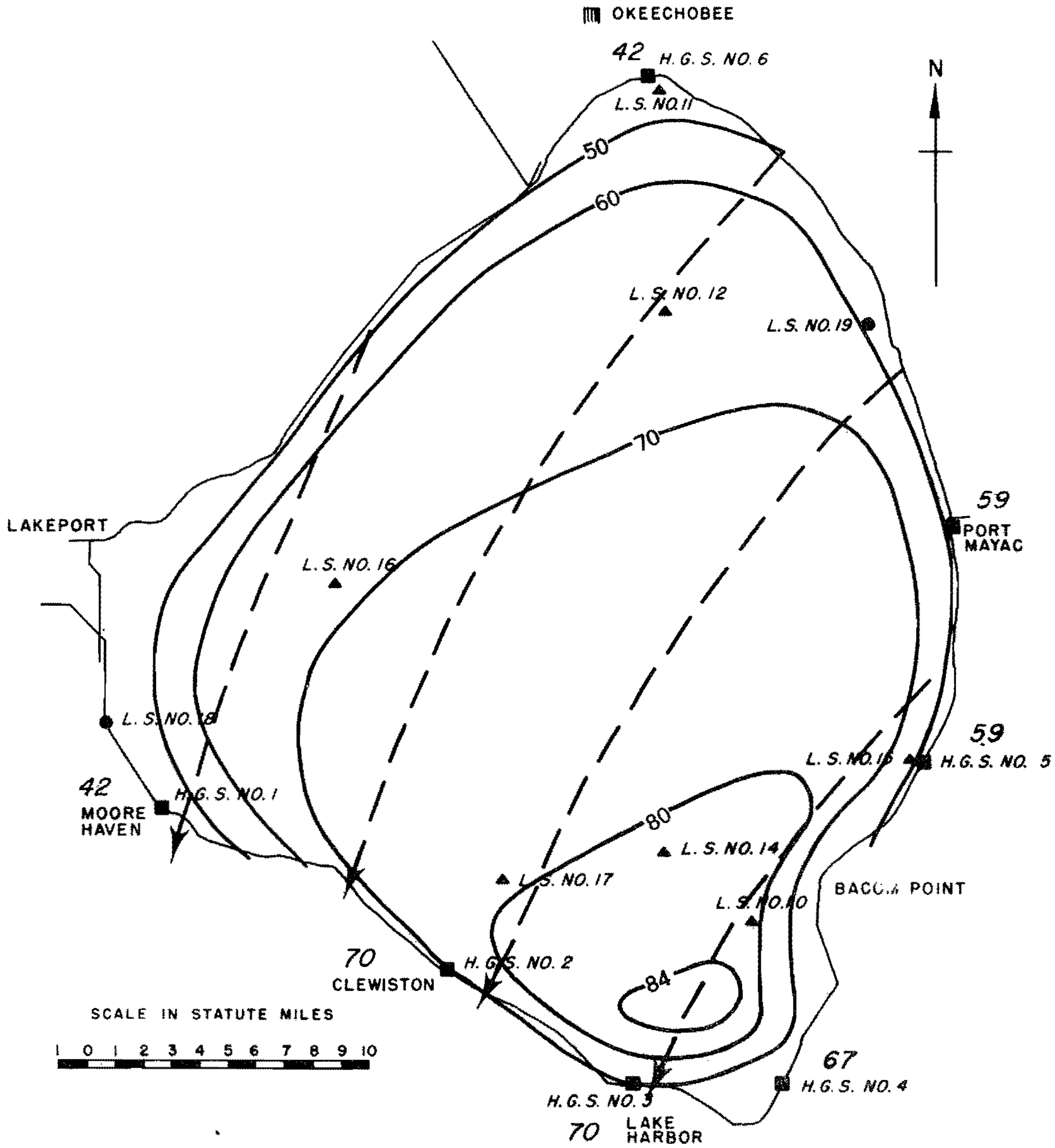


SYNTHESIZED HURRICANE WINDS OVER LAKE OKEECHOBEE

Time: -5 Hours

Speed 10 m.p.h., Path from 145°, P_o = 931 mbs., P_n = 1015 mbs., R= 20 miles

FIG. 20 (b)

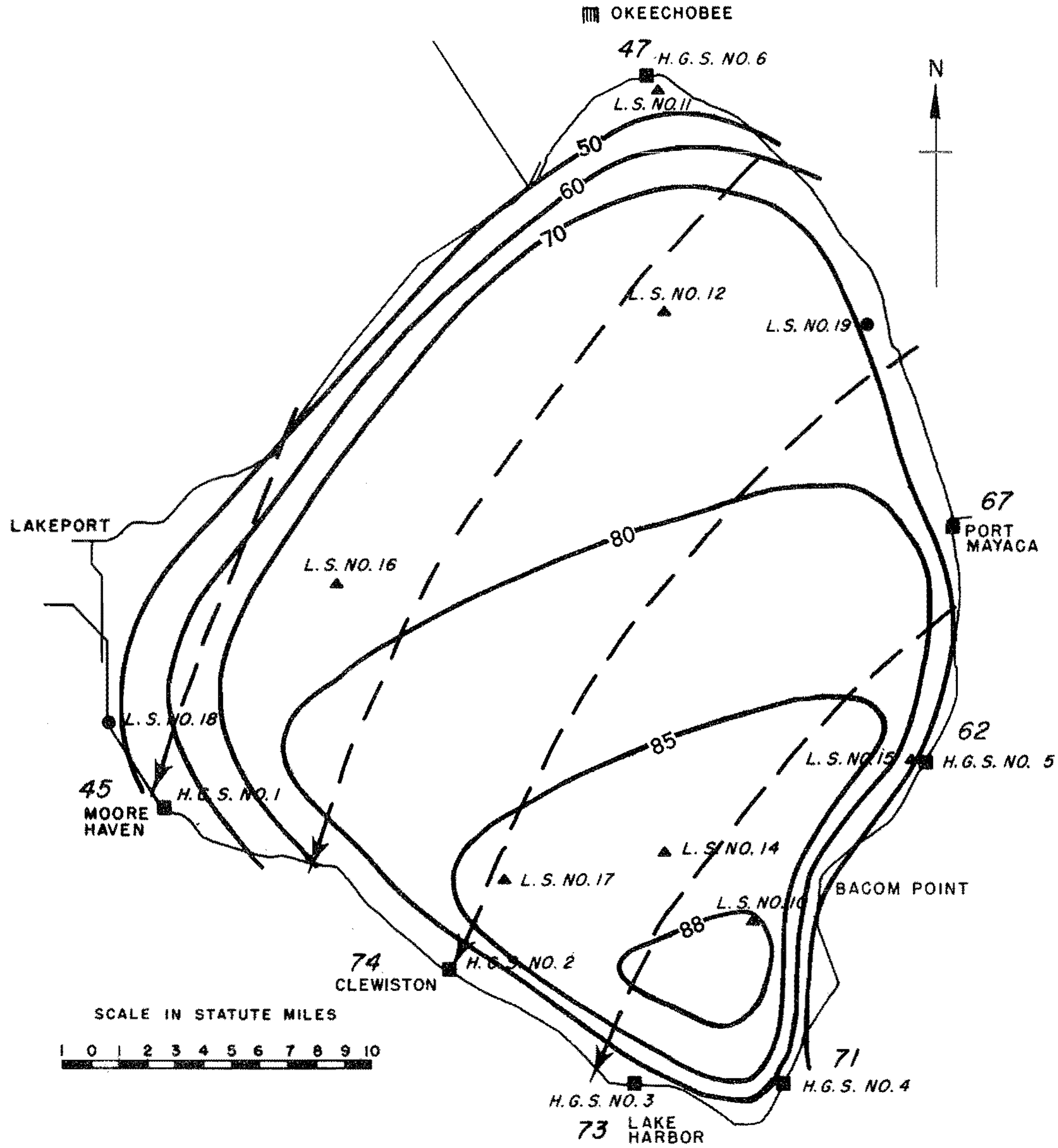


SYNTHESIZED HURRICANE WINDS OVER LAKE OKEECHOBEE

Time: -4 Hours

Speed 10 m.p.h., Path from 145°, P_o = 931 mbs., P_n = 1015 mbs., R = 20 miles

FIG. 20 (c)

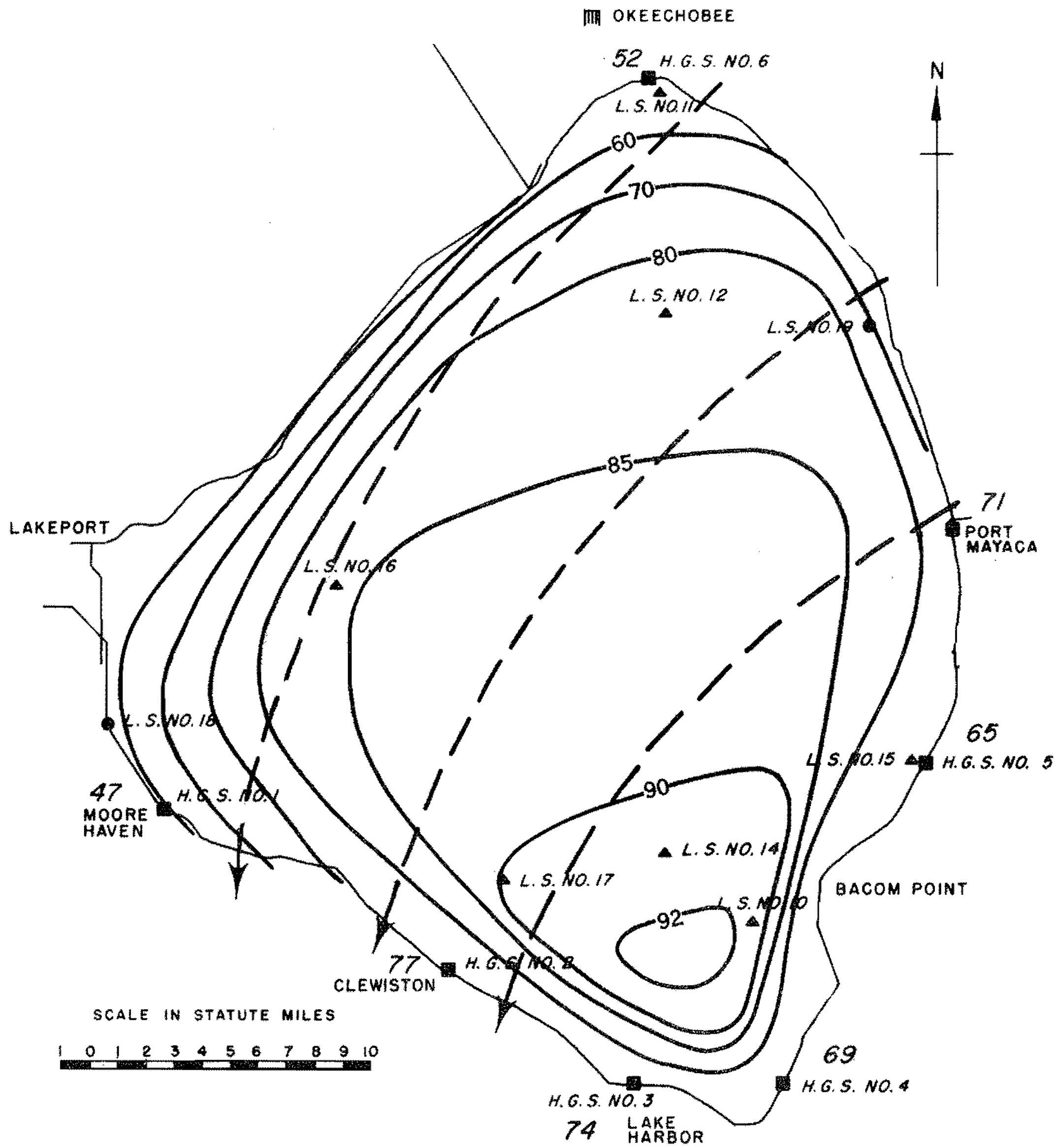


SYNTHESIZED HURRICANE WINDS OVER LAKE OKEECHOBEE

Time: -3 Hours

Speed 10 m.p.h., Path from 145°, P_o = 931 mbs., P_n = 1015 mbs., R= 20 miles

FIG. 20 (d)

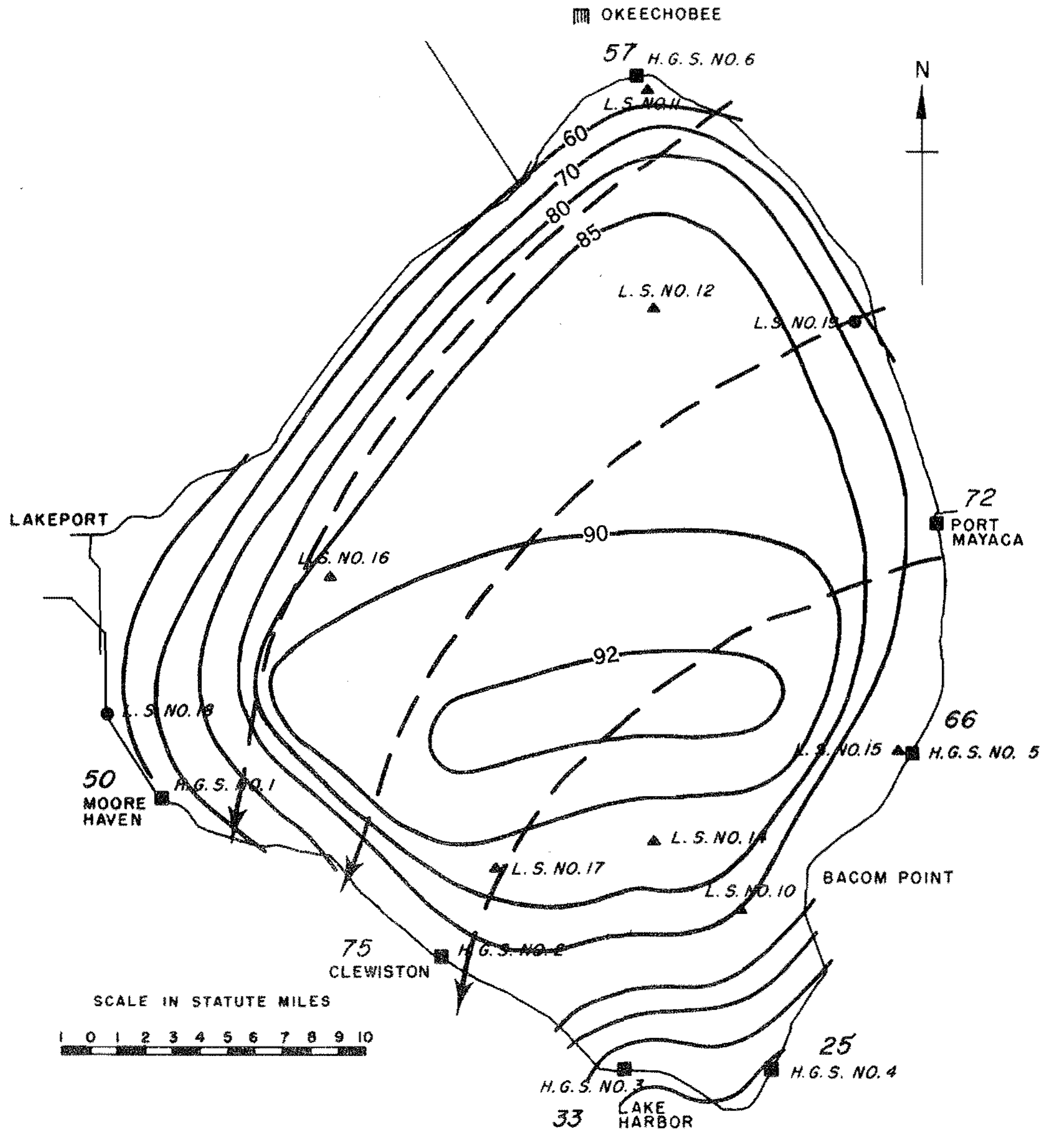


SYNTHESIZED HURRICANE WINDS OVER LAKE OKEECHOBEE

Time: −2 Hours

Speed 10 m.p.h., Path from 145°, P_o = 931 mbs., P_n = 1015 mbs., R= 20 miles

FIG. 20 (e)

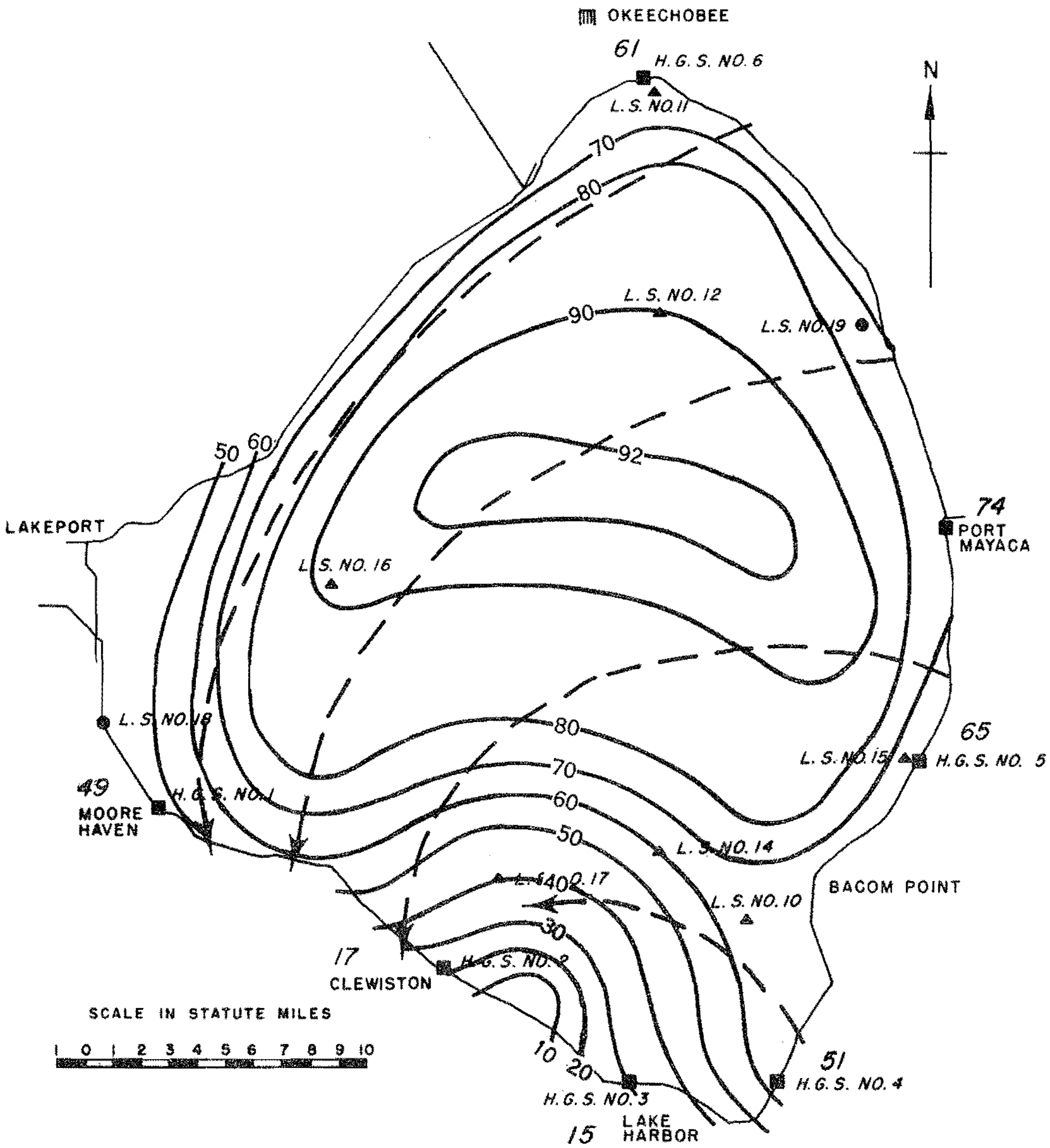


SYNTHESIZED HURRICANE WINDS OVER LAKE OKEECHOBEE

Time: -1 Hour

Speed 10 m.p.h., Path from 145°, P_o = 931 mbs., P_n = 1015 mbs., R = 20 miles

FIG. 20 (f)

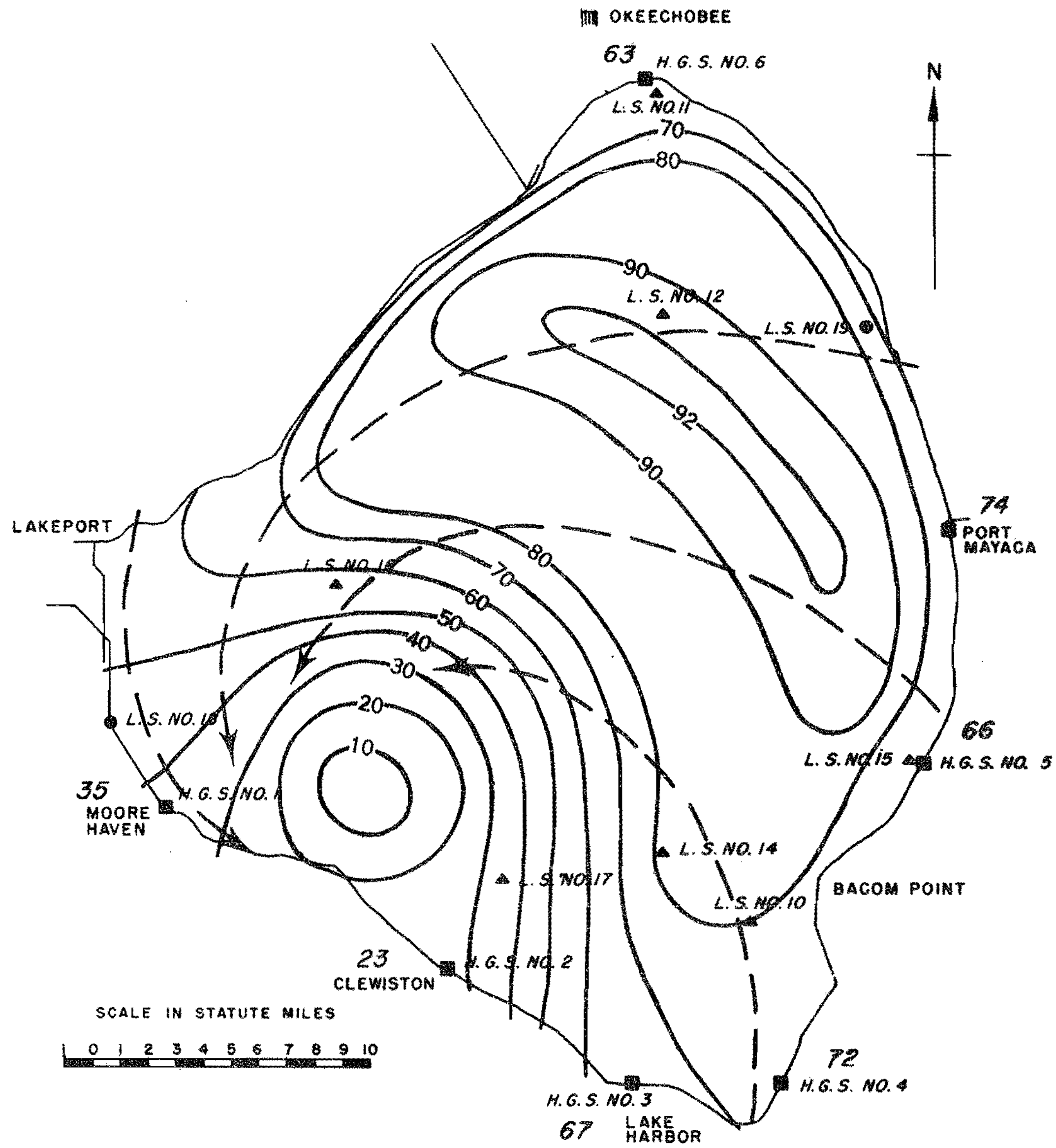


SYNTHESIZED HURRICANE WINDS OVER LAKE OKEECHOBEE

Time: -0 Hour

Speed 10 m.p.h., Path from 145°, P_o = 931 mbs., P_n = 1015 mbs., R= 20 miles

FIG. 20 (g)

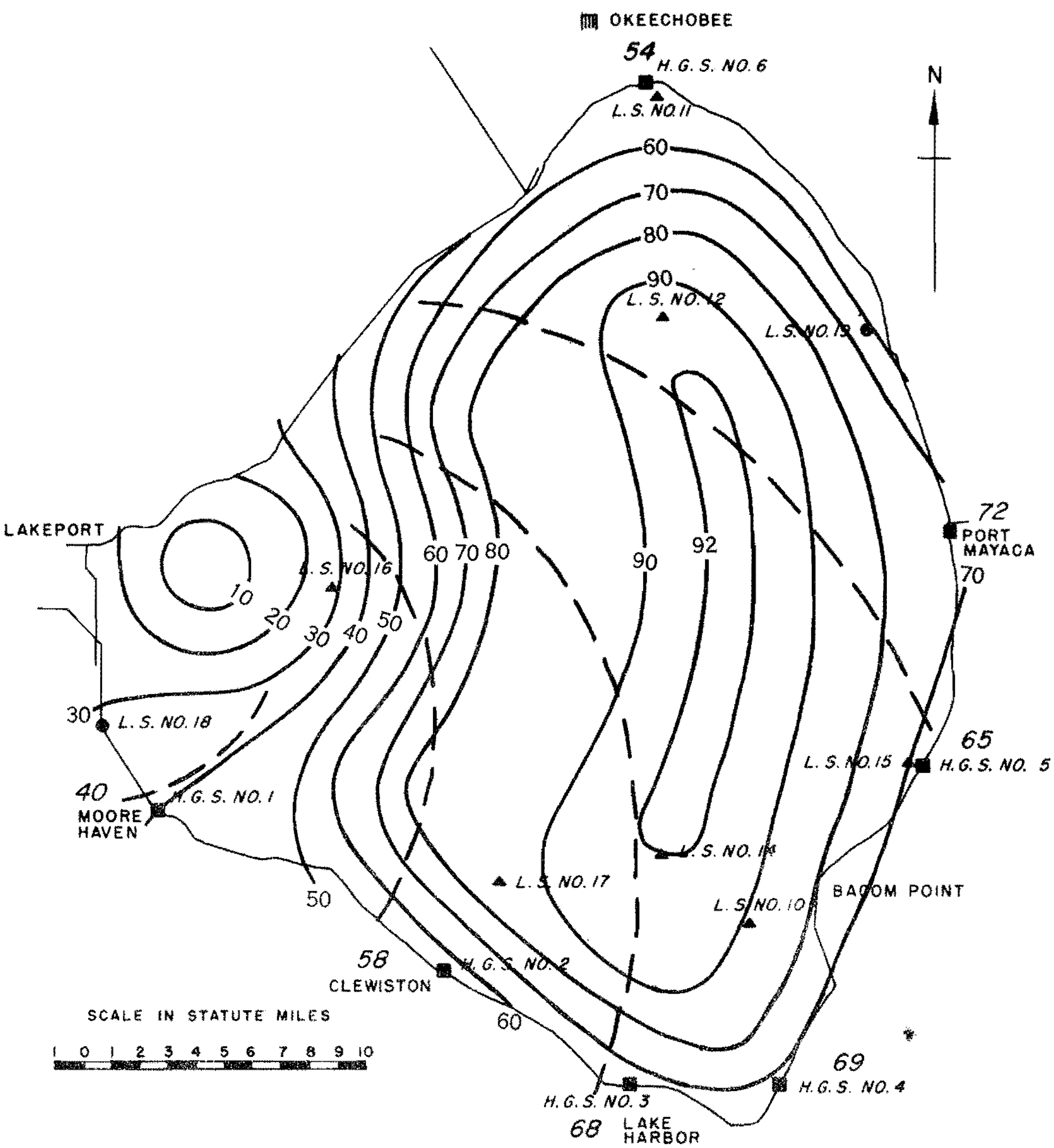


SYNTHESIZED HURRICANE WINDS OVER LAKE OKEECHOBEE

Time: + 1 Hour

Speed 10 m.p.h., Path from 145°, P_o = 931 mbs., P_n = 1015 mbs., R= 20 miles

FIG. 20 (h)



SYNTHESIZED HURRICANE WINDS OVER LAKE OKEECHOBEE

Time: + 2 Hours

Speed 10 m.p.h., Path from 145°, P = 931 mbs., P = 1015 mbs., R = 20 miles

FIG. 20 (i)

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